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# A SAFETY ASSESSMENT OF ROTARY MODE CORE SAMPLING IN FLAMMABLE GAS SINGLE SHELL TANKS: HANFORD SITE, RICHLAND, WASHINGTON

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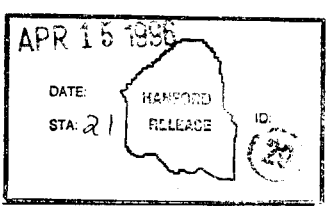


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# A SAFETY ASSESSMENT of ROTARY MODE CORE SAMPLING in FLAMMABLE GAS SINGLE SHELL TANKS: HANFORD SITE, RICHLAND, WASHINGTON

by

Waste Tank Safety Analysis Team

Nuclear Systems Design and Analysis Group
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WHC-SD-WM-SAD-035, Rev. 0

U.S. DEPARTMENT OF ENERGY

March 22, 1996

LOS ALAMOS NATIONAL LABORATORY

## EXECUTIVE SUMMARY

This safety assessment (SA) addresses each of the required elements associated with the installation, operation, and removal of a rotary-mode core sampling (RMCS) device in flammable-gas single-shell tanks (SSTs). The RMCS operations are needed in order to retrieve waste samples from SSTs with hard layers of waste for which push-mode sampling is not adequate for sampling.

In this SA, potential hazards associated with the proposed action were identified and evaluated systematically. Several potential accident cases that could result in radiological or toxicological gas releases were identified and analyzed and their consequences assessed. Administrative controls, procedures and design changes required to eliminate or reduce the potential of hazards were identified.

The accidents were analyzed under nine categories, four of which were burn scenarios. In SSTs, burn accidents result in unacceptable consequences because of a potential dome collapse. The accidents in which an aboveground burn propagates into the dome space were shown to be in the "beyond extremely unlikely" frequency category. Given the unknown nature of the gas-release behavior in the SSTs, a number of design changes and administrative controls were implemented to achieve these low frequencies. Likewise, drill string fires and dome space fires were shown to be very low frequency accidents (< 1.0E-6/yr) by taking credit for the design changes, controls, and available experimental and analytical data. However, a number of Bureau of Mines (BOM) tests must be completed before some of the burn accidents can be dismissed with high confidence.

Under the category of waste fires, the possibility of igniting the entrapped gases and the waste itself were analyzed. Experiments are being conducted at the BOM to demonstrate that the drill bit is not capable of igniting the trapped gas in the waste. Laboratory testing and thermal analysis demonstrated that, under normal operating conditions, the drill bit will not create high enough temperatures to initiate a propagating reaction in the waste. However, system failure that coincides in a waste layer with high organic content and low moisture may initiate an exothermic reaction in the waste. Consequently, a conservative approach based on the current state of the knowledge resulted in limiting the drilling process to a subset of the flammable-gas tanks.

Accidents from the chemical reactions and criticality category are shown to result in acceptable risk. A number of accidents are shown to potentially result in containment (tank liner) breach below the waste level. Mitigative features are provided for these accidents. Gas-release events without burn also are analyzed, and radiological and toxicological consequences are shown to be within risk guidelines. Finally, the consequences of potential spills are shown to be within the risk guidelines.

Accidents associated with external events also are addressed in this SA. For the SSTs, large seismic events with low frequency may result in catastrophic dome failure.

However, such events and their consequences are independent of the RMCS operations. Lightning is considered a potential initiator for burn accidents.

The conservative consequences of the accidents are compared with the WHC risk guidelines using accident frequencies obtained on a per tank and per year basis. All of the accidents analyzed in this SA are shown to meet the radiological and toxicological risk guidelines. The on-site and off-site consequences of a burn in an SST dome space are high because of a potential dome collapse and do not meet the risk guidelines if not mitigated. Mitigated frequency of the dome collapse accident is shown to be $<10^{-6}$/yr.

There are a number of unresolved issues or open items that must be resolved before this SA can be used as a safety basis document for the RMCS operations in flammable-gas tanks. Unresolved issues and open items are listed in Section 7 of this SA. The major issues are summarized below.

1. The most important issue is related to the ignition tests that are being conducted at the BOM. This SA very strongly relies on the results of the BOM experiments. The requirements and acceptance criteria for the ignition tests are listed in Appendix T of this SA.

2. This SA is taking considerable credit for the reliability and detection capacity of the flammable-gas meters (FGMs) as the primary flammable-gas detection and shut-down system. This system is currently being designed. The requirements for the flammable-gas detection system are discussed in Appendix U of this SA.

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## ACRONYMS

| ACRONYM | DEFINITION |
|---|---|
| 1-D | one-dimensional |
| 2-D | two-dimensional |
| AED | aerodynamic equivalent diameter |
| AIChE | American Institute of Chemical Engineers |
| ALARA | as low as reasonably achievable |
| AMCA | American Metal Constructors Association |
| ANL | Argonne National Laboratory |
| ANSI | American National Standards Institute |
| ARC | Accelerated rate calorimetry |
| ASA | Accelerated Safety Analysis |
| ASTM | American Society for Testing and Materials |
| BOM | Bureau of Mines |
| CAA | Chronic annual average |
| CANDU | Canadian reactor licensing |
| CB | Containment Breach |
| CC | concentrated complexant |
| CEDES | committed effective dose equivalents |
| CEL | Chemical Engineering Laboratory |
| CGM | Combustible Gas Meter |
| CL | convective layer |
| DBA | design basis accident |
| DBA | Design Basis Accident |
| DBE | design basis earthquake |
| DC | dilute complexed (waste) |
| DCRT | double-contained receiver tank |
| DDT | Deflagration-to-Detonation |
| DIP | Differential Indicating Probe |
| DOE | Department of Energy |
| DOE-RL | Department of Energy-Richland |
| DR | damage ratio |
| DS | drill string |

| ACRONYM | DEFINITION |
|---|---|
| DSC | Differential Scanning Calorimetry |
| DSF | dome space fire |
| DSSF | double-shell slurry feed |
| DST | double-shell tank |
| DTA | Differential Thermal Analysis |
| EDE | effective dose equivalents |
| EDTA | Ethylenediaminetetra-acetic acid |
| ERDA | (US) Energy Research & Devlopment Adminstration |
| ERPG | Emergency Response Planning |
| EXF | external fire |
| FGWL | Flammable Gas Watch List |
| GRE | gas-release event |
| HA | hazard analysis |
| HASP | Health and Safety Plan |
| HAZOP | hazards and operaability |
| HBD | hydraulic bottom detector |
| HEDTA | Hydroxyethyl-ethylenediaminetriacetic acid |
| HEPA | high-efficiency particulate air (filter) |
| HIS | Hazards Identification Study |
| HMS | Hanford Meteorlogical Station |
| HTWRS | Hanford tank waste remediation system |
| I&C | instumentation and control |
| IEEE | Institute of Electrical and Electronic Engineers |
| IRRAS | Interim Reliabililty Risk Assessment System |
| ISB | Interim Safety Basis |
| L/D | length-to-diameter |
| LANL | Los Alamos National Laboratory |
| LASAN | Los Alamos Systems Analysis |
| LCO | Limiting Conditions for Operation |
| LFL | lower (or lean) flammability limit |
| LOW | Liquid observation well |
| LPF | leak path factor |
| MAF | mitigated accident frequency |

| ACRONYM | DEFINITION |
|---|---|
| MAR | material at risk |
| MEI | Maximum Exposed Individual |
| MIST | Minimum ignition surface temperature |
| MMD | mass median diameter |
| NCPLX | noncomplexed waste |
| NEC | National Electric Code |
| NFPA | National Fire Protection Association |
| NRC | Nuclear Regulatory Commission |
| NSSFC | National Severe Storms Forecast Center |
| NUREG | US Nuclear Regulatory Commission |
| OSD | operational safety document |
| OSR | Operational Safety Requirement |
| PEL-TWA | permissable exposure limit time-weighted average |
| PG | (gas switch) |
| PIC | person in charge |
| PLC | Programmable Logic Controller |
| PLM | programmable logic module |
| PM | plume meander |
| PNNL | Pacific Nortwest Larboratories |
| PPF | pump pit fire |
| PVC | polyvinyl chloride |
| RAG | Risk Acceptance Guidelines |
| RCV | ram control valve |
| RF | respirable fraction |
| RLU | remote latch unit |
| RMCS | rotary-mode core sampling |
| RSST | Reactive Systems Screening Tool |
| SA | safety assessment |
| SC I | Safety Class I |
| SEI | seismic event |
| SHMS | Standard Hydrogen Monitoring Systems |
| SOV | solenoid-operated valve |
| SR | shielded receiver |

| ACRONYM | DEFINITION |
|---|---|
| SSFGWLT | Single-Shell Flammable Gas Watch List Tank |
| SMM | Supernate mixing model |
| SST | Single-shell tank |
| SWF | salt well fire |
| SWP | Salt well pumping |
| TC | thermocouple |
| TEDE | Total Effective Dose Equivalent |
| TGR | toxic gas release |
| TI | Total Inventory |
| TLM | Tank layer model |
| TLS | Transfer line spills |
| TOC | Total organic compound |
| TRG | Test Review Group |
| TWRS | Tank Waste Remediation System |
| UAF | unmitigated accident frequency |
| ULD | unit-liter dose |
| UOR | Unusual occurrence report |
| USQ | unresolved safety question |
| WHC | Westinghous Hanford Company |
| ZPA | Zero-Period Accleration |

# 1.0. SCOPE

This safety assessment (SA) addresses each of the proposed elements required to evaluate the installation, operation, and removal of rotary-mode core sampling (RMCS) equipment in single-shell tanks (SSTs) on the Flammable Gas Watch List (FGWL) or those tanks recommended by the contractor to be included on the FGWL, hence referred to as FG/RMCS operations. These tanks, referred to as flammable-gas tanks (FGTs), are located within the 200 Area in Hanford Site, Richland, Washington. Specifically, this SA addresses the proposed action to install, operate, and remove an FG/RMCS device in the subject tanks.

The objective of this SA is to (1) systematically identify each of the potential hazards associated with these proposed sampling actions, (2) analyze each of the resultant accident sequences, (3) assess the consequences of the accident sequences, and (4) identify the controls and procedures necessary to eliminate or reduce the potential hazards. Section 1 of this SA provides the background information for the proposed actions, discusses the no-action alternative, and outlines the safety assessment approach and scope. Also included in Section 1 is a summary of the significant characteristics of the single-shell tank (SST) farms.

## 1.1. Background and Purpose of the Proposed Action

The Department of Energy (DOE) is responsible for the management and storage of the waste accumulated from processing defense reactor irradiated fuels for plutonium recovery at the Hanford Site. Currently, there are 177 waste tanks, including 149 SSTs and 28 double-shell tanks (DSTs) located in the 200 area of the Hanford reservation. These wastes, consisting of liquids and solids, are stored in underground storage tanks pending final disposition. A systems approach, managed as part of the tank waste remediation system (TWRS), has been adopted to address the complex and interrelated activities associated with the management and disposal of Hanford tank wastes. The goal of the TWRS is to reduce the environmental, safety, and health risks inherent in the Hanford tank waste operation and remediation. The highest priority for this program is to identify a corrective action strategy for each waste tank safety issue and to mitigate known safety concerns. The four safety issues include (1) flammable-gas generation and concentrations that exceed the lower flammability level (LFL); (2) tanks containing mixtures of ferrocyanide compounds and nitrate/nitrite materials that could, if specific concentrations and conditions were to occur, support an exothermic reaction leading to an explosion; (3) tanks containing organic compounds that could, if locally concentrated, support an exothermic reaction; and (4) Tank 241-106-C, which contains a strontium source generating high heat that requires periodic cooling.

This SA is primarily concerned with SSTs that are on the FGWL or have been recommended by the contractor for inclusion on the FGWL. These tanks are listed and discussed in Section 2.

Rotary-mode drilling is necessary only for the SSTs with hard waste layers where waste samples cannot be obtained using the push-mode sampler. The rotary core sampling yields certain hazards that result, if not mitigated, in consequences beyond those analyzed in the push-mode sampling safety assessment.[1] Therefore, an Unreviewed Safety Question (USQ) evaluation was performed. It was concluded that the FG/RMCS operations are not covered by the current authorization and that a separate SA was needed to perform rotary-mode core sampling operations on FGTs. This SA fulfills that need.

### 1.2. Safety Assessment—Scope and Approach

The scope of this SA is to provide a safety basis for the FG/RMCS operations in the single-shell FGTs. In order to develop an SA that aims to be bounding for FG/RMCS operations on all FGTs, the following methodology was implemented. The identification of hazards associated with the installation, operation, and removal of the FG/RMCS was performed in a generic tank. Accident sequences are also developed from the evaluated hazards in a generic way. Accident analysis and resulting controls required the discussion of specific parameters pertinent to each SST. A set of bounding tank parameters was not determined through detailed analysis. Instead, a representative tank was chosen that was shown to have bounding tank parameters by performing a preliminary screening process. Accident analyses were performed with this anticipated set of bounding tank parameters. At the time the first revision of this SA was issued, the anticipated bounding tank parameters were not screened in detail for all the tanks of interest. Furthermore, it is anticipated that additional tanks will be designated as FGTs in the near future after the completion of this SA. One must especially be careful in applying this SA to tanks that are on other watch-lists (organic, ferrocyanide, etc). This SA was primarily concerned with the flammable-gas issues, and hazards specific to tanks on other watch lists may not have been properly addressed in this document. Thus, a screening process with a checklist of items was developed. The controls produced in this SA will require the review and approval of the screening results against the checklist for performance of the FG/RMCS in specific tanks by the Plant Review Committee (PRC). The PRC may charter a separate technical review group to perform the review and approval responsibilities of the PRC. Also the WHC Design Authority is responsible for all aspects of equipment design.

This SA is developed using the guidelines provided in Ref. 2. The approach implemented in this SA incorporates a systematic evaluation of the potential hazards related to rotary-mode core sampling in tanks with a flammable environment and the activities required for the installation, operation, and removal of the equipment. For the potential hazards identified, evaluations were completed to establish their potential severity and the resultant consequences of accidents that may occur in response to these hazards. These evaluations consisted of detailed analyses and evaluations using analytical and numerical techniques, routine engineering calculations, and/or a review of existing information to

establish the consequences, if any, of these hazards. Finally, this SA identifies the procedures and controls implemented to prevent or mitigate the consequences of these hazards.

Commensurate with this approach, an SA format is developed in Ref. 3. Section 2 of the SA describes the equipment, subsystems, and procedures used during FG/RMCS operations. Section 3 then systematically defines the hazards, causes, and potential accident sequences anticipated, not only with the FG/RMCS operational phase, but also with installation and removal activities. Section 4 assesses the identified hazards in Section 3, followed by a consequence analysis of the postulated accidents in Section 5. Section 6 defines both design changes and administrative/procedural controls that are required to ensure an acceptable level of safety during FG/RMCS operations, especially in a flammable environment. In Section 7, a checklist is provided which contains the open issues that must be closed and the items that must be addressed in applying this SA to all FGTs.

This format addresses all the activity related elements listed in U.S. Department of Energy (DOE) Guidance document 3011-94 (Ref. 4). Reference 4 is primarily aimed at safety documents developed for a facility whereas this SA is aimed at a specific activity, namely the RMCS operations in FGTs. Thus, most of the facility related sections of the 3011 Guidance are not addressed in this SA. However, a brief summary of the significant characteristics of the single-shell tank farms and their environment are provided in Section 1.4 of this SA.

### 1.3. No-Action Alternative

Tank characterization is a high-priority activity at the Hanford site, and FG/RMCS is the proposed retrieval technique for SST samples. A "no-action" alternative would prevent or delay full-depth core sampling activities in SSTs that are FGTs. The analysis of these waste samples is very important for the following reasons:

- For addressing the issues associated with the safe storage of the waste, and
- For developing sound strategies for the retrieval and ultimate disposal of the waste.

Currently, there is no engineered or conceptualized design that can replace the FG/RMCS equipment for obtaining samples from hard waste layers for which the push mode sampling is not adequate.

### 1.4. Summary of Significant Characteristics of the Single-Shell Tank Farms and Their Environment

All the SSTs of interest are located in the 200-Area at the Hanford Reservation, as shown in Fig. 1-1. Detailed descriptions of the SSTs and SST tank farms are provided in Refs. 5 and 6. Specific characteristics of the SSTs pertinent to this SA are

discussed in Section 2 and other parts of the SA when needed. This section provides a summary of the descriptive information for the site.

A detailed and comprehensive description of the Hanford Site is presented in documents developed by the (US) Energy Research and Development Administration (ERDA), DOE, and the Pacific Northwest Laboratory (PNL).[7-9] This section summarizes results presented in these references and others as they apply to the 200-Areas. The DOE Hanford Site lies within the semiarid Pasco Basin of the Columbia Plateau in southeastern Washington State. The Hanford Site occupies an area of ~1450 $km^2$ (570 $mi^2$) north of the confluence of the Snake, Yakima, and Columbia Rivers. This land, with restricted public access, provides a buffer for the smaller areas currently used for the production of nuclear materials, waste storage, and waste disposal; only ~6% of the land area has been disturbed and is actively used. The Columbia River flows through the northern part of the Hanford Site, and, turning south, it forms part of the site's eastern boundary (Fig. 1-2).[10]

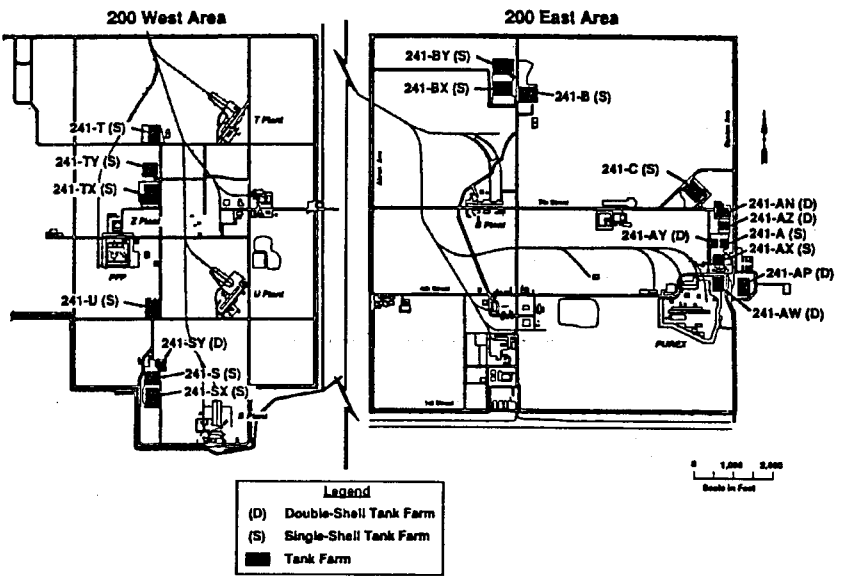


**Fig. 1-1. Location of the Tank Farms within the 200 Area.**

The terrain of the central and eastern parts of the Hanford Site is relatively flat, with evidence in the central part of the Site (including the 200-Area Plateau) of minimal

erosion since the deposition of Hanford Formation sediments by glacial floodwaters ~13,000 yr ago. The soil beneath the tank farm consists of silt, sand, and gravel. The principal geologic units beneath much of the 200-West Area are, in ascending order: (1) the Columbia River Basalt Group, with interbedded sediments of the Ellensburg Formation; (2) the Ringold Formation; (3) the Plio-Pleistocene unit; and (4) the Hanford Formation. The Ringold Formation is ~47.2 m (155 ft) below the surface of the SY Tank Farm.[11]

Two areas of shallow, swarm seismic activity, Coyote Rapids and Cold Creek, are located within 16.1 km (10 mi) of the 200-West Area. The Coyote Rapids swarm area has been the site of eight swarms consisting of 91 shallow seismic events during the period between 1969 and 1986. The depth distribution of these seismic events is bimodal, with maximum activity occurring near the surface and at a depth of 4.0 to 6.9 km (2.5 to 4.3 mi). The Cold Creek swarm area, located 12.9 km (8 mi) south of the 200-West Area, includes 32 events from 1979 to 1986 that occurred at depths up to 4.8 km (3 mi).

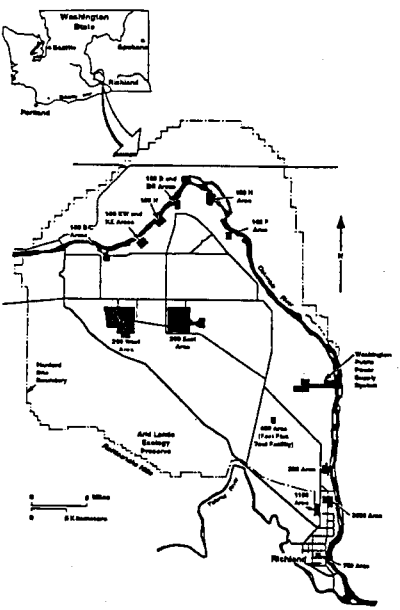

**Fig. 1-2. Location of 200 Area within the Hanford Site.**

Several surface ponds and ditches associated with fuel and waste processing activities are present within the 200-Area (Fig. 1-3).[12] These ponds and ditches are used primarily as wasteways for process and cooling water and sometimes contain small quantities of radionuclides (both fission products and transuranic elements). Cold Creek and its tributary, Dry Creek, are ephemeral streams within the Yakima River drainage system along the southern boundary of the Hanford Site. Both streams drain areas to the west of the Hanford Site and cross the southwestern part of the Site toward the Yakima River. The potential for flash flooding from the Cold Creek drainage system has been examined, and a maximum flood depth of 2.1 m (7 ft) was estimated along the southwestern part of the 200-Area plateau. However, the maximum probable flood has not been well defined for the Cold Creek drainage system. A 100-yr peak stage flood, estimated to be ~0.9 m (3 ft) above the Cold Creek Valley floor, would not reach the 200-West Area.[13]

Wastewater ponds on the Hanford Site have recharged the unconfined aquifer below the 200-Area artificially. The increase in water-table elevations was most pronounced from 1950 to 1960 and had approached equilibrium between the unconfined aquifer and the recharge between 1970 and 1980, when only small increases in water-table elevations occurred. Wastewater discharges from the 200-Area were reduced significantly in 1984 (Ref. 14) with an accompanying decline in water-table elevations. The depth to groundwater currently is ~50 to 60 m (164 to 197 ft) in the 200 Area. Groundwater flow direction is generally in an easterly and southeasterly direction, toward the Columbia River.

Lateral groundwater movement occurs within a shallow, unconfined aquifer consisting of fluvial and lacustrine sediments lying on top of the basalts and within deeper confined-to-semiconfined aquifers consisting of basalt flow tops, flow bottom cones, and sedimentary interbeds.[15] Sources of natural recharge to the unconfined aquifer are rainfall and runoff from the higher bordering elevations, water infiltrating from small ephemeral streams, and river water along influent reaches of the Yakima and Columbia Rivers. Artificial recharge to the unconfined aquifer results from the disposal of wastewater to the ground below the 200 Areas from the surrounding highlands. This recharge to the aquifer [5.5 by 104 $m^3/d$ (1.5 by 107 gal./d)] is ~10 times the natural recharge entering the unconfined aquifer below the 200-Areas.[15] Beneath the disposal ponds, groundwater mounds have developed in response to the artificial recharge. Beneath U Pond, located in the 200-West Area, the water table rose ~24.4 m (80 ft) from the start of disposal operations in 1944 (Refs. 16 and 17) until U Pond was decommissioned in 1985. From the recharge areas to the west, the groundwater flows down the gradient to the discharge areas along the Columbia River, interrupted locally by the groundwater mounds in the 200-Areas. The horizontal and vertical extent of these mounds appears to be related directly to the surface discharge of wastewater from facilities in this area.[18]

Climatological data are available from the Hanford Meteorological Station (HMS), which is located between the 200-East and 200-West Areas. Data have been collected at this location since 1945. Temperature and precipitation data also are available from nearby locations for the period of 1912 through 1943. A summary of these data through 1980 has been published in Ref. 19. Data from the HMS are representative of the general climatic conditions for the region and describe the specific climate of the 200-Area Plateau.

The prevailing winds on the 200-Area Plateau are from the northwest. Secondary maxima occur for southwesterly winds. Diurnal and monthly averages and extremes of temperature, dew point, and humidity are contained in Stone et al.[20] Ranges of daily maximum temperatures vary from a normal 2°C (36°F) in early January to 35°C (95°F) in late July. The record maximum temperature is 46°C (115°F), and the record minimum temperature is -32.8°C (-27.0°F). Relative humidity/dew-point temperature measurements are made at the HMS and at the three 61.0-m (200-ft) monitoring tower locations. The annual average relative humidity at the HMS is 45%. It is highest during the winter months

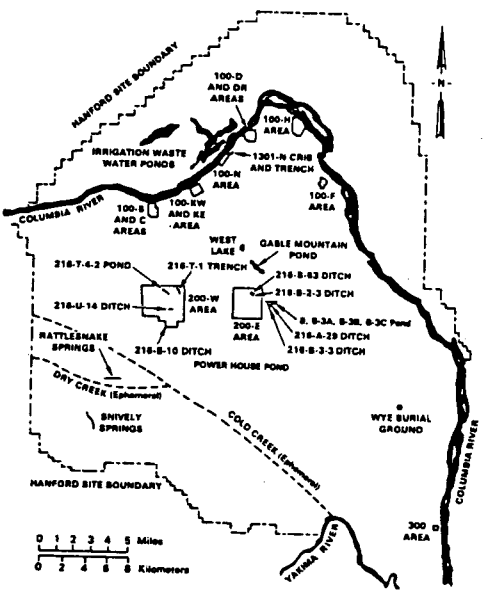


**Fig. 1-3. Locations of surface-water ponds, ditches, and ephemeral streams on the Hanford Site.**

(averaging ~75%) and lowest during the summer (averaging ~35%). At the Hanford Site, the severe-weather phenomenon that occurs most frequently and has the greatest effect is the dust storm.[19] The maximum recorded peak gust at 15 m (50 ft) aboveground was 128 km/h (80 mi/h), which occurred in January 1972. A 100-yr return period peak gust of 138 km/h (86 mi/h) has been calculated at the 15-m (50-ft) elevation.

Precipitation measurements have been made at the HMS since 1945. Average annual precipitation at the HMS is 16 cm (6.3 in.). Most of the precipitation occurs during the winter, with nearly half of the annual amount occurring in the months of November through February. Rainfall intensities of 1.3 cm/h (0.5 in./h) persisting for 1 h are expected once every 10 yr. Rainfall intensities of 2.5 cm/h (1.0 in./h) for 1 h are expected only once every 500 yr. The Hanford Site is not a major thunderstorm area. On average, only about 10 thunderstorm days per year are recorded at the Hanford Site, although this number has varied from a low of 3 to a high of 23 thunderstorm days per year. Thunderstorms theoretically can occur during any month of the year; however, they occur most frequently from April through September. The largest number of thunderstorm days recorded in a single month is eight, which has occurred in both June and August. Large differences in electric potential can occur during thunderstorms, which, in turn, can lead to lightning strikes. In general, ~20% of lightning strikes are cloud-to-ground/ground-to-cloud discharges. Lightning strikes in the summer have occasionally ignited range fires in the Hanford Site region. Estimates of the extreme thunderstorm winds, based on peak gusts observed from 1945 through 1980, are given in Ref. 19. Using the National Weather Service criteria for classifying a thunderstorm as "severe" [i.e., hail with a diameter ≥20 mm (0.8 in.) or wind gusts ≥93 km/h (84.8 ft/s)], only 1.9% of all thunderstorm events observed at the HMS have been "severe" storms; all met the criteria based on wind gusts.

The nearest volcano is in the Cascade Range, more than 100 km (62 mi) from the Hanford Site, and most eruption products are deposited within 50 km (31 mi) of their source. There is no evidence that volcanic lava flows, debris flows, or mudflows from the Cascade Range volcanoes reached the Pasco Basin during the Quaternary period.

Flows of lava, debris, and mud tend to be confined to existing drainage channels, and because no streams flow directly from the Cascade Range to the Hanford Site, these types of volcanic deposits are not considered likely at the 200 Area.

Tornadoes are infrequent and generally small in the northwest portion of the United States. The HMS climatological summary and the National Severe Storms Forecast Center (NSSFC) database list 22 separate tornado occurrences within 161 km (100 mi) of the Hanford Site from 1916 through August 1982. Two additional tornadoes have been reported since August 1982.

## 1.5. References

1. N. J. Milliken and G. R. Geschke, "Safety Analysis for Push-Mode and Rotary-Mode Core Sampling," Westinghouse Hanford Company report, WHC-SD-WM-SARR-031, Rev. 2 (July 1995).

2. Westinghouse Hanford Company, "Safety Analysis Manual," Westinghouse Hanford Company report WHC-CM-4-46 Rev. 4 (September 30, 1995).

3. Westinghouse Hanford Company, "Interim Guidance for Preparing Safety Assessments," in *Safety Analysis and Engineering Manual: Work Procedures*, Westinghouse Hanford Company report WHC-CM-6-32, Rev. 1 (November 1992).

4. US Department of Energy, "Guidance for Preparation of DOE 5480.22 (TSR) and DOE 5480.23 (SAR) Implementation Plans," DOE Standard 3011-94 (November 1994).

5. H. R. Brager, "Summary of Information on Flammable Gas Watch List Tanks," Westinghouse Hanford Company report WHC-EP-0711 (January 1994).

6. Westinghouse Hanford Company, "Hanford Site Tank Farm Facilities Interim Safety Basis," WHC-SD-WM-ISB-001, Rev. 0, Vol. 1 (August 1993).

7. US Energy Research and Development Administration, "Final Environmental Impact Statement of Waste Management Operations, Hanford Reservation, Richland, Washington," US Energy Research and Development Administration report ERDA-1538, 2 vols. (1975).

8. US Department of Energy, "Draft Environmental Assessment, Reference Repository Location, Hanford Site, Washington," US Department of Energy report DOE/RW-0017 (1984).

9. Pacific Northwest Laboratory, "Hanford Site National Environmental Policy Act (NEPA) Characterization," Pacific Northwest Laboratory report PNL-6451 (1990).

10. M. Gerber, "Legend and Legacy: Fifty Years of Defense Production at the Hanford Site," Westinghouse Hanford Company report WHC-MR-0293, Rev. 1 (1992).

11. "Investigation to Determine Dynamic Soil Properties at the 241-SY-Tank Site," URS/John A. Blume & Associates, Atlantic Richfield Hanford Company (1974).

12. "Environmental Impact Statement, Disposal of Hanford High-Level and Transuranic and Tank Wastes, Hanford Site, Richland, Washington," US Department of Energy report DOE/EIS-0113, Vol. 1-III (1987).

13. R. L. Skaggs and W. H. Walters, "Flood Risk Analysis of Cold Creek near the Hanford Site," Pacific Northwest Laboratory for Rockwell Hanford Operations report RHO-BWI-C-120 (PNL-4219) (1981).

14. W. A. Stone, J. M. Thorp, O. P. Gifford, and D. J. Hoitink, "Climatological Summary for the Hanford Area," Pacific Northwest Laboratory report PNL-4622 (1983).

15. US Department of Energy, "Consultation Draft: Site Characterization Plan, Reference Repository Location, Hanford Site, Washington," US Department of Energy report DOE/RW-0164, Vol. 2 of 9 (1988).

16. C. C. Meinhardt and J. C. Frostenson, "Current Status of 200 Area Ponds," Rockwell Hanford Operations report RHO-CK-798 (1979).

17. J. D. Jamison, "Standardized Input for Hanford Environmental Impact Statements Part II: Site Descriptions," Pacific Northwest Laboratory report PNL-3509, Part 2 (1982).

18. D. A. Zimmerman, A. E. Reisenauer, G. D. Black, and M. A. Young, "Hanford Site Water Table Changes 1950 through 1980—Data Observations and Evaluation," Pacific Northwest Laboratory report PNL-5506 (1986).

19. D. I. Herborn et al., "Hanford Waste Vitrification Plant Preliminary Safety Analysis Report," Westinghouse Hanford Company report WHC-EP-0250 (1991).

## 2.0. DESCRIPTION OF ACTION

This section presents the detailed descriptions required to evaluate the installation, operation, and removal of rotary-mode core sampling (RMCS) equipment in single-shell tanks (SSTs) on the Flammable Gas Watch List (FGWL) or those tanks recommended by the contractor to be included on the FGWL, hence referred to as FG/RMCS operations. The safety of RMCS operations in flammable gas tanks has been questioned because of the potential to induce a spark within the flammable environment of the tanks. The descriptions reflect an understanding of the FG/RMCS equipment and processes at the time of the SA and are provided for the information of the reader only.

This section details the safety criteria surrounding tanks on the FGWL and tanks recommended by the contractor for inclusion on the FGWL, collectively to referred to as FGT, the gas and ignition phenomenology anticipated during sampling operations in these tanks, and descriptions of the tanks and their characteristics. Descriptions of the equipment and systems required for rotary-mode core sampling follow, along with a summary of the drilling operations under normal, and certain abnormal conditions.

Because tank characterization and sampling are of the highest priority at Hanford as stated in Public Law 101-510, Section 3137, "Safety Measures for Waste Tanks at Hanford Nuclear Reservation," (1990), a suite of sampling methods have been incorporated into characterization and stabilization strategies, including grab sampling, vapor sampling, auger operations, and push-mode sampling. However, rotary-mode core sampling is used for obtaining full-depth core samples in tanks with salt cake waste.

Rotary-mode sampling operations and procedures are similar to push-mode sampling techniques with several differences: the drill bit differs, a nitrogen purge system is activated to cool the drill bit as it rotates, and an exhauster is used to compensate for the nitrogen purge flow and aerosol introduced into the tank dome. In general, a sampling truck capable of rotary-mode sampling, a nitrogen supply system, an exhauster, and a variety of support equipment is set up on or near the tank. The sampling truck is located at the appropriate riser, and the drill string with a universal sampler is inserted into the tank. With the nitrogen purge and exhauster systems activated, the rotary drilling collects a cylindrical waste sample that is withdrawn from the tank, transferred in a shielded receiver to a mobile X-ray system for preliminary examination, then into a cask for transport to the analytical laboratories for full characterization. The drilling/sampling sequence is repeated until a set of samples representing a full-depth core is acquired.

Specific design features and assumptions, provided in Section 6, shall be used to assess the extent to which changes or modifications alter the functions or operational characteristics of the FG/RMCS processes, systems, or components. The Department of Energy (DOE) Order 5480.21, Unreviewed Safety Questions (USQs)

process shall be used to assess which SA results could be altered or negated by said changes or modifications, and to what extent SA revisions could be required.

## 2.1. Principal Safety Criteria

Safety criteria for this section include a consideration of DOE Orders, existing Westinghouse Hanford Company (WHC) documents and procedures, and the more specific criteria associated with FGWL tanks. Because several of the tanks on the FGWL are also on the Organic Watch List, the organic criteria are also provided.

### 2.1.1. DOE Safety Criteria

The DOE Orders cited in Table 2-1, are the relevant and applicable principal safety and design requirements for controlling the rotary-mode core sampling operations.

**TABLE 2-1**
**RELEVANT DOE ORDERS**

| DOE Order | Title |
|---|---|
| DOE Order 1540.2 | "Hazardous Material Packaging" |
| DOE Order 4330.4A | "Maintenance Management Program" |
| DOE Order 5000.3B | "Occurrence Reporting and Processing of Operations Information" |
| DOE Order 5400.1 | "General Environmental Protection Program" |
| DOE Order 5400.5 | "Radiation Protection of the Public and the Environment" |
| DOE Order 5480.4 | "Environmental Protection, Safety, and Health Protection Standards" |
| DOE Order 5480.5 | "Safety of Nuclear Facilities" |
| DOE Order 5480.7 | "Fire Protection" |
| DOE Order 5480.10 | "Contractor Industrial Hygiene Program" |
| DOE Order 5480.11 | "Radiation Protection for Occupational Workers" |
| DOE Order 5480.19 | "Conduct of Operations Requirements for DOE Facilities" |
| DOE Order 5480.20 | "Personnel Selection, Qualification, Training, and Staffing Requirements at DOE Reactor and Non-Reactor Nuclear Facilities" |
| DOE Order 5480.21 | "Unreviewed Safety Questions" |
| DOE Order 5480.22 | "Technical Safety Requirements" |
| DOE Order 5480.23 | "Nuclear Safety Analysis Report" |
| DOE Order 5480.31 | "Start-up and Re-start of Nuclear Facilities" |
| DOE Order 5483.1A | "Occupational Safety and Health Program for DOE Contractor Employees at Government Owned Contractor Operated Facilities" |
| DOE Order 5500.2B | "Emergency Categories, Classes and Notification and Reporting Requirements" |
| DOE Order 5500.3A | "Planning and Preparedness for Operational Emergencies" |
| DOE Order 5700.6C | "Quality Assurance" |
| DOE Order 5820.2A | "Radioactive Waste Management" |
| DOE Order 6430.1A | "General Design Criteria" |

### 2.1.2. WHC General Safety Criteria

WHC standard controls include a series of WHC documents that define the safety envelope for the tank farm. The primary documents include the following:

- "Tank Farm Health and Safety Plan,"[1]
- "Hanford Site Tank Farm Facilities Interim Safety Basis."[2]

Other pertinent WHC documents are referenced as necessary throughout the SA.

### 2.1.3. Safety Criteria for Tanks on the FGWL

Initially, Hanford tanks were identified for inclusion on the FGWL by considering a qualitative set of criteria including the following:[3]

- The presence of specific types of waste in the tank,
- The presence of a high radiation field in the tank,
- Observation of certain gaseous components in the dome space,
- Observation of pattern changes in the surface level,
- Observation of periodic pressure surges in the dome space, and
- Observations of the axial temperature profiles in the waste.

There are currently 19 SSTs on the FGWL that require hydrogen concentrations to be less than 25% in the dome of a full tank with a decay heat generation of 30,000 Btu/h. They were placed on the watch list more for the *potential* of containing flammable gas rather than the verified presence of hazardous concentrations.

Further details of these criteria are provided in Ref. 3. Currently, there are 25 tanks that are on the FGWL; 19 of these tanks are single-shell tanks. These tanks are

| | | | |
|---|---|---|---|
| A-101 | S-102 | SX-101 | U-103 |
| | S-111 | SX-102 | U-105 |
| AX-101 | S-112 | SX-103 | U-107 |
| AX-103 | | SX-104 | U-108 |
| | T-110 | SX-105 | U-109 |
| | | SX-106 | |
| | | SX-109 | |

The hydrogen SSTs were placed on the watch list mainly because waste level increases were observed without liquid addition. That is, slurry growth acted as the

main criterion for watch list designation. There was concern that the growth of slurry could indicate a situation similar to that experienced with Tank 101-SY, even though the available data indicate total growth values as opposed to episodic-type behavior.

Alternate criteria for tanks included having a surface crust, having a total organic compound (TOC) level >3g/L, or containing B-Plant waste. The B-Plant wastes are organic-bearing wastes generated from the B-Plant fractionation process, primarily during strontium recovery. The compounds making up the organic fractions are complexing/chelating agents or their degradation products.

Recently, a new methodology was developed to identify tanks that may be candidates for inclusion on the FGWL. The new method involves evaluating the waste surface level changes in response to changes in barometric pressure.[4] By applying this criterion, a number of additional tanks were identified as candidates for potential storage of flammable gases. These tanks are

| | | | | | |
|---|---|---|---|---|---|
| A-103 | BY-101 | C-104 | S-101 | TX-102 | U-102 |
| | BY-102 | C-107 | S-103 | TX-111 | U-106 |
| B-111 | BY-105 | | S-104 | TX-112 | U-110 |
| B-201 | BY-106 | T-201 | S-105 | TX-113 | U-111 |
| B-202 | BY-109 | T-102 | S-106 | TX-115 | |
| | | T-203 | S-107 | TX-116 | |
| BX-107 | | T-204 | S-109 | TX-117 | |

Hereafter, these 34 tanks along with the original 19 FGWL single-shell tanks are referred to as the flammable-gas tanks (FGTs). Presently, the total number of single-shell FGTs is 53.

### 2.1.4. Safety Criteria for Tanks on the Organic Watch List

Table 2-2 defines the three levels of safety for tanks on the Organic Watch List.[5] The safety criteria are based on a set of tests in which dry sodium acetate nitrate/nitrite mixtures exhibited propagating behavior at about 300°C (572°F) with a TOC value greater than 6 wt%. Exothermic behavior produced significant gas generation at 180°C (356°F) at all TOC values tested: 3 wt%, 5 wt%, and 7 wt%.

## 2.2. Phenomenology

Gas phenomena include considerations of gas storage and release mechanisms, gas composition, waste characteristics, and flammability and ignition.

TABLE 2-2
SAFETY CRITERIA FOR ORGANIC WATCH LIST TANKS

| | | Criteria | |
|---|---|---|---|
| Level | Waste Classification | Parameter | Value |
| 1 | Safe | Waste organic concentration | ≤ 5 dry wt% TOC |
| | | Waste temperature | < 149°C |
| 2 | Conditionally Safe | Waste organic concentration | >5 wt% TOC |
| | | Waste moisture | ≥17 wt% |
| | | Waste temperature | ≤90°C |
| 3 | Unsafe | Failure to meet Level 2 criteria | |

### 2.2.1. Gas Storage and Release Mechanisms in SSTs

The model and data available that describe gas storage and release mechanisms are discussed in Appendix L. The conclusion is that large and prompt releases are not likely in single shell tanks.

The 19 single-shell tanks on the FGWL were separated by Los Alamos National Laboratory (LANL) in 1994[6] into the following four gas-release categories:

1. Tanks that do not experience episodic behavior nor exhibit long-term growth in the waste level,
2. Tanks for which not enough data are available to evaluate the behavior,
3. Tanks that potentially exhibit episodic gas-release behavior, and
4. Tanks that exhibit long-term waste growth but do not exhibit episodic gas-release behavior.

Table 2-3 provides selected data pertaining to the SSTs on the FGWL, including the designated gas-release category. A similar analysis for all the FGTs currently is not available. Table 2-3 also notes which tanks are on the Organic Watch List.

### 2.2.2. Gas Composition

The gas-concentration measurements in the SST dome space are very scarce compared to some of the DSTs (e.g., Tank 101-SY). The available limited data obtained from the grab samples are analyzed in Appendix C of this SA. As shown in Appendix C, hydrogen, nitrous oxide, ammonia and methane are detected at varying concentrations in the dome space of the FGTs.

TABLE 2-3
GAS DATA FOR SSTS ON THE FGWL

| Tank | FGWL | Organic Watch List | Vapor Space Volume, $m^3$ | Gas-release Category |
|---|---|---|---|---|
| A-101 | • | • | 1,454 | 3 |
| AX-101 | • | | 2,481 | 2 |
| AX-103 | • | | 4,892 | 1 |
| S-102 | • | • | 1,955 | 4 |
| S-111 | • | • | 916 | 1 |
| S-112 | • | | 760 | 1 |
| SX-101 | • | | 3,283 | 2 |
| SX-102 | • | | 2,953 | 2 |
| SX-103 | • | • | 2,540 | 1 |
| SX-104 | • | | 22,684 | 2 |
| SX-105 | • | | 2,422 | 2 |
| SX-106 | • | • | 2,972 | 1 |
| SX-109 | • | | 4,064 | 1 |
| T-110 | • | | 1,738 | 4 |
| U-103 | • | • | 11,401 | 4 |
| U-105 | • | • | 1,590 | 4 |
| U-107 | • | • | 1,636 | 4 |
| U-108 | • | | 1,401 | 4 |
| U-109 | • | | 1,420 | 4 |

### 2.2.3 Waste Characteristics

Sludge and salt cake are generally the two forms of waste in single-shell tanks of concern, although supernatant liquid also exists in some tanks. Sludge results from the precipitates formed during the neutralization of chemical separation wastes and is composed principally of hydrous metal oxides. Salt cake results from actual dewatering by pumping and from thermal evaporation of aged chemical and miscellaneous wastes. For SSTs that contain both types of solids, the salt cake layer is typically on top of the sludge layer. Liquid is present in SSTs as free-standing supernatant and/or as interstitial liquid existing in the void spaces of the solid wastes. Data on waste type and volume[7] are provided in Table 2-4 for information purposes only.

The waste types found in the SSTs on the FGWL are of four types: concentrated complexant; dilute complexed (DC) waste; double-shell slurry feed; and noncomplexed waste. Concentrated complexant (CC) is a concentrated product from the evaporation of dilute complexed waste. DC waste is characterized by a high content of organic carbon, including organic complexants. Ethylenediaminetetra-acetic acid (EDTA), citric acid, and hydroxyethyl-ethylenediaminetriacetic acid

(HEDTA) are the major complexants used. The main sources of DC waste are the salt well liquid inventory from the SSTs. Double-shell slurry feed (DSSF) is waste concentrated just before reaching the sodium aluminate saturation boundary (of 6.5 molar hydroxide) in the evaporator without exceeding receiver tank composition limits. Noncomplexed waste (NCPLX) is a general waste term applied to all Hanford Site liquors not identified as complexed.

TABLE 2-4
WASTE INFORMATION FOR FGWL SSTS

| Tank | Waste Type | Total Waste Vol, Kgal | Super-natant Vol, Kgal | Sludge Vol, Kgal | Salt cake Vol, Kgal | Waste Temp, °F | Waste Depth, Inches |
|---|---|---|---|---|---|---|---|
| A-101 | DSSF | 953 | 0 | 3 | 950 | 154 | 354 |
| AX-101 | DSSF | 748 | 0 | 3 | 745 | 136 | 279 |
| AX-103 | CC | 112 | 0 | 2 | 110 | 111 | 48 |
| S-102 | DSSF | 549 | 0 | 4 | 545 | 107 | 207 |
| S-111 | NCPLX | 596 | 10 | 139 | 447 | 92 | 224 |
| S-112 | NCPLX | 523 | 0 | 5 | 518 | 83 | 239 |
| SX-101 | DC | 456 | 1 | 112 | 343 | 138 | 173 |
| SX-102 | DSSF | 543 | 0 | 117 | 426 | 151 | 206 |
| SX-103 | NCPLX | 652 | 1 | 115 | 536 | 174 | 245 |
| SX-104 | DSSF | 614 | 0 | 136 | 478 | 167 | 231 |
| SX-105 | DSSF | 683 | 0 | 73 | 610 | 180 | 256 |
| SX-106 | NCPLX | 538 | 61 | 12 | 465 | 111 | 203 |
| SX-109 | NCPLX | 250 | 0 | 0 | 250 | 148 | 98 |
| T-110 | NCPLX | 379 | 3 | 376 | 376 | 63 | 145 |
| U-103 | NCPLX | 468 | 13 | 32 | 423 | 87 | 178 |
| U-105 | NCPLX | 418 | 37 | 32 | 349 | 89 | 159 |
| U-107 | DSSF | 406 | 31 | 5 | 360 | 78 | 155 |
| U-108 | NCPLX | 468 | 24 | 29 | 415 | 88 | 178 |
| U-109 | NCPLX | 463 | 19 | 48 | 396 | 86 | 176 |

### 2.2.4. Flammability and Ignition

Flammability issues are highlighted by two aspects in tanks with a flammable environment, the broad flammability range of hydrogen in air (4% to 75%) and the low energy required for ignition (0.01 mJ). The ignition hazard is increased because nitrous oxide is a strong oxidant and is cogenerated with the hydrogen in amounts that place the gas mixture well within the flammability range before mixing with air. Burning hydrogen releases a relatively large amount of energy. The heat of combustion is 57.8 and 77.3 kcal/g-mol of hydrogen for oxygen and nitrous oxide

reactions, respectively. Ammonia has a flammability range in air of 15% to 30%, and the heat of reaction with oxygen is 75.8 kcal/g-mol $NH_3$ (25°C).

Secondary exothermic reactions in the waste surface crust can also be induced by a hydrogen burn. The surface crust usually contains an oxidant, such as a mixture of sodium nitrate and sodium nitrite, in which various amounts of organic carbon are well mixed.

The presence of flammable gases and the release of chemical energy are compounded by the presence of radioactive waste, thereby increasing the potential hazards of a release. Toxic gases, especially ammonia, are known to be associated with the waste and may have the greatest potential for release during an episodic event.

## 2.3. Flammable-Gas Tanks

The 53 FGTs are spread over 11 of the 12 single-shell tank farms: A, AX, B, BX, BY, C, S, SX, T, TX and U. The cylindrical, dome-roofed tanks are constructed of reinforced concrete with a structurally independent mild carbon-steel liner covering the bottom and sidewalls. Each tank is buried with a minimum of 6.5 ft of earth for shielding and heat dissipation from radioactive decay. The tanks were designed to hold approximately 15 to 30 feet of liquid, with a nominal capacity of 530,000, 758,0000, and 1,0000,000 gallons. Of the three possible tank configurations, the 1,000,000-gal.-capacity tank used in Farms A, AX, and SX is schematically shown in Fig. 2-1. The BY-, TX- and S-Tank Farm has tanks with 758,000-gal. capacity, but tanks in Farms B, BX, C, T and U have a capacity of 530,000 gallons.

A typical single-shell tank has numerous vertical pipes called risers that penetrate the tank dome and extend to various depths of the tank. The dome risers, which vary in diameter from 4, 12, or 42 inches, provide access to the tank interior for a variety of operating and monitoring equipment, such as the breather inlet, a camera observation point, the center pump pit, a dome elevation bench mark, a solids level detector, a liquid observation well, a surface level probe, the temperature thermocouple assembly, and a leak detection drywell.

Most SSTs use a passive form of ventilation[2] that allows airflow through the tanks to be dictated by atmospheric conditions such as temperature and atmospheric pressure. The system, called the breather inlet, minimizes the pressure changes that could damage the tank structure if the tanks were completely sealed. Each breather filter is mounted on a tank riser, and consists of a housing containing a HEPA (high efficiency particulate air) filter, an outlet screen, and a small seal loop that acts as a pressure relief should the filter become plugged. An isolation valve, which is normally open, allows flow between the tank vapor space and the environment through the filter. The flow moves horizontally through the 12 in. x 12 in. filter, and then vertically through the downward-facing exit weather hood. During

FG/RMCS operations, the breather inlet will be fitted with a portable, sealable, 15-ft tall, 4-in.-diameter stack to control the direction of gases exiting the tank.

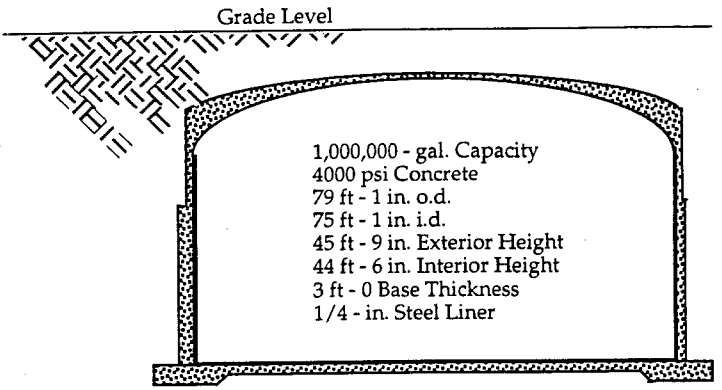


**Fig. 2-1. Single-shell tank schematic.**

## 2.4. RMCS System and Associated Equipment

The system required for retrieving waste samples in the rotary-mode consists of the sampling truck, the portable exhauster, the $N_2$ supply system, the generator, and associated equipment. Primary components associated with the sampling truck include the grapple hoist assembly, the shielded receiver (SR) with remote latch unit (RLU), the drill string (DS), the nitrogen purge system, and the change-out assembly.[8, 9, 10, 11] Associated equipment includes the X-ray machine, cask stand and truck, power distribution trailer, and support vehicles.

Functional criteria for the FG/RMCS are found in Refs. 12 and 13. Several critical elements of the former document include the following:

- Equipment with energized circuits that can come in contact with waste degradation gases before dilution by the tank vapor space or other gases shall be protected in accordance with National Fire Protection Association (NFPA) for use in Class I, Division 1, Group B for a flammable hydrogen atmosphere. Protection may be in the form of intrinsically safe electrical components, purging in accordance with NFPA Article 496, or other acceptable method as defined by the requirements of the National Electric Code (NEC) Article 501, for use in flammable hydrogen atmospheres.

- Equipment where energized circuits have the potential, under abnormal conditions, to come in contact with waste degradation gases before dilution by

the tank vapor space or other gases shall be protected in accordance with NFPA for use in Class I, Division 2, Group B for a flammable hydrogen atmosphere. Protection may be in the form of intrinsically safe electrical components, purging in accordance with NFPA Article 496, or other acceptable method as defined by the requirements of NEC Article 501, for use in flammable hydrogen atmospheres.

### 2.4.1. RMCS Trucks

Three RMCS trucks provide mobility to position and move the core sampling equipment from tank to tank. Fig. 2-2 shows the general arrangement of equipment on the rotary platform that is mounted on the rear of each of the three sampling trucks. The rotating platform supports and positions core sampling equipment, including the platform hoist, the grapple hoist assembly, the drill rig and drill string, and the shielded receiver over the tank riser to be sampled. Five stationary hydraulic jacks act as outriggers to level the truck for drilling operations.

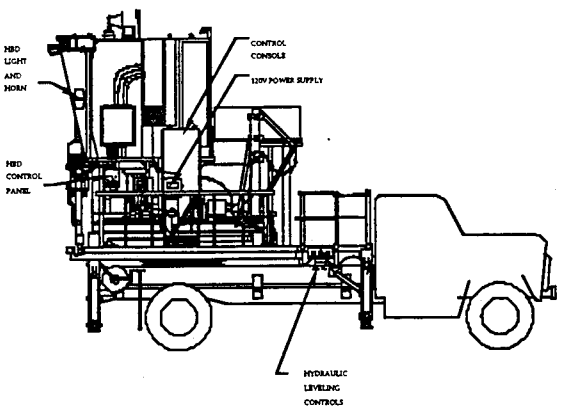


**Fig. 2-2. Sampling truck configuration.**

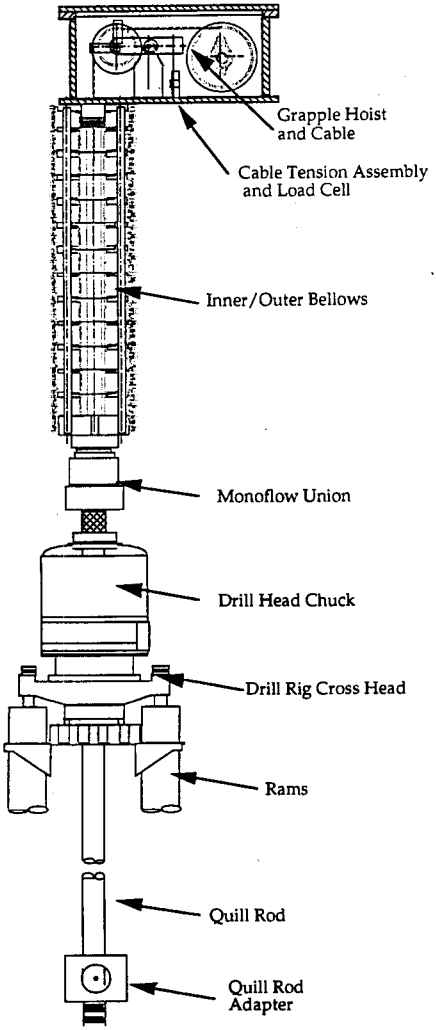


**Fig. 2-3. Grapple hoist assembly.**

capability of the hoist shaft.

Two of the three trucks have diesel engines, but the third truck has a gasoline engine. All drill engines are gasoline fueled.

**2.4.1.1. Platform Hoist.** The electric platform hoist is located on the rotating platform between the grapple hoist assembly and the shielded receiver assembly. With a capacity of 500 lb, it provides an on-site method to handle riser adapter equipment, insert and remove drill rods, and position the cask stand.

**2.4.1.2. Grapple Hoist Assembly.** The grapple hoist assembly, shown in Fig. 2-3, consists of an electric motor-driven hoist contained in a pressurized box, the electric motor (external to the pressure vessel), and a grapple connected to the hoist cable. The grapple hoist assembly controls the sampler piston movement.

**Grapple Hoist and Box.** The grapple hoist box houses the grapple cable, cable reel, and a load cell. The grapple box and the pneumatic piping connecting it to the purge gas enclosure provide containment of drill purge gases.

The hoist is used to lower the grapple into the drill string after a sampler has been installed. The 3/4 hp grapple motor lowers the cable at a maximum speed of 58 ft/min, and employs a cable with a breaking strength of 2400 lb. A load cell attached to the cable tension assembly is designed to shut off the motor with a maximum load of 250 lb. Roll pins on the hoist shaft are designed to shear before the hoist motor can exceed the structural

**Grapple.** The grapple (sample actuator) is a spring-loaded device, schematically represented in Fig. 2-4 that is lowered to connect with the pintle rod of the sampler and holds the sampler piston in position while a sample is being taken.

**Inner and Outer Bellows Assembly.** The inner and outer bellows assembly, also shown in Fig. 2-3 provides a collapsible pressure boundary between the grapple box and the quill rod for containment of purge gas.

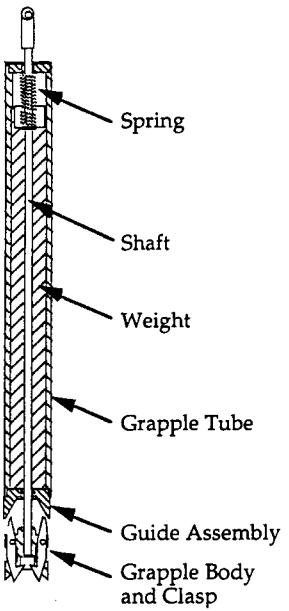


**Fig. 2-4. Grapple Schematic.**

**2.4.1.3. Drill Unit and Quill Rod.** The drill unit is composed of the drill rig, the drill head, and a hydraulic chuck that clamps to the quill rod.

**Drill Rig.** The drill rig engine provides energy through the drill head for drill rotation and through the hydraulic rams for down force to the quill rod, which in turn transfers these motions to the drill string. The drill head raises and lowers the quill rod, and a hydraulically operated chuck clamps the quill rod in place. Manual hydraulic controls are provided for quill rod and shielded receiver positioning.

**Quill Rod.** The quill rod, which transfers power to the drill string, is the topmost rod of the drill string. This unit remains in the drill head and transmits power through the hydraulic chuck.

**Quill Rod Adapter.** The stainless-steel quill rod adapter is attached at the bottom of the quill rod and is a 6-in. section with the same diameter as the quill rod. The adapter has a quick connection feature that allows for the addition of water to wash the drill bit. The adapter connection feature is also used for flammable-gas sniffing.

**2.4.1.4. Drill String Assembly.** The drill string assembly is comprised of the drill bit and core barrel assembly, mated to multiple interconnected drill rods.

**Drill Bit.** The drill bit rotationally bores into the waste to produce a nominal 1-in.-diameter core sample, and acts as the leading tip of the drill string. The bit has a hollow-cored center section surrounded by cutting teeth and holes on the drilling surface for nitrogen purge flow. The commercially available unit (nominally 2.5-in. o.d.) is made of a proprietary material with teeth designed to "smear" when they come into contact with the bottom of the tank to prevent penetration.

**Core Barrel.** The core barrel, when screwed onto the drill bit, forms an assembly that houses the universal sampler. The fluted core barrel with drill bit is 40 in. long with a 2.25-in. o.d (an effective 2.5 o.d. with 1/8" flutes. It also is a commercially available unit made of nickel-plated carbon steel.

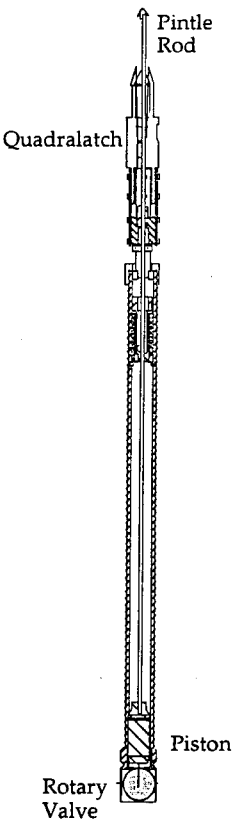


**Fig. 2-5. Universal sampler.**

**Drill Rods.** The drill string is comprised of drill rods that are sections of thin-walled pipe that when mated together transmit power between the quill rod and the drill bit/core barrel assembly. The commercially available drill rods used in the waste have a 2.25-in. o.d., with a spirally-wound, fluted ribbing (approximately 1/4 pitch) on the nickel-coated exterior surface to remove drill debris; drill rods above the waste surface are unfluted. Each drill rod has an internally threaded (female) end and an externally threaded (male) end, and is available in 19-in., 60-in., 24-in., 12-in. and 6-in. lengths. The drill string is constructed of rods until the drill bit is just above the waste surface. At that point, only 19-in. rods are attached to the top of the drill string, consistent with drilling 19-in. core samples of waste.

**Drill String.** The drill string transmits power from the quill rod to the drill bit and core barrel assembly and consists of the drill bit/core barrel assembly and multiple sections of drill rod screwed together. The drill string provides containment for purge and hydrostatic head gases. The total length of the drill string is generally calculated by determining the distance between the bottom of the tank and the bottom of the quill rod on the leveled truck. The equivalent number of differently-sized rods is calculated using the drill string calculation sheet.

**2.4.1.5. Universal Sampler.** The universal sampler is a mechanical device that is used to collect and retain the waste sample. After drilling, the sampler is transferred from the drill string to the shielded receiver, then to a cask for shipment to the analytical laboratory. The universal sampler, as depicted in Fig. 2-6, consists of the quadralatch, the

pintle rod, a piston, bearings, seal, and a rotary valve. Latched in the core barrel assembly, the sampler provides a seal to prevent waste from entering the drill string.

**Quadralatch.** The stainless-steel sampler quadralatch latches the sampler into the core barrel grooves. Subsequently, the remote latch unit in the shielded receiver locks onto the quadralatch fingers and disengages the quadralatch mechanism from the core barrel's internal bore, thus providing a method for retrieving the sampler.

**Pintle Rod.** The pintle rod attaches to the piston in the sampler and holds the piston in place during sampling when the grapple is attached. A pin on the pintle rod trips the trigger mechanism to close the rotary valve. The grapple removes the pintle rod by releasing a spring clip connecting the rod to the piston.

**Seal.** A chevron seal is used to prevent the flow of waste into the drill string when hydrostatic pressure is not present.

**Rotary Valve.** The rotary valve is located at the bottom of the sampler and is rotated closed after completing the sampling of a 19-in. segment of waste. The sample is sealed inside the sampler when the valve is closed by actuating a spring-loaded trigger mechanism as the pintle rod is separated from the piston during the sampling operation.

**2.4.1.6. Shielded Receiver Assembly.** The SR assembly is schematically represented in Fig. 2-6, and consists of the weatherproof cover, sampler hoist box with an enclosed winch system, the shielded receiver tube, the RLU that is attached to the sampler hoist cable, and an isolation ball valve attached to the bottom end of the SR tube. The shielded receiver design is independent of the core sampling mode and provides interim sampler shielding. A power winch internal to the weatherproof covering, a cable, and a reel internal to the sampler hoist box are used to retrieve the sampler from the drill string, and to deposit the sampler in the transfer cask. The SR assembly is also used to remove a clean sampler from the transfer cask and transfer it to the drill string for the next sampling operation. The receiver valves, receiver tube, pressure vessel, and pneumatic piping connecting the shielded receiver to the purge gas enclosure provide containment for hydrostatic head gases. The receiver has a load cell to detect cable tension and slack cable, and has a decontamination spray wash. A mechanical counter and digital encoder are used to determine the depth of the RLU and are attached to the cable reel shaft inside the weather cover.

**Sampler Hoist.** The 1.5 hp sampler hoist motor raises and lowers the cable at a maximum speed of 23 ft/min, and employs a cable with a breaking strength of 3000 lb. A load cell shuts off the motor at a maximum load of 300 lb.

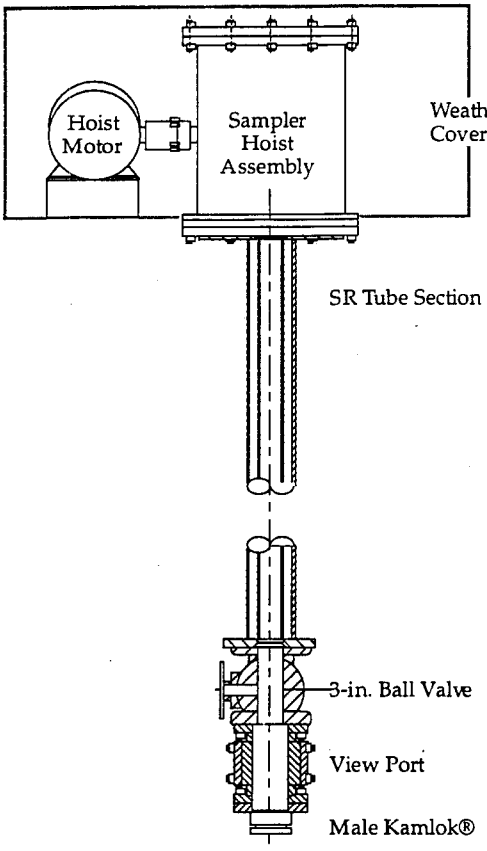


**Fig. 2-6. Shielded receiver assembly.**

**Shielded Receiver Tube.** The SR tube provides shielding for personnel, thereby reducing radiation exposure, and aids in transferring and depositing samplers into the transfer casks.

**Remote Latch Unit.** The RLU is a mechanical latching device that provides a mechanism for latching onto and releasing the sampler. The configuration shown in Fig. 2-7 schematically represents the most recent design, as provided by WHC personnel in December 1995. The RLU is raised and lowered by the sampler hoist assembly.

**Ball Valve.** The 3-in. ball valve at the bottom of the shielded receiver tube isolates the shielded receiver from the surrounding environment and has a male Kamlok®[1] interface.

**Kamlok® adapter assemblies.** The Kamlok® adapter assembly is a commercially available, two-part, male/female assembly that provides rapid, manually actuated connect and disconnect capabilities. In general, the male Kamlok® adapter is connected to the female Kamlok® adapter. The design convention was established so that movable components, like the shielded receiver, have a male Kamlok® adapter, and the stationary components that are connected to the shielded receiver, such as the change-out assembly, X-ray system, and cask system, have female Kamlok® adapters.

[1] Kamlok is a registered trademark of the Dover Corporation.

**2.4.1.7. Purge Gas Enclosure Assembly.** The purge gas enclosure assembly is located on the truck's rotary platform, and houses, protects, and includes the pneumatic components used to monitor and distribute the hydrostatic head and purge gas nitrogen supplies (including regulators, solenoid valves, analog gauges, control valves, piping, wiring, and instrument transducers.)

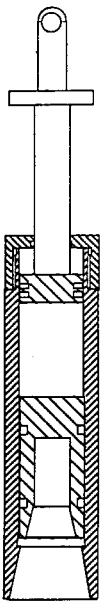

**Fig. 2-7. Mechanical remote latch unit configuration.**

Nitrogen is supplied for five different functions during FG/RMCS operations: the DS purge gas system used during FG/RMCS drilling; the purge through the riser sleeve annulus, the hydrostatic head in the drill string and in the shielded receiver, and the Z-purge (NFPA 496) in the SR weather cover. The systems provide drill bit cooling and cleaning during rotary drilling, help prevent waste flooding in the drill string, and prevent gas accumulation.

**2.4.1.8. Instrumentation and Control System.** This section is primarily focused on the systems for drill engine shutdown, and the instrumentation used by the operator for operational controls.

**2.4.1.8.1. Programmable Logic Controller (PLC).** The PLC processes out-of-tolerance alarm signals to activate alarm strobe, horn, and indicator lights, followed by engine shut-down signals sent to the shut-down relay. Located in the instrument cabinet, the PLC controls the alarm sequencing and interlock logic for the RMCS Truck System. Alarm contacts from the truck instrumentation and external sources (exhauster) are monitored. When a valid alarm is received by the PLC, it initiates both visual and audible annunciation as appropriate. Additionally, if the received alarm requires a drill rig engine shutdown, the PLC deenergizes the shut-down relay, shutting down the drill rig engine.

**2.4.1.8.2. Engine shutdown.** The following mechanisms are elements of a safety system referred to as the sampling truck engine shutdown, as defined in Ref. 8. The drill rig engine will automatically shut down for out-of-tolerance drilling parameters, exhauster shutdown, or detection of a GRE.

**Shutdown Interlock (K5 relay).** The shut-down interlock relay is controlled by the PLC and shuts down the drill rig engine by interrupting electrical power to the drill rig ignition.

**RPM (Revolutions per Minute) Measurement.** Two drill rotation sensors measure drill rotational speed and send signals to two digital units that display drill rpm. If out of tolerance, an alarm signal is sent to the programmable logic controller, and the drill rig engine is shut down. Exhauster operation and nitrogen purge flow are not terminated under this shut-down condition.

**Down Force Measurement System.** The down-force measurement system electronically measures and calculates the down force of the drill string, provides a signal to the digital display unit, and digitally displays the measurement. If the down force is above the designated down force limit, an alarm signal is sent to the PLC which shuts down the drill rig engine. Exhauster operation and nitrogen purge flow are not terminated under this shut-down condition.

**Riser sleeve Purge.** Two differential pressure switches measure the pressure drop across a flow controller, and provide a shutdown signal to the PLC on low differential pressure. Exhauster operation and nitrogen purge flow are not terminated under this shut-down condition.

**DS Purge Gas Measurement.** The purge gas measurements include three turbines to measure flow and transducers to measure pressure and temperature. Signals are sent from the purge gas enclosure to the three digital flow indicators that display compensated flow in scfm (standard cubic feet per minute) units. Any of the three indicators can detect an out-of-tolerance condition and send an alarm signal to the PLC; the PLC then executes two-out-of-three voting logic to activate drill rig engine shutdown.

**Penetration Rate Shutdown.** The penetration rate measurement system electronically measures the penetration rate of the DS and provides a signal to the digital display unit, and digitally displays the measurement. If the penetration rate is below the designated limit, an alarm signal is sent to the PLC which shuts down the drill rig engine. Exhauster operation and nitrogen purge flow are not terminated under this shut-down condition.

**Exhauster-Induced Shutdown.** The exhauster can induce drill rig engine shutdown based on signals from the flammable-gas detection system or based on exhauster operational parameters. The operational parameters that provide a shut-down signal to the PLC to shut down the drill rig engine are discussed in Section 2.4.2. A keylock override switch allows operation of the truck when the exhauster is not needed.

**2.4.1.8.3. Instrumentation Cabinet.** The instrumentation that the operator has available on a directly accessible panel for control of the sampling operations is discussed in this section.

**Enclosure Temperature Instrument/Display.** The instrument enclosure is temperature-controlled with separate air conditioning and heating systems. The

temperature instrument/display measures and digitally displays the cabinet temperatures, and an alarm sounds for out-of-bounds 50°F< T >90°F.

**Purge Gas Temperature Display.** This instrument displays purge gas temperature, and alarms for out-of-bounds conditions that are < 10°F and > 140°F.

**Purge Gas Pressure Display.** This instrument converts a transducer signal to a digital display of purge gas pressure, and if greater than the currently set value of 0.3 psig, sends a signal to the PLC. This display is for information only during drilling modes.

**Shielded Receiver and Drill String Pressure Displays.** These instruments convert transducer signals to a digital display of pressure in the shielded receiver and drill string, respectively, and if greater than the currently used value of 0.2 psig, send a signal to the PLC. The displays are used by the operators to ensure sufficient pressure for sample change-out operations and to verify that the DS and SR are depressurized when breaking containment. If hydrostatic head pressure is not maintained at the required level, then waste intrusion into the drill string could result.

**Other Informational Displays.** The Lower Ram Pressure Display converts transducer signals to digital displays for the walkdown or hydraulic bottom function (HBD) setpoint pressure with a selector switch. The Enclosure Indicator Lights provide visual status of various limits and logic controller functions. The Purge Gas Flow Display selects and digitally displays the output from one of three purge gas flow meters.

**2.4.1.8.4. Hydraulic bottom detector.** When obtaining the final sample, the hydraulic bottom detector detects loss of lower ram pressure, and energizes a solenoid valve to automatically reverse the ram direction to raise the drill head.

### 2.4.2. Exhauster Assembly

The exhauster train[14] depicted in Fig. 2-8 is composed of a flexible, conductive duct connecting the exhauster to the riser, a heater to dehumidify exhaust gases, a filter housing containing a prefilter with two high-efficiency particulate air (HEPA) filters in series, and a stack assembly. The exhauster system, designed to operate continuously, is required during all FG/RMCS activities to maintain a negative tank pressure with respect to atmospheric pressure and to prevent uncontrolled particulate emissions.

**Exhauster.** The exhauster filter train is composed of a prefilter immediately upstream of two HEPA filters in series mounted on a single skid (15 by 7 ft). To limit filter loading, the allowed dose rate on contact with the HEPA filter housing is 100 mrem/h.[14] Flow into the exhauster from nitrogen purge and tank in-leakage is designed for 9.4 x $10^{-2}$ $m^3/s$ (200 $ft^3$/min), resulting in a tank pressure of about -250 Pa (-1 in. w.g.).

The flexible exhauster duct connects the tank riser to the exhauster and is held in place with stand assemblies. The conductive duct is 1/32 in. thick, neoprene over a polyester base. A seal pot assembly is positioned between the riser and the exhauster, and the drain lines to the seal pot are 1/2-in. stainless steel.

Some tanks have high humidity levels. Therefore, a hot-water heat exchanger meeting Class-1, Div.-I, Group-B electrical requirements is supplied upstream of the HEPA filters to lower the relative humidity of the tank gases being exhausted. The heater meets the constraints of the Washington State Operating permit that limits the humidity of the air stream passing through the HEPA filters to be no greater than 80%.

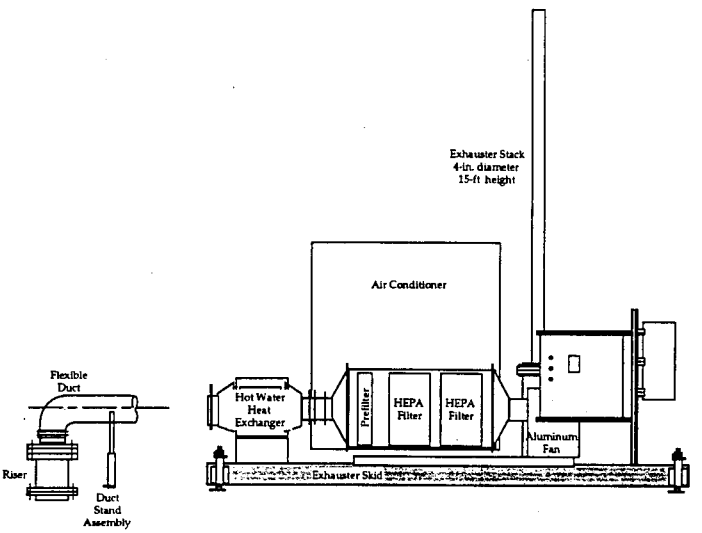


**Fig. 2-8. Exhauster system.**

**Fan and Stack.** The fan, driven by a 7.8 hp electric motor, is qualified for operation in a flammable-gas environment, provides the motive force for drawing tank gases from the riser through the filters and prevents tank overpressurization during core sampling activities. The fan/motor combination are capable of drawing 1900 scfm, so the motor has a speed controller to reduce the rpm to obtain the nominal 200 scfm flow rate. The controller uses output from the stack velocity transmitter to automatically adjust motor rpm to maintain constant flow as loading increases and flow decreases.

Exhaust gases are drawn from the prefilter/HEPA bank into the 4-in.-diameter stack for release into the environment at a constant nominal flow of 200 scfm. The 15-ft-high stack provides adequate dispersion of the gases.

**Exhauster Control and Gas Monitoring.** The exhauster is designed to automatically shut down when flow through the stack is greater than 250 scfm for greater than 5 min., or shutdown immediately when flow is less than 150 scfm. Two pressure conditions can also induce automatic exhauster shutdown: when the tank pressure falls to less than -3 in. w.g.; and when the differential pressure across the prefilter/HEPA filter bank is greater than 5.9 in. w.g. (Vendor information indicates that the HEPA filter performance is undetermined at a differential pressure of 10 in. w.g. after 15 minutes, but there are no relief valves or vacuum breakers installed to protect the HEPA from excessive delta pressure.)

The tank pressure, HEPA differential pressures, and flow through the exhauster are continuously monitored using intrinsically safe systems in the exhauster. Even though totalized flow is continuously data-logged in the exhauster instrumentation cabinet, only pressure alarms are recorded.

Exhaust gases can be monitored for radionuclides, ammonia, and total vapor space organic compounds at the stack outlet. The exhauster has no organic or toxic vapor control technology.

### 2.4.3. Riser and Adapter Equipment

This section discusses equipment attached to the riser as illustrated in Fig. 2-9.

**Riser and sleeve.** The riser to be sampled will have an internal sleeve of spark-resistant stainless steel with a nominal length of 15 ft. The annulus between the sleeve and the DS will be purged with nitrogen during FG/RMCS operations to prevent the accumulation of flammable gas. The riser purge gas system will have two differential pressure detectors, either of which are interlocked to the PLC and can cause an automatic trip of the drill rig. Each detector's set point will be approximately 40 psid across a flow controller that is sized for 5 scfm. The sleeve has a separate spray wash assembly with operational parameters like the DS spray wash system.

**Riser Adapters.** The riser adapter is basically a flanged plate, located on top of the riser, with an offset orifice to allow for the connection of riser equipment, regardless of the size of the riser.

**Drill String Spray Washer/Frisbee Wiper Assembly.** The drill string is washed to reduce contamination with a hot-water spray wash of the exterior surfaces as the drill string is being extracted through the drill string spray washer/frisbee wiper assembly. Water is supplied to the spray washer at a temperature less than or equal to 140°F and a flow rate less than or equal to 3 gal./min from the water heater and 55-gal. water supply on the support truck.

The frisbee seal around the drill rod provide a wiping action during drill rod recovery operations and serves to stabilize the drill string during rotation. The frisbee also effectively provides a seal between the tank and the environment by sealing around the drill string outer diameter, and between the spray washer and the foot clamp. It is fabricated of a nonconductive material.

**Pneumatic Foot Clamp.** The pneumatic foot clamp holds the drill string when it is disconnected from the platform hoist, the quill rod, or the shielded receiver. The three-legged, spider-like clamp must be pneumatically opened to release the drill string. If the pneumatic pressure is lost, the clamp fails in the closed position and the spider-like legs rotate for a three-point positioning around the drill string, locking the drill string in place. The foot clamp does not prevent upward motion of the drill string.

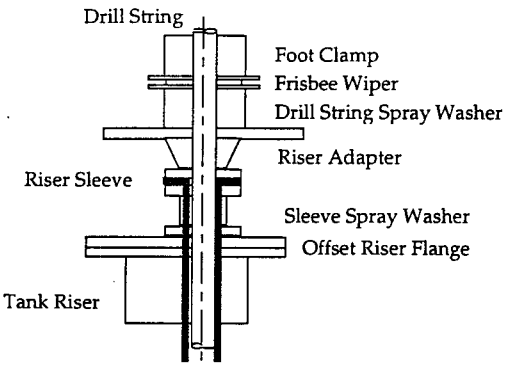


**Fig. 2-9. Riser adapter, washer/frisbee wiper assembly and foot clamp.**

### 2.4.4. Cable Spray Washer Assembly and Change-out Assembly

The change-out assembly, Fig. 2-10, is placed on top of the cable spray washer when the drill string is disconnected from the quill rod. It provides a means to isolate and maintain hydrostatic head pressure within the drill string while samplers are exchanged. It also provides containment of hydrostatic head and DS gases. It is comprised of a male Kamlok® adapter assembly, a 3-in. ball valve, and a female Kamlok® adapter. Once attached to the DS, the change-out assembly provides quick connect and disconnect capabilities to the shielded receiver.

**Cable Spray Washer Assembly.** The cable spray washer assembly connects to the drill string before installation of the change-out assembly in order to wash the internal cables of the shielded receiver and grapple cables, and to internally wash the drill rods if required.

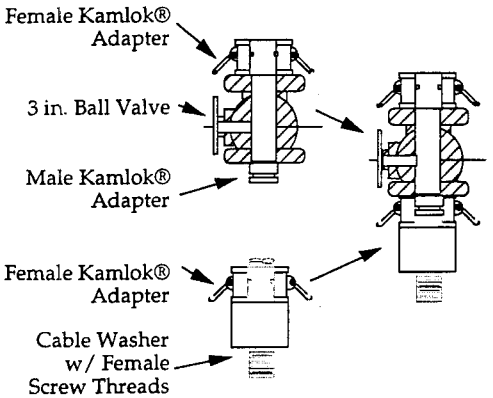


**Fig. 2-10. Change-out assembly.**

### 2.4.5. Primary Support Equipment

The primary support equipment for rotary sampling operations include the $N_2$ supply system, an X-ray imaging capability, power generation and distribution, washer supply systems, and casks and the cask truck. Operational support equipment include the power distribution trailer, the breathing air compressor, the service and support truck and trailers, lights, and the crane used during equipment setup and teardown.

**2.4.5.1. Liquid Nitrogen Supply Trailer and Heater.** The liquid nitrogen support trailer and vaporizer supply the nitrogen used for the purge and hydrostatic head systems during FG/RMCS operations.

**Nitrogen Trailer.** In the nitrogen trailer, liquid nitrogen is vaporized by a propane-fired, forced-convection, water bath vaporizer. The 1500-gal. nitrogen tank and liquid supply piping stores liquid nitrogen and includes a passive closed-loop evaporator (to supply tank pressure), valves, piping, regulators, and gauges to accommodate tank filling and liquid nitrogen supply to the vaporizer.

The normal nitrogen system pressure in the $N_2$ trailer is 100 to 250 psig while the system is in operation, with a tank relief valve set to relieve pressure at 250 psi. Nitrogen provided to the sampling truck is 100 to 150 psi. The nitrogen trailer remains outside of the tank farm at all times.

**Vaporizer.** The vaporizer vaporizes both the liquid propane to supply the water heaters and the liquid nitrogen to supply the nitrogen gas regulator and supply hose. The vaporizer includes self-igniting, thermostatically controlled water heaters, a water circulation pump, and closed-loop water piping and expansion tanks. The control panel and instruments automatically regulate water flow and gas exit temperatures. A nitrogen gas regulator with a shutoff valve regulates the pressure of the gas at the exit of the vaporizer. A supply hose with a quick disconnect fitting supplies gas to the core sample truck. The vaporizer is electrically-powered by a propane-fueled engine generator, or alternate 240 v power source.

The vaporizer's propane tank stores pressurized propane and includes piping to supply the water heaters with propane gas, the generator engine with propane gas, and the vaporizer with propane liquid.

2.4.5.2. **Mobile X-ray Imaging System.** The X-ray imaging system is used for a preliminary assessment of the core sample to verify how complete the sample was and the characteristics of the waste form. This assessment is intended to help the operator more accurately set operational controls for the next sample. The system is equipped with a female Kamlok® adapter for connection to the SR.

2.4.5.3. **Casks and Sample Transfer Truck.** The sample casks and transfer truck are discussed in this section.

**Transfer Casks.** The transfer casks are held at the sample site in a five-cask holder, or cask stand, in an upright position. The transfer casks are lead-lined chambers that provide shielding and containment for the core samples during shipment to the analytical laboratory. Each cask is 40 in. long, about 6 in. in diameter, and weighs 480 lbs. Casks are equipped with a female Kamlok® adapter for connection to the SR.

**Sample Transfer Truck.** The sample transfer truck, or cask truck, transports the sampler/cask assemblies to and from the laboratory and moves samples in the field. The truck is capable of carrying three casks at a time, and field positioning is facilitated through an overhead crane on the truck.

2.4.5.4. **Portable Generator Set.** Two types of generators are available to support FG/RMCS activities—150 kVA and 200 kVA. The portable generator set described in Ref. 15 provides standalone power for the core sample truck and auxiliary equipment. The grounded generator is powered by a turbocharged-diesel engine to produce power with a rating of 1500 kW, 480 Vac, 60 Hz, 3Ø, 4-wire and 120/240 Vac, 60 Hz, 1Ø. The diesel generator remains outside of the tank farm at all times.

2.4.5.5. **Power Distribution Trailer.** The power distribution trailer distributes power from the generator to the sampling equipment such as the sampling truck, the exhauster, the water heater on the support truck, the X-ray imaging system, the truck's air compressor, and 120V outlets.

2.4.5.6. **Breathing Air Trailer/Compressor.** The compressor is a two-stage, oil-free design powered by a 30 hp, 480 Vac, 60 Hz, three-phase electric motor. A 30-gal. receiver tank and a 30-gal. surge tank allow the compressor to cycle, and collected moisture is manually drained in the receiver tank. The breathing-air compressor remains outside the fenced area and away from sources of contamination and toxic fumes.

2.4.5.7. **Support Truck and Trailer.** The support truck transports personnel and miscellaneous equipment, and can be parked on the tank. The support truck acts as a lock-up rack for drill rods, and also carries a drum heater and pump for supplying water. The support trailer, located outside the tank farm, provides equipment storage and shelter for personnel.

2.4.5.8. **Crane.** A standard crane is used in the setting up and taking down of the sampling activities. It is used on an as-needed basis only and is not normally retained at the job site except when in use.

2.4.5.9. **Light Units.** Diesel-powered portable light units are used on and off the tank farm during drilling operations. Each light is capable of producing 2500 W of light (5 halogen lights at 500 W per light). The diesel generator units are refueled on an as-needed basis.

### 2.4.6. RMCS System Weights

RMCS operations for single-shell FGWL tanks increase the dead weight on the tank dome. Table 2-5 lists the calculated weights of various components that could be placed on the tank dome surface.[16] However, all of the listed components cannot be simultaneously placed on the tank because of component physical limits. The dome loading for SSTs is controlled by limits specified in the approved procedure,[17] and the additional tank dome loading is considered to be a live load in the WHC evaluation of the tank structural integrity.

Tank structural integrity can be at risk if the FG/RMCS drill string falls and impacts the tank bottom. For this reason, the total weight of the drill string suspended over the tank bottom is an important factor. The total weight will be the sum of the core barrel, sampler, and drill string, but will vary as a function of the drill string length. The drill rod nominally weighs 4 lb/ft, and the universal sampler, which includes the quadralatch and pintle rod, weighs 10.3 lb.[16] The combined suspended weight for an FG/RMCS operation will peak as sample operations approach the tank bottom (e.g., a 50-ft drill string length effectively would weigh more than 210 lb), but the impact energy will peak at an intermediate sampling depth because it is a product of the suspended weight and drop height.

TABLE 2-5
RMCS COMPONENT WEIGHT BREAKDOWN

| Component | Weight (lb) |
|---|---|
| Core sample truck (includes grapple hoist assembly and shielded receiver assembly) | 30,000 |
| Truck platform | 6,000 |
| Universal sampler (11 @ 10.3 lb) | 113 |
| Drill String (50 ft @ 4 lb/ft) | 200 |
| Change-out assembly | 45 |
| Riser adapter and drill rod washer | 280 |
| Riser sleeve | 200 |
| Inlet breather filter stack | 2,000 |
| Support truck | 7,000 |
| Cask truck | 8,000 |
| Cask stand | 300 |
| Casks (5 @ 480 lb) | 2,400 |
| Mobile X-ray system | 5,000 |
| Exhauster system | 10,000 |
| Light plants (2 @ 1000) | 2,000 |
| Video vehicle | 5,000 |
| Tent | 7,000 |
| Tent weights | 33,000 |
| People (10 total) | 2,000 |
| Total Potential Weight | 120,538 |

## 2.5. RMCS Operations

For the purposes of this safety assessment, FG/RMCS operations are divided into four phases as depicted in Fig. 2-11: (1) preinstallation activities, (2) installation, (3) drilling operations, and (4) removal. Key steps and limits are then provided within each phase. The following section describes the operations associated with rotary-mode core sampling, and is a summarization of input from safety analyses in Refs. 9, 10, and 11, and verbal discussions with WHC personnel.

The fundamental premise of FG/RMCS operations is the capability to enact safe shutdown upon detection of unacceptable levels of flammable gas and shut down sampling operations until it becomes safe to continue operations.

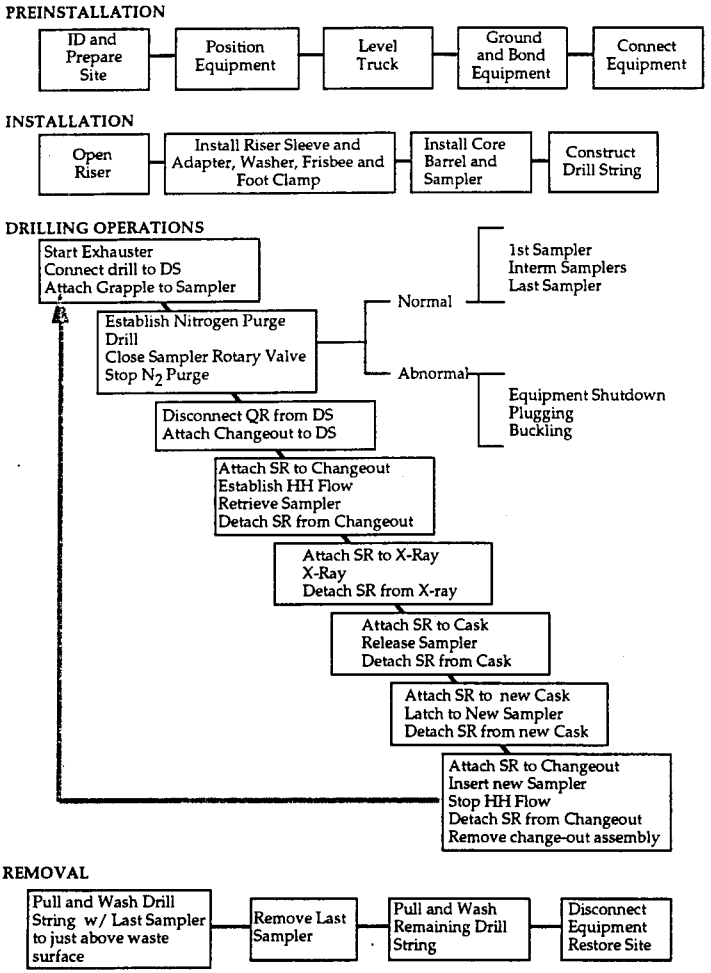


**Fig. 2-11. FG/RMCS process.**

### 2.5.1. Preinstallation

Preinstallation activities are assumed to include site preparations, equipment setup and connection, electrical bonding, and verifying critical alarms and trips. Fig. 2-12 schematically shows the relative positions of the pieces of FG/RMCS equipment on and surrounding any given tank, along with the anticipated power requirements.

Setup and operation of all equipment is assumed to be in compliance with appropriate procedures. For information only, several commonly used procedures are listed in Table 2-6.

Preinstallation activities include:

- Collect all appropriate procedures.
- Obtain sign off on all necessary conditions, concurrence, forms, and permits.
- Comply with all contractor safety, radiation and contamination, environmental protection, permitting and quality assurance controls, procedural limits and precautions, and records maintenance.
- Investigate and identify farm, tank, and riser locations. Prepare the site. Acquire and stage all supplies and equipment needed to perform operations. Calibrate measurement devices as procedurally required.
- Verify tank ventilation method and operability. Verify spark resistance of tools and lanyard as necessary to prevent tool entry into tank.
- Set up auxiliary support equipment, including the generator, the compressor, power distribution trailer, the support truck with the drum $H_2O$ heater, nitrogen trailer, and service trailer. Position and set up primary systems, including the sampling truck, exhauster, the cask stand with casks, and the mobile X-ray image system.
- Perform grounding and bonding activities. Call the weather service to verify that there are no lightning storms within a 50-mile radius of the sample site.
- Measure the quill-rod-to-riser distance, and determine the number and size of drill rods needed in accordance with the procedure data sheet. Obtain drill rods. Place drill rods in the lockup rack on the support truck.
- Place the quill rod in a full down position, hydraulically level the sampling truck, and verify stability. Verify alarms and annunciators.

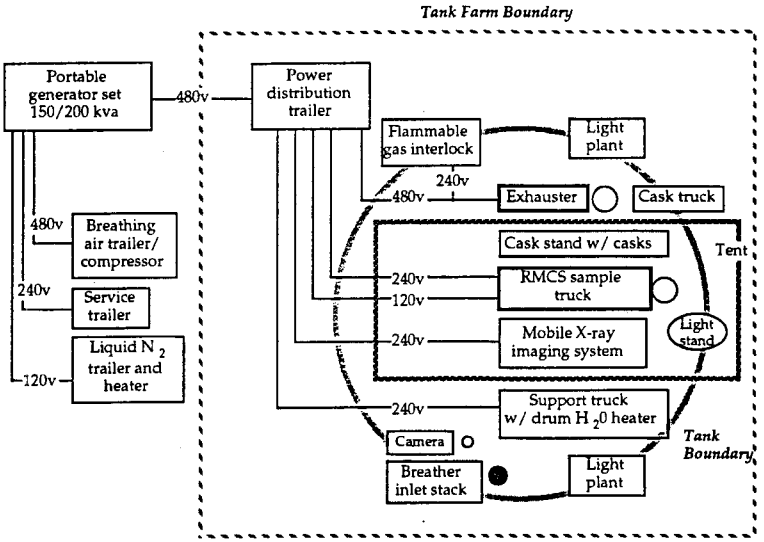


**Fig. 2-12. Relative placement of equipment required for core sampling in the rotary mode.**

### 2.5.2. Installation

Installation activities are assumed to include removing the riser blank flange and gasket, installing the riser sleeve and riser equipment (riser adapter, spray washer, frisbee wiper, and foot clamp), and core barrel/drill bit/sampler unit through the riser equipment. It should be noted that during the opening of a riser, either toxic gases (i.e., ammonia, organic vapors, and nitrogen dioxide), and/or combustible gases (i.e., methane, hydrogen) could be released and are monitored in a way consistent with appropriate procedures. Operations may proceed only if the combustible-gas meter, calibrated according to appropriate procedures, reads $\leq$ 25% LFL.

- Crack open the blank flange or pipe cap to off-gas the tank for 5 minutes. Start air sampling. Perform a breathing zone survey and sniff the riser and surrounding area.

- Install the riser assembly, using the mobile crane or the platform hoist. The riser assembly is assumed to include the riser adapter, conductive sleeve, spray washer/frisbee wiper assembly, and foot clamp.

- Screw the drill bit onto the core barrel and gently insert a universal sampler. Attach and install the drill rods in the order specified by the procedural worksheet. Screw the bonded lifting bail onto each newly attached drill rod, open the foot clamp, and lower the DS with the platform hoist. Close the foot clamp each time before releasing the DS to attach another drill rod.

- Install drill rods until the string is just above the waste surface or until only 19-in. drill rods remain. The predrilling configuration should resemble Fig. 2-13.

**TABLE 2-6**
**EQUIPMENT PROCEDURES USED IN SA**

| | | |
|---|---|---|
| • | Perform Rotary Core Sampling of Ferrocyanide, Organic, Organic/Ferrocyanide Watch-List Waste Storage Tanks[18] | TO-080-056 |
| • | Liquid Nitrogen Trailer, Nitrogen Chiller, and Indeeco Nitrogen Heater Operations | TO-060-345 |
| • | ONAN[2] 150DGFA Generator Set Operation | TO-020-900 |
| • | AEROFLOW[3] Model 2AN137 Breathing Air Compressor Operation | TO-020-056 |
| • | Transfer the On-site Transfer Cask | TO-080-090 |
| • | Sample Transfer Truck Operation | TO-080-075 |
| • | Pick Up/Transport Radioactive Material and Waste Packages | TO-100-010 |
| • | Katolight[4] Model D200FRJ4 Standby Power System Operation | TO-020-825 |
| • | Perform Waste Generation, Segregation and Accumulation | TO-100-052 |
| • | X-ray Procedure | To be specified following SA approval |
| • | Exhauster Procedure | To be specified following SA approval |

[2]ONAN is a trademark of the ONAN Corp., Minneapolis, MN.

[3]AEROFLOW is a trademark of the AEROFLOW Corp., Etna, WY.

[4]Katolight is a trademark of the Katolight Corp., Mankato, MN.

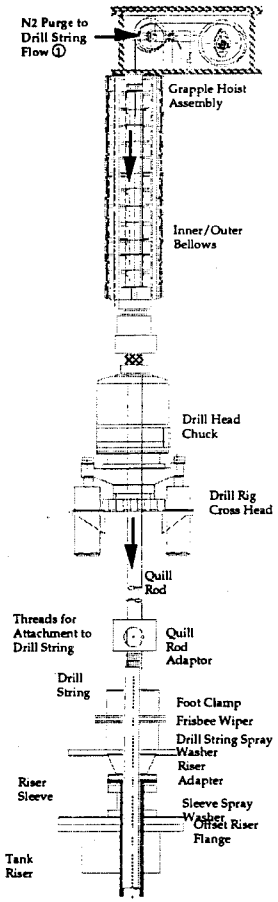


**Fig. 2-13. Predrilling configuration.**

### 2.5.3. Sampling Operations

Sampling operations are assumed to include drilling operations, removal of the universal sampler from the drill string, X-ray imaging, placing the sampler into the receiving cask, obtaining a new sampler, and placing the new sampler into the drill string.

#### 2.5.3.1. Drilling.

- Monitor and record flammable-gas concentrations and other appropriate parameters, according to the operational safety document (OSD) requirements.
- Rotate the truck platform to position the grapple hoist assembly/drill unit over the drill string. Attach a 19-in. drill rod to the drill string. Open the drill chuck, connect the quill rod, and close the chuck. Open the foot clamp. Raise the drill rams if necessary.
- Establish nitrogen purge flow through the riser/sleeve annulus.
- Ensure that the exhauster is operating according to the appropriate procedure, verify that the exhauster interlock is activated, and initiate nitrogen purge gas flow through the DS.
- Lower the grapple through the quill rod with grapple hoist until it latches onto the pintle rod of the universal sampler. Record the mechanical grapple counter value. Raise the grapple only enough to remove the slack in the grapple hoist cable.
- If obtaining a final sample, activate the hydraulic bottom detector, with independent verification.
- Establish the nitrogen purge gas flow at about 40 scfm, or as necessary. Engage the clutch, adjust the DS rpm, and proceed with rotary drilling by adjusting the ram control valve to obtain the desired penetration rate, i.e., down force, as

appropriate, within the operating parameter envelope. Operational limits on FG/RMCS parameters are provided in Section 2.5.5.1.

- If the drill bit becomes plugged, refer to Section 2.5.5.2.4.

- If the drill string becomes stuck, refer to Section 2.5.5.2.5.

- When a full sample stroke is completed, close the ram control valves, disengage the clutch, and close the nitrogen purge flow control valve.

- Raise the grapple to pull the pintle rod, release the spring clip that separates the pintle rod from the sampler piston, and close the rotary valve at the bottom of the universal sampler. Pull the pintle rod up through the drill string and into the quill rod.

- Raise the drill string about 1 in. to ensure trouble-free installation of the next sampler. Close the foot clamp. Depressurize the grapple hoist box, and verify depressurization.

- Open the chuck, disconnect the quill rod adapter from the DS, and close the chuck. Screw the cap with the male Kamlok® adapter onto the quill rod adapter. Rotate the platform to place the grapple hoist assembly aside from the drill string.

- Screw the cable wash assembly onto the DS. Connect the male Kamlok® of the change-out assembly to the female Kamlok® of the spray washer assembly. Close the change-out isolation valve. Pressurize the DS to maintain hydrostatic head.

- Kamlok®-connect the quill rod overpack to the bottom of the quill rod adapter, and mechanically release the pintle rod from the grapple into the overpack. Disconnect the overpack from the Kamlok® cap on the quill rod adapter.

#### 2.5.3.2. Removing the Universal Sampler.

- Rotate the truck platform to position the SR over the change-out assembly connected to the DS. Connect the Kamlok® on the end of the SR tube to the Kamlok® of the change-out assembly.

- Open the SR ball valve. Establish hydrostatic pressure in the SR. Open the change-out isolation valve. Lower the RLU at full speed to impact on and engage with the quadralatch of the universal sampler.

- If the DS pressure is greater than 0.5 psi times the sample number, vent the excess SR pressure.

- Slowly increase the hoist upward speed to unseat the sampler. The load cell value should read 60 to 70 lbf, but if the value is >150 lbf, then waste could be in the core barrel.

- Raise the sampler through the DS and into the SR tube. Inspect the sampler in the sight glass for cleanliness and record abnormal conditions.

- If the sampler exhibits visible waste material, wash the sampler by connecting the hot water line to the cable spray washer and raising the sampler slowly through the washer. Record water usage on proper data sheets and chain-of-custody documents.

- Raise the sampler into the SR tube. Close the change-out isolation ball valve. Depressurize the SR. Close the SR ball valve. Disconnect the SR Kamlok® from the change-out Kamlok®.

#### 2.5.3.3. Mobile X-ray Image System Operations

- Rotate the truck platform to position the SR over the mobile X-ray image system. Connect the SR Kamlok® to the Kamlok® of the X-ray system.

- Open the SR ball valve. Lower the sampler into the mobile X-ray image system. Complete the imaging and raise the sampler into the SR tube. Close the SR ball valve.

- Disconnect the SR Kamlok® from the Kamlok® of the X-ray system.

#### 2.5.3.4. Sampler Into Receiving Cask

- Rotate the truck platform to position the SR over the receiving cask, and remove the cap from the cask adapter. Connect the SR Kamlok® to the Kamlok® of the cask.

- Open the SR ball valve. Lower the sampler into the cask until the cable is slack. Disengage the RLU from the sampler quadralatch mechanism. Raise the RLU back into the SR tube. Close the SR ball valve.

- Disconnect the SR Kamlok® from the Kamlok® of the receiving cask.

- Prepare the cask for shipping. Remove the PVC sleeve from the cask. Remove the Kamlok® adapter from the cask; install the inner cask container plug, flange, and a new gasket; and install flange bolts. Complete the appropriate data sheets and chain-of-custody documents. Place a Waste Tank Sample Seal on the cask so that the seal must be broken to open the cask.

#### 2.5.3.5. New Sampler Preparation

- If another sample is required, place a new universal sampler into a cask liner, and gently insert the sampler into a new cask.

- Rotate the truck platform to position the SR over the new cask. Connect the SR Kamlok® to the Kamlok® of the new cask.

- Open the SR ball valve. Lower the RLU at full speed to impact on and engage with the quadralatch of the new universal sampler. Visually verify that the sampler is attached while raising the sampler into the SR tube. Close the SR ball valve.

- Disconnect the SR Kamlok® from the Kamlok® of the new cask.

#### 2.5.3.6. New Sampler Insertion into Drill String

- Rotate the truck platform to position the SR over the change-out assembly connected to the DS. Connect the SR Kamlok® to the Kamlok® of the change-out assembly. Open the SR ball valve.

- If directed by the PIC (person in charge), wash the drill bit by adding 0.1 to 0.3 gal. of hot water through the cable wash assembly. Criteria for this direction are circumstances in which the drill string has been idle for >4 hours or purge flow has not been established. Record water usage on the appropriate data sheets and chain-of-custody documents.

- Pressurize the SR. Open the change-out isolation valve. Lower the RLU and new sampler into the DS until the cable is slack (NOTE: there is no indication that the new sampler is fully latched into the core barrel/drill bit assembly.) Disengage the RLU from the sampler quadralatch mechanism. Raise the RLU back into the SR tube. Close the change-out isolation valve.

- Depressurize the SR. Close the SR ball valve.

- Disconnect the SR Kamlok® from the change-out Kamlok®.

- Rotate the truck platform to position the grapple hoist assembly/drill unit next to the drill string.

- Depressurize the drill string. Remove the change-out assembly.

- Return to Section 2.5.3.1 until the last core segment is obtained.

### 2.5.4. DS Removal

Removal operations are assumed to occur when the DS equipment is washed and removed. The hoist or drill head is connected to the drill string, and the DS is retrieved and externally washed. The hoist or drill head is disconnected, and the drill sections are discarded. Auxiliary equipment is disassembled, and the site is restored.

Two methods may be used for washing the drill string. With the first method, retain the last sampler in the core barrel, or install a new sampler. Depressurize the drill string, connect the water line to the drill rod washer, disconnect the change-out assembly and cable spray washer, and use the drill head to remove all 19-in. drill rods, washing while removing. Retrieve the final sampler when above the waste surface. Rotate the platform, and use the platform hoist to retrieve the remaining segments of drill rod and the core barrel, washing while removing.

The second method utilizes hot water to establish a hydrostatic head balance with the tank waste. Depressurize the drill string, and add hot water through the cable washer to balance with the waste level. Change the water line to the drill rod washer, and disconnect the change-out assembly and the cable spray washer. Position the drill head over the drill string and use it to remove all of the 19-in. drill rods. Rotate the platform, and use the platform hoist to retrieve the remaining segments of drill rod and the core barrel, washing while removing.

### 2.5.5. Operational Conditions and Characteristics

RMCS activities include both normal and abnormal operating conditions during drilling and sample retrieval.

**2.5.5.1. Normal Operations.** Normal operations include normal rotation within the established parameter envelope, a walkdown mode, and a bottom-detection mode. Truck stabilization can also be described in certain cases as a normal condition.

**2.5.5.1.1. Normal Drilling and Sample Retrieval.** Table 2-7 lists pertinent operational characteristics associated with the normal drilling and sample retrieval activities described in Section 2.5.3. Nominal values are provided, along with minimum and maximum range values. Alarm and trip points, if appropriate, are specified.

TABLE 2-7
OPERATIONAL PARAMETERS FOR ROTARY-MODE CORE SAMPLING METHOD

| Parameter | Normal Range | High Value | Low Value | Alarm | Trip |
|---|---|---|---|---|---|
| Down force (lb) | 0 to 750 | 750 | 0 | 750 | >750 |
| DS rotational speed (rpm) | 2 to 55 | 110 | 2 | 55 | >55 |
| RMCS enable system (rpm) | 2 | 2 | 2 | NA | 2 |
| DS purge gas flow (scfm) | 30 to 50 | 100 | 0.1 | 30 | <30 |
| DS purge gas pressure (psig) | 30 to 50 | 90 | 0.3 | NA | NA |
| Riser purge gas flow | 5 scfm | NA | NA | 40 psid | 40 psid |
| Purge gas temperature (°F) | 60 to 80 (atmospheric) | 140 | 10 | <10 >140 | NA |
| Instrument enclosure temperature (°F) | 70 to 80 | 90 | 50 | <50 >90 | NA |
| Penetration rate (in./min) | 3 to 10 | 25 | 0 | 0.75 | <0.75 |
| Lower ram pressure (psi) (walkdown mode) | 50 to 250 | 250 | 20 | NA | NA |
| Hydrostatic DS pressure (psi) | 0.5 to 30 | 35 | 0.2 | NA | NA |
| Hydrostatic DS flow (scfm) | 0.5 to 2 | 7.8 | 0.2 | NA | NA |
| Hydrostatic SR pressure (psi) | 0.5 to 30 | 35 | 0.2 | NA | NA |
| Hydrostatic SR flow (scfm) | 0.5 to 2 | 7.8 | 0.2 | NA | NA |

2.5.5.1.2. **Walkdown mode.** The walkdown mode establishes a setpoint to allow the drill to "walk" through the drill stroke. The mode utilizes a solenoid-operated valve (SOV) to automatically start and stop ram motion by stopping hydraulic fluid flow through the drill rams when the specified pressure is reached.

2.5.5.1.3. **Bottom detection.** To prevent penetration of the tank bottom, a hydraulic bottom detector (HBD) is activated with the last sample. The four-way valve controls whether hydraulic fluid flows into the top or bottom side of the drill rams, thus controlling the direction of drill ram movement. During normal operation, the flow control valves control the amount of fluid that flows from the downstream side of the drill ram, which controls the drill penetration rate and the amount of force applied to the drill string. When activated, the HBD monitors the pressure on the lower or downstream side of the drill ram. When the hydraulic pressure sensors detect a loss of lower ram pressure, the drill direction is automatically

reversed. When the stroke is complete, the HBD alarms may have triggered; the operator will silence the siren, stop the stroke, and disable the HBD.

**2.5.5.1.4. Stabilized mode.** A stabilized mode for the tank and sampling truck can be defined to include the following:

- If stabilization is required when the tank is open, then the open riser is covered.
- If the sampling truck is connected to the drill string, then it remains connected unless lightning is approaching, in which case, the drill string is disconnected and capped.
- If the sampling truck is not connected to the drill string, then stabilization assumes that the truck is placed in stabilized mode: the sampler is in the drill string; the drill string, the shielded receiver and quill rod are sealed; the shielded receiver and quill rod are above the rotary platform; the skid is traverse centered; the quill rod is to the back of the truck; all control panel breakers on the truck are off, unless the air temperature is >90°F or <50°F; the PG, SR and DS Gas switches are off; PG mode switch is positioned to DRILL; PG, SR and DS flow control valves are closed; the foot clamp is closed; the four-way valve is in FLOAT position; the Up and Down ram-control valves (RCVs) are closed; and the hydraulic bypass valve is closed.
- The PIC should record the status of sampling in the log book for recovery from the stabilized mode.

### 2.5.5.2. Abnormal Drilling Conditions

**2.5.5.2.1. Reduced nitrogen flow.** If nitrogen purge flow is less than the total of 30 scfm, then the drill rig will be automatically tripped, and drilling will be immediately terminated. The exhauster shall remain operational. The cause of the loss will be determined and corrected before drilling operations are reinitiated.

**2.5.5.2.2. Excess rpm or down force on drill string.** If the rotational speed exceeds 55 rpm or the down force is greater than 750 lbf, then the drill rig will be automatically tripped and drilling will be immediately terminated. The nitrogen purge and exhauster shall remain operational. The cause of the loss will be determined and corrected before drilling operations are reinitiated.

**2.5.5.2.3. Penetration Rate.** If the penetration rate falls below 0.75 in./min, then an alarm is triggered, and a 60-second period is provided for operator intervention to increase the penetration rate. If the rate is not increased, then the drill rig will be automatically tripped and drilling will be immediately terminated. The exhauster shall remain operational. The cause of the loss will be determined and corrected before drilling operations are reinitiated.

**2.5.5.2.4. Drill bit plugging.** If 30 scfm nitrogen purge flow cannot be maintained in normal operations, then the drill bit could be plugged with waste. In this case, the grapple hoist box is depressurized, and 0.1 to 0.3 gallons of hot water are added to the drill string through the quill rod adapter. The water usage is noted on the chain-of-custody for that sample.

Purge flow is then reestablished at 40 to 70 scfm. If the bit is cleared, then operations can resume. If not, then the cognizant engineer is consulted for alternate methods to unplug the bit.

**2.5.5.2.5. Stuck drill bit.** If the drill bit becomes stuck in the waste, then the grapple hoist box is depressurized if necessary and about 1 gal. of hot water is added to the drill string through the quill rod adapter. The water usage is noted on the chain-of-custody for that sample.

Purge flow is then reestablished at 40 to 70 scfm. If the bit becomes unstuck, then operations can resume. If not, then the cognizant engineer is consulted for alternate methods to loosen the bit.

**2.5.5.2.6. DS flooding or structural failure.** The procedures for handling DS flooding or unplanned maintenance activities are not covered in this safety analysis. The actions needed to handle DS structural failure or extreme jamming of the DS are not delineated in this document.

**2.5.5.3. Loss of exhauster.** Exhauster operation can be automatically terminated as a result of exhauster operational issues. Operationally tripping the exhauster will automatically trip the drill rig through the PLC on the truck. Similarly, the PLC also deenergizes the SOV in the nitrogen purge enclosure, which stops the purge flow to the DS.

Operationally, the exhauster automatically shuts down under the following conditions:

- Excessive negative tank pressure (-750 Pa or -3 in. w.g.).
- High differential pressure of 10 in. of water across the optional in-riser prefilter.
- High differential pressure of 5.9 in. of water across the HEPA filter bank.
- Exhaust stack flow greater than 250 scfm or less than 150 scfm.

A seismic event will not invoke automatic shutdown of the exhauster.

**2.5.5.4. Gas-release event.** A gas-release event can be measured by the flammable gas detection system, discussed in Appendix U, that is connected upstream of the exhauster, or by the tank pressure system in the tank dome. The flammable gas detection system is setpoint-limited at the equivalent of 5000 ppm hydrogen

concentration, or a rate of rise of 100 ppm/second. Likewise, an increase in the tank pressure of 2 in. w.g. above back ground will trip the drill rig.

With out-of-tolerance conditions, the exhauster remains operational, but the drill rig engine operation is terminated. Personnel evacuate the site, don protective clothing, and can return to the tank for further equipment stabilization.

#### 2.5.5.5. Emergency Response

All emergency conditions that could result in personnel injury or equipment damage are handled by the PIC in the following manner.

- Direct personnel to attend to any injured personnel, and evacuate as appropriate. Notify the fire department and the occurrence notification center.

- Depending on the nature of the emergency, and at the discretion of the PIC, stabilize the drill site as much as feasible commensurate with Section 2.5.5.1.4.

- Monitoring should be continued in support of all emergency activities.

- Evacuate personnel, and ensure the prevention of uncontrolled access to the drill site area.

Notify the Sampling Operations and Tank Farms Shift Management of the emergency.

### 2.5.6. Restart

Restart could be required for numerous reasons, including a power outage, exhauster shutdown, loss of nitrogen purge, exceeding drilling setpoints, or even starting a new work day. In general, the following conditions would be verified before sampling is reinitiated. Restart following off-normal incidents should be performed in a way consistent with the requirements of the Interim Safety Basis.

- Complete the Daily Core Sample/Inspection Data Sheet as required by the procedure.

- Turn all breakers on the truck's Core Sampler Power panel to ON. Acknowledge all alarms, and reset all immediate alarms. Resume exhauster operation. Resume sampling operations.

## 2.6. References


1. "Tank Farm Health and Safety Plan," Westinghouse Hanford Company report WHC-SD-WM-HSP-002, Rev. 0A (September 28, 1993).

2. "Hanford Site Tank Farm Facilities Interim Safety Basis," Westinghouse Hanford Company report WHC-SD-WM-ISB-001, Rev. 0 (August 1, 1993).

3. D. Hopkins, "Criteria for Flammable Gas Watch List Tanks," Westinghouse Hanford Company report WHC-EP-0702 (August 1994).

4. P. Whitney, "Screening the Hanford Tanks for Trapped Gas," Pacific Northwest Laboratory report PNL-10821 (October 1995).

5. H. Babad and Turner , "Interim Report for Organic Watch List Tanks at the Hanford Site, Westinghouse Hanford Company report WHC-EPP-0681 (1993).

6. "Bounding Gas Release Calculations of Flammable Gas Watch List Single-Shell Tanks," Los Alamos National Laboratory report LA-UR-94-1323, Rev. 0 (1994).

7. B. M. Hanlon, "Waste Tank Summary Report for Month Ending October 31, 1995," Westinghouse Hanford Company report WHC-EP-0182-91 (January 1991).

8. "Safety Equipment List," Westinghouse Hanford Company report WHC-SD-WM-SEL-032, Rev. 1. (February 15, 1994).

9. Safety Assessment for Push-Mode Core Sampling in Tank 101-SY," Westinghouse Hanford Company report WHC-SD-WM-SAD-008, Rev. O-A (May 1991).

10. Safety Assessment for Push- and Rotary-Mode Core Sampling in Ferrocyanide Tanks," Westinghouse Hanford Company report WHC-SD-WM-SAD-013, Rev 3-A (November 1993).

11. "Safety Analysis for the Push Mode and Rotary Mode Core Sampling," Westinghouse Hanford Company report WHC-SD-WM-SARR-031, Rev. 2 (July 1995).

12. "Safety Requirements for Safety Basis for Rotary-Mode Core Sampling Flammable Gas Safety Issue Tanks," Westinghouse Hanford Company report WHC-SD-WM-FDC-048 (September 1995).

13. R. J. Blanchard, "Justification on Functional Criteria for Rotary Mode Core Sample Truck," Westinghouse Hanford Company memo (January 19, 1995).

14. "System Design Description for the Rotary Mode Core Sampling Exhauster," Westinghouse Hanford Company report WHC-SD-WM-SDD-035, Rev. 2 (September 9, 1995).

15. "Tank Farm Operating Procedure, ONAN 150DGFA Generator Set Operation," Westinghouse Hanford Company procedure TO-020-900, Rev. B-3 (July 1995).

16. D. Hamilton, J. Smalley, and J. Criddle, Westinghouse Hanford Company personal communication (November 1995).

17. Boyles, "Operating Specifications for Single-Shell Waste Storage Tanks," Westinghouse Hanford Company report OSD-T-151-00013, Rev.0 (1994).

18. "Tank Farm Operating Procedure, Perform Rotary Core Sampling of Ferrocyanide, Organic, Organic/Ferrocyanide Watch-List Waste Storage Tanks," Westinghouse Hanford Company procedure TO-080-056, Rev. A-1 (October 10, 1995).

## 3.0. IDENTIFICATION OF HAZARDS

This section presents the methodology and results of a hazard identification study used to formally identify all hazards associated with the proposed action of the installation, operation, and removal of rotary-mode core sampling (RMCS) equipment in single-shell tanks (SSTs) on the Flammable Gas Watch List (FGWL) or those tanks recommended by the contractor to be included on the FGWL, hence referred to as FG/RMCS operations. This process, called hazard identification, is equivalent to the hazard analysis (HA) or hazard evaluation process in a safety analysis report. The final product of this hazard identification process is a list of design basis accidents (DBAs) that will be examined in more detail in the accident analysis section of the safety analysis (SA).

According to Ref. 1, hazard is defined as "A source of danger (i.e., material, energy source or operation) with the potential to cause illness, injury or death to personnel or damage to an operation or to the environment. A hazard is not an accident initiator, cause or deviation. Rather, it is a property, typically radiological and toxicological, inherent to the danger. Based on this definition, the hazards associated with the FG/RMCS operations in flammable gas tanks are:

- Existence and potential ignition of flammable gases;
- Existence and potential ignition of flammable chemicals in the waste;
- Existence and potential release of radioactive chemicals;
- Existence of fissile materials;
- Existence and potential release of toxic gases;
- Existence and potential release of toxic chemicals;
- Introduction of electrical, mechanical and thermal energy;
- Operation of heavy equipment and vehicles over the tank;
- Introduction of flammable material into the tank farm; and
- Natural phenomena (lightning, earthquake, etc) coinciding with RMCS operations.

The major consequence of accidents in the flammable gas SSTs is the release of radioactive and toxic materials that might expose the public sector and/or on-site personnel to unacceptable doses. Airborne, underground, and surface release pathways are considered in the study. In addition, any structural damage of the tank that would cause major damage in the dome area or leaks in the liquid region are evaluated. Radiological and toxicological consequences resulting from dome

collapse are also evaluated in this safety assessment. Leaks below the waste level, however, are identified as potential environmental hazards and the long-term consequences are not evaluated.

### 3.1. Methodology

The guidance used to perform the hazard identification (or HA) is DOE-STD-3009 (Ref. 1). DOE-STD-3009 provides the following guidance on the requirements for a complete hazards analysis. A complete hazards analysis should (STD-3009, p. 31)

1. Consider the complete spectrum of accidents that may occur due to facility operations;
2. Analyze potential consequences to the public and worker;
3. Estimate the likelihood of occurrence;
4. Identify and assess associated preventive and mitigative features;
5. Identify safety-significant structures, systems, and components; and
6. Identify a select subset of accidents to be formally defined in accident analysis.

In the hazards identification performed for rotary-core mode drilling, four of the six requirements listed above were met in full. Namely, (1) a complete consideration of the spectrum of accidents, (2) analysis of the potential consequences, (3) estimation of likelihood, and (6) identification of a select subset of accidents for accident analysis (the end product for this hazard identification). However, two of the requirements, (4) the identification of preventive and mitigative features; and (5) identification of safety-significant structures, systems, and components, were only partially met. For the rotary core mode drilling activity, hardware design and procedures were being developed during the hazard identification (hazard analysis) process. Therefore, at that time, preventive and mitigative procedures were not fully identified. By not identifying the preventive and mitigative features, the identification of safety-significant structures, systems, and components could also not be performed. However, identification of preventive and mitigative systems is performed in the design change/control implementation phase of this SA and documented in Section 6. A safety-class equipment list will be developed (Section 7) prior to the beginning of the FG/RMCS operations.

Hazard identification is the first step in the safety analysis process. The goals of hazard identification for this SA are a subset of the hazard analysis requirements presented earlier, namely;

- Consideration of the complete spectrum of potential accidents,

- Qualitatively assess the consequences to the worker and the public,
- Qualitatively estimate the frequency (or likelihood) of occurrence,
- Identification of a select set of representative and unique accidents (DBAs) for further evaluation.

Because of the relative complexity of the rotary-core drilling system and its unique intrinsic hazards, a detailed hazards identification study was performed considering all phases and aspects of the rotary-core drilling operation. The intent was to meet the requirements of Department of Energy (DOE) Order 5480.23 (Ref. 2) to identify all the hazards and accidents scenarios. The rotary-core drilling hazard identification process was performed by a multidisciplinary team consisting of Los Alamos and Westinghouse personnel, using a combination of two standard techniques, the hazard and operability (HAZOP) technique and "what if" checklist techniques. The operations examined were the installation of the equipment, the individual steps of the rotary-mode sampling, and the removal of the equipment. The operation was tracked in this way to ensure completeness of the HA.

At the beginning of the HA, the Westinghouse Hanford Company (WHC) Characterization Project Engineering and Operations personnel presented and described the operations. Subsequently a process-flow diagram was prepared to describe all phases of the installation, operation, and removal of the rotary-mode sampling equipment on a typical tank. Previous safety analyses, the available design documentation, and the operating procedures were reviewed prior to another meeting with FG/RMCS engineering and operations personnel. The hazards analysis was developed based on the process-flow sheets and the questions that resulted from the documentation review. Hazards identified in previous safety assessments[3-6] were reviewed and included in this study. The results of the hazards identification study are documented in Appendix A.

The HA includes estimates of the frequencies and consequences of the hazards that have been combined to provide a risk ranking. The risk ranking is one factor used to select the accidents. The accident database was examined and nine accident classes were selected for further analysis. Section 4 of this SA evaluates these nine accident classes. Alternative groupings are possible, and inevitably the grouping in some cases is not very clear. However, although the boundary between the groups may be subjective, the grouping process was complete, and all of the identified hazards are captured in these groupings.

This SA discusses all of the hazards identified and how they are managed to acceptable levels of risk. Some of this will be a discussion of the design features and controls. In some cases, analyses are used to show that the accident cannot happen physically. Also, analyses are presented to quantify the bounding consequences in the event that preventative and mitigation features are ineffective.

## 3.2. Results of the Rotary-Core Drilling System Hazards Identification

The hazard identification conducted for the proposed action in a representative single-shell tank (Tank 101-A) examined three processes; installation, operation, and removal of the rotary-core drilling unit. The hazards associated with transportation, of a contaminated rotary-core drilling unit or its auxiliary equipment from the tank farm or its ultimate decontamination and disposal are not considered. Transportation of the cask where core samples are stored also is not considered. These activities are included in the safety analysis reports for site transportation waste storage, and handling, and are subject to the applicable controls listed there. Operations evaluated included X-ray examination and storing the core sampler in the cask.

The results of the hazards identification indicate that the potential contributors to the release of radioactive and toxic materials and structural damage to the tank can be categorized in nine general categories of accidents. In Appendix A, details of the hazards identification and the general accident categories are presented. A total of 180 scenarios resulting in waste and toxic-gas releases were identified. The individual accidents are evaluated based on their qualitative accident frequency and resulting consequences. In Appendix A, a frequency and a dose class are assigned to each accident in order to rank them. The dose rates indicated in Appendix A are qualitative values. Likewise, frequency determination did not include a detailed failure-rate evaluation, but qualitative frequency estimates are provided. Selection of representative and unique accidents consider frequency and consequence in order to rank individual hazards. These representative unique accidents are categorized in nine groups based on their release characteristics.

The results of the hazards identification process are summarized in Tables 3-1 to 3-9. For each accident category, a separate table is given. The accident, the applicable scenario, principal causes, and design safety features are given for each case.

Specific design-related features, primarily those provided to manage identified hazards, are included because their failure may cause an evaluated accident or unevaluated accident result.

The relationship between hazards and accident analyses is determined for each accident in a given category. The accident analysis is cross-referenced to the section in Chapter 4 where the potential accident is evaluated. In some cases, the same accident analysis covers more than one hazard or initiator. In other cases, several accident analyses will be required to assess the various manifestations of the hazard.

The following is the summary of the tables in which the different accident hazard groups are summarized. Industrial hazards such as installations in the wrong tanks or risers, operation of the liquid nitrogen tank, traffic accidents, slips, falls, etc., are beyond the scope of this safety assessment.

SUMMARY OF TABLES

| Group | Table |
|---|---|
| Aboveground fire | Table 3-1 |
| Dome fire | Table 3-2 |
| Drill string fire | Table 3-3 |
| Waste fire | Table 3-4 |
| Gas releases | Table 3-5 |
| Chemical reactions and criticality | Table 3-6 |
| Containment breach | Table 3-7 |
| Spills and radiation exposure | Table 3-8 |
| External events | Table 3-9 |

## 3.3 REFERENCES

1. "DOE Standard Preparation Guide for U. S. Department of Energy Nonreactor Nuclear Facility Safety Analysis Reports," DOE-STD-3009-94 (July 1994).

2. "Safety Analysis Report," US Department of Energy Order 5480.23 (April 30, 1992).

3. N. J. Milliken and G. R. Geschke, "Safety Analysis for Push-Mode and Rotary-Mode Core Sampling," Westinghouse Hanford Company report WHC-SD-WM-SARR-031, Rev. 2 (July 1995).

4. N. J. Milliken, "Safety Assessment for Push-Mode and Rotary-Mode Core Sampling in Ferrocyanide Tanks," Westinghouse Hanford Company report WHC-SD-WM-SAD-013 (June, 1993).

5. R. M. Marusich, "Safety Assessment for Push Mode Core Sampling in Tank 101-SY," Westinghouse Hanford Company report WHC-SD-WM-SAD-008, Rev. 0-A (May 10, 1991).

6. R. L. Koontz, "Hazards Identification and Evaluation for Waste Tank Core-Sampling Equipment," Westinghouse Hanford Company report WHC-SD-WM-SAR-007 (June 1985).

## TABLE 3-1
## ABOVEGROUND FIRE HAZARD ASSESSMENT RESULTS

| Accident | Scenario | Design Safety Features | Analysis |
|---|---|---|---|
| Flammable-gas release to exhauster and burn | • Flammable-gas release from waste into exhauster and ignition source.<br>• Ignition in the exhauster and burn back to the tank dome (see Dome Fires) | • All electrical equipment in the exhauster flow stream must be rated to Class-1, Div.-I, Group-B environment.<br>• Do continuous exhausting with spark-resistant fan.<br>• Use heavy-duty, tear-resistant, conductive hose.<br>• Use redundancy/diversity in gas-release detection system (flammable gas and pressure). | Sec. 4.1.1. |
| Flammable gas release through torn duct and burn | • Gas release through torn hose | • Use heavy-duty, tear-resistant, conductive hose.<br>• Non-qualified equipment behind deflectors or in enclosures. | Sec. 4.1.2. |
| Flammable-gas release and burn outside an open riser | • Flammable-gas release from waste through open risers and ignition source<br>• Ignition above the tank and burn back to the tank dome (see Dome Fire) | • Inlet and exhaust have a stack height of 5 m (15 ft).<br>• All electrical equipment near open risers must be rated to Class-1, Div.-I, Group-B environment or Class-1, Div.-II, Group-B environment with automatic shutdown. | Sec. 4.1.3. |
| Flammable-gas release and burn in shielded receiver. | • Flammable-gas release from shielded receiver, drill string, and ignition source. | • Use hydrostatic head purge in the shielded receiver.<br>• Electrical equipment is designed for Class I, Division 1, Group B in the shielded receiver.<br>• Spark-resistant mechanical RLU. | Sec. 4.1.4. |
| Flammable-gas release and burn in the X-ray or cask | • Flammable-gas release into X-ray machine and into storage casks. | • X-ray sample liner is made of plastic.<br>• No unqualified equipment in Class I, Division 1 or Class I, Division 2 space in x-ray machine.<br>• Liner is painted with conductive graphite paint, and grounded and bonded. | Sec. 4.1.5. |
| Flammable-gas release and burn | • Flammable-gas accumulation or release from the loss of electrical power and ignition source | • No unqualified equipment in Class I, Division 1 or Class I, Division 2 space | Sec. 4.1.6. |
| Flammable-gas release and burn | • Release from propane tank on nitrogen trailer | • No credited design feature. | Sec. 4.1.7. |

TABLE 3-1 (cont.)
ABOVEGROUND FIRE HAZARD ASSESSMENT RESULTS

| Accident | Scenario | Design Safety Features | Analysis |
|---|---|---|---|
| Flammable material and burn | • Flammable diesel and gasoline fuel | • No credited design feature. | Sec. 4.1.8. |
| Equipment fire | • Collision caused by trucks and other equipment | • No credited design feature. | Sec. 4.1.9. |

TABLE 3-2
GAS RELEASE AND DOME FIRE HAZARD ASSESSMENT RESULTS

| Accident | Scenario | Design Safety Features | Analysis |
|---|---|---|---|
| Flammable gas and burn | • Drill string break | • Automatic shutdown on high down force and rpm.<br>• Automatic shutdown on high flammable gas. | Sec. 4.2.1. |
| Flammable gas and burn | • Equipment, tools, or drill string/ component drop on riser induces mechanical spark. | • Use spark-resistant tools. | Sec. 4.2.2. |
| Flammable gas and burn | • Equipment, tools, or drill-string/component drops on crust. | • Pneumatic clamp is designed to fail closed.<br>• Use of spark resistant tools. | Sec. 4.2.3. |
| Flammable gas and burn | • Frictional spark in the riser. | • Use stainless-steel sleeve in the riser.<br>• Inject nitrogen into riser sleeve to prevent hydrogen penetration.<br>• Automatic shutdown on loss of sleeve purge.<br>• Automatic shutdown on high flammable gas.<br>• Unique connectors for sleeve purge. | Sec. 4.2.4. |
| Flammable gas and burn | • Electrostatic spark in the riser | • Conductive material in the riser. | Sec. 4.2.5. |
| Flammable gas and burn | • Frictional spark caused by drill bit on crust | • Drill bits do not have spark-inducing carbide teeth. Cutting teeth are brass-based soft material.<br>• Drill bit design must be qualified by testing to non sparking.<br>• Automatic shutdown on high rpm and down force.<br>• Use of walkdown function and HBD. | Sec. 4.2.6. |

TABLE 3-2
GAS RELEASE AND DOME FIRE HAZARD ASSESSMENT RESULTS (cont.)

| Accident | Scenario | Design Safety Features | Analysis |
|---|---|---|---|
| Flammable gas and burn | • Spark sources<br>– in the dome<br>– in the ventilation system,<br>– in connected tanks | • All electrical equipment in the dome is rated for operations in Class-1, Div.-I, Group-B environment or Class-1, Div.-II, Group-B environment with automatic shutdown. | Sec. 4.2.7. |
| Dust explosions | • Aerosol accumulation | • Use of qualified exhauster. | Sec. 4.2.8. |

TABLE 3-3
DRILL STRING FIRE HAZARD ASSESSMENT RESULTS

| Accident | Scenario | Design Safety Features | Analysis |
|---|---|---|---|
| Flammable gas in the drill string | • Failure of sampler chevron seal<br>• Hydrogen diffusion<br>• Waste in the drill string<br>• Depressurization of waste<br>• Loss of $N_2$<br>• Incompatible material | • Sampler chevron seal.<br>• Drill string purge gas.<br>• Hydrostatic head purge.<br>• Shut down on low nitrogen flow.<br>• Use of compatible material. | Sec. 4.3.1. |
| Flammable gas and burn in drill string | • Drop impact<br>• Drop sampler<br>• Drop remote latch unit<br>• Drop grapple | • Components within the drill string must be qualified by testing to be non sparking.<br>• Sampler chevron seal. | Sec. 4.3.2. |
| Flammable gas and burn in drill string | • Ignition caused by assembly/disassembly of drill strings<br>• Ignition by drill-rod/quill-rod adapter impact | • Using spark-resistant tools/materials.<br>• Electrical equipment meets Class-1, Div.-I, Group-B requirements. | Sec. 4.3.3. |
| Flammable gas and burn in drill string | • Drill string failure | • Use $N_2$ purge of drill.<br>• Sampler chevron seal<br>• Automatic shutdown on high rpm, down force, flammable gas | Sec. 4.3.5. |

TABLE 3-3 (cont.)
DRILL STRING FIRE HAZARD ASSESSMENT RESULTS

| Accident | Scenario | Design Safety Features | Analysis |
|---|---|---|---|
| Ignition source and flammable gas in the drill string | • Friction<br>– bearings<br>– RLU<br>– Grapple | • Use $N_2$ purge.<br>• Components within the drill string must be qualified by testing to be non sparking.<br>• RLU/grapple insertion rate limited to 1 ft/s. | Sec. 4.3.6. |
| Flammable gas in the drill string | • Shear pin break | • Shear pin is replaced by a clip. | Sec. 4.3.7. |
| Detonation and ejection | • Flammable gas ignition in the drill string | • Sampler chevron seal.<br>• Electrical equipment meets Class-1, Div.-I, Group-B requirements.<br>• Shut down on low nitrogen flow.<br>• Components within the drill string must be qualified by testing to be non sparking.<br>• Use of compatible materials. | Sec. 4.3.8. |
| Ignition in the drill string caused by lightning strike | • Lightning strike | • No credited design feature. | Sec. 4.3.9. |
| Ignition in drill string caused by static electricity | • Static electricity between O-rings<br>• Static electricity on the Frisbee | • Maintain continuos in contact with metal and bonded.<br>• Sampler design maintains contact with drill string. | Sec. 4.3.10. |

TABLE 3-4
WASTE FIRE-HAZARD ASSESSMENT RESULTS

| Accident | Scenario | Design Safety Features | Analysis |
|---|---|---|---|
| Drill bit over-temperature | • Loss of $N_2$<br>• Down force<br>• Rotational speed<br>• Low penetration rate | • $N_2$ purge is done.<br>• Rotational-speed shutdown is carried out.<br>• High-force shutdown is done.<br>• Use bottom detector and walkdown function.<br>• Automatic shutdown on low penetration rate | Sec. 4.4.1. |
| Exothermic reactions | • Incompatible materials | • Use of compatible material. | Sec. 4.4.2. |
| Impact on crust of waste | • Drop of drill string or tool | • Use of pneumatic foot clamp. | Sec. 4.4.3. |
| Gas fire under surface | • Spark induced with drill bit impact<br>• Inadvertent increase in force and rpm | • Components in contact with the waste must be qualified by testing to be non-sparking.<br>• Automatic shutdown on high rpm, down force.<br>• Automatic shutdown on low nitrogen purge flow and penetration rate. | Sec. 4.4.4. |

TABLE 3-5
CHEMICAL REACTIONS AND CRITICALITY HAZARD RESULTS

| Accident | Scenario | Design Safety Features | Analysis |
|---|---|---|---|
| Criticality | • Drilling operation | • No credited design feature | Sec. 4.5.1. |
| Gas release caused by water addition | • Water addition | • Limited supply of water.<br>• Temperature control on water heater. | Sec. 4.5.2. |
| Exothermic runaway reactions<br>Waste melting | • Drill bit frictional energy<br>• Water addition<br>• $N_2$ addition<br>• Plugged purge holes | • Carry out $N_2$ purge during rotation.<br>• Automatic shutdown on high rpm, and down force.<br>• Automatic shutdown on low penetration rate and nitrogen purge flow. | Sec. 4.5.3. |
| Energy transfer to/from the waste | • Frictional heating<br>• Nitrogen cooling | • Automatic shutdown on high rpm, and down force.<br>• Automatic shutdown on low penetration rate and nitrogen purge flow. | Sec. 4.5.4. |
| Impact sensitive compounds | • Drilling<br>• Pushing | • No credited design feature. | Sec. 4.5.5. |

TABLE 3-6
CONTAINMENT BREACH HAZARD ASSESSMENT RESULTS

| Accident | Scenario | Design Safety Features | Analysis |
|---|---|---|---|
| Dome Loading | • High static loading<br>• Dynamic loads<br>• Truck falls off platform<br>• Crane drop | • No credited design feature. | Sec. 4.6.1. |
| Vacuum | • Exhauster failure<br>• Inadvertent closure of inlet riser | • Automatic shutdown on exhauster with high vacuum.<br>• Seal loop on breather filter. | Sec. 4.6.1. |
| Tank bottom penetration | • Drill into bottom<br>• Drill string drop and penetration | • Use hydraulic bottom detector.<br>• Use soft drill bit material.<br>• Automatic shutdown on high down force.<br>• Use of pneumatic foot clamp. | Sec. 4.6.2. |
| Drill-string break | • Excessive down force | • Automatic shutdown on high down force and rpm. | Sec. 4.6.3. |
| Riser damage | • Equipment (conductive sleeve and drill string) and tool drops | • No credited design feature. | Sec. 4.6.4. |
| Side penetration | • Drill string failure | • Automatic shutdown on high down force. | Sec. 4.6.5. |

TABLE 3-7
GAS RELEASE WITHOUT BURN HAZARD ASSESSMENT RESULTS

| Accident | Scenario | Design Safety Features | Analysis |
|---|---|---|---|
| Toxic-gas release | • Drilling operations<br>• Multiple release modes<br>• Additional $N_2$ purge | • Automatic shutdown on high gas concentration.<br>• Use exhauster stack for worker protection.<br>• Use of inlet breather filter stack. | Sec. 4.7.1. |
| Unfiltered release | • Ventilation failure<br>• Tank pressurization | • Use of qualified exhauster HEPA and breather HEPA filters | Sec. 4.7.2. |
| Steam release | • Drill temperature induces steam | • Automatic shutdown on high rpm and down force.<br>• Automatic shutdown on low penetration rate and nitrogen purge flow. | Sec. 4.7.3. |
| $N_2$ addition | • Accumulation in waste causing a gas-release event<br>• Ammonia scrubbing | • Use of qualified exhauster.<br>• Automatic shutdown on tank pressure and gas concentration. | Sec. 4.7.5. |

TABLE 3-8
SPILLS AND RADIATION EXPOSURE HAZARD ASSESSMENT RESULTS

| Accident | Scenario | Design Safety Features | Analysis |
|---|---|---|---|
| Exhauster releases | • HEPA failure | • Use $\Delta P$ limits.<br>• Use high- and low-flow shut down exhauster.<br>• Loss of exhauster flow shuts down $N_2$ and drill. | Sec. 4.8.1. |
| Exhauster continuous release after filter failure | • HEPA failure | • Use $\Delta P$ limits.<br>• Use high- and low-flow shut down exhauster.<br>• Loss of exhauster flow shuts down $N_2$ and drill. | Sec. 4.8.2. |
| Inlet duct failure | • Breather HEPA filters fail | • No credited design feature. | Sec. 4.8.3. |
| Aerosol | • Loss of ventilation flow and failure to shutdown purge | • Use of qualified exhauster.<br>Use of breather inlet HEPA filter stack.<br>Use of exhauster stack. | Sec. 4.7.2. |
| Sprays | • No initiators | • No credited design feature. | NA |
| Drops: DS sampler | • Operational hazard | • No credited design feature. | Sec. 4.8.4. |

TABLE 3-8 (cont.)
SPILLS AND RADIATION EXPOSURE HAZARD ASSESSMENT RESULTS

| Accident | Scenario | Design Safety Features | Analysis |
|---|---|---|---|
| Open sampler | • Stuck ball valve | • Use viewing window.<br>• Use transfer to shielded cask through closed system. | Sec. 4.8.5. |
| Spill in core barrel | • Waste accumulation in core barrel | • Drill rod spray washer.<br>• Cable spray washer. | Sec. 4.8.6. |
| Drop of contaminated drill string | • Ineffective decontamination and drop | • Spray wash system. | Sec. 4.8.7. |
| Radiation exposure | • High loading in HEPA<br>• Spills<br>• Open riser<br>• Failure of decontamination | • No credited design feature. | Sec. 4.8.8. |

TABLE 3-9
RESULTS OF HAZARD ASSESSMENT FOR EXTERNAL EVENTS

| Accident | Accident Scenario | Design Safety Features | Analysis |
|---|---|---|---|
| Lightning | • Ignition of flammable gases | • No credited design feature. | Sec. 4.9.1. |
| Winds | • Flow induced vibration<br>• Static electricity buildup<br>• Spread of contamination<br>• Operator errors/equipment drop | • Conductive duct.<br>• Heavy skid.<br>• Exhauster stack and inlet breather HEPA stack is designed for high winds. | Sec. 4.9.2. |
| Range fires | • Ignition of flammable gases | • No credited design feature. | Sec. 4.9.3. |
| Seismic | • Tank failure<br>• Gas-release event | • No credited design feature. | Sec. 4.9.4. |
| Tornadoes | • See lightning/flooding/high winds | • No credited design feature. | Sec. 4.9.5. |
| Flooding/ heavy rains | • Tank overfill<br>• Equipment malfunction<br>• Operator errors | • No credited design feature. | Sec. 4.9.6. |
| Volcanoes | • Flooding, gas ignition, dome loading | • No credited design feature. | Sec. 4.9.7. |
| Dust devils | • Spread of contamination<br>• Operator error/equipment drop | • No credited design feature. | Sec. 4.9.8 |

## 4.0. HAZARD ANALYSIS

In Section 3, the hazards associated with the installation, operation, and removal of rotary-mode core sampling (RMCS) equipment in single-shell tanks (SSTs) on the Flammable Gas Watch List (FGWL) or those tanks recommended by the contractor to be included on the FGWL, hence referred to as FG/RMCS operations, were identified, and the resulting accidents were grouped into nine categories. In Section 4, each accident category is quantitatively discussed in the following subsections:

Section 4.1: Aboveground Fire Accidents

Section 4.2: Dome Fire Accidents

Section 4.3: Drill String Fire Accidents

Section 4.4: Waste Fire Accidents

Section 4.5: Chemical Reactions and Criticality Accidents

Section 4:6: Containment Breach Accidents

Section 4.7: Gas Releases without Burn

Section 4.8: Spills, Releases, and Hazardous Material and Radiation Exposure

Section 4.9: External Events

Radiological and toxicological consequences of the above accidents are discussed in Section 5 of this SA.

In this section, for each accident, the frequencies are estimated and discussed in the corresponding subsection. Both the unmitigated accident frequency (UAF) and the mitigated accident frequency (MAF) for each accident are provided in which credit is taken for the administrative controls established in this safety assessment (SA) and in other safety basis documents. In Appendix D, the equipment reliabilities are computed for each FG/RMCS activity. An FG/RMCS activity is defined to include preinstallation equipment setup, installation of the FG/RMCS equipment, the collection of a complete set of core samples representing an entire tank depth, and removal of the FG/RMCS equipment. One hundred forty-four hours are required to complete an entire activity. Within this 144-h period, 40 h (approximately 2 samples collected per shift) are required to retrieve the 11 samples [based on an average single-shell tank (SST) waste depth]. Total drilling time is approximately 4 h (20 min. per sample). Exhauster and truck shutdown instrumentation systems and calibration are checked and calibrated within six months. Assuming there are two FG/RMCS activities per year per tank, the accident frequency is calculated per year per tank.

There are several key assumptions that underlie assigning a probability to a given event (Appendix E). The probability of a human error was assumed to be 0.003 based on assumptions defined in NUREG-CR-4772[1] and listed in Appendix E. FG/RMCS operations are required to comply with these assumptions. Therefore, they are listed in Section 6 as administrative controls.

Also considered in determining the accident frequencies is the probability of phenomenological events such as gas-release events (GREs), fraction of the waste causing propagating exothermic reaction, spark generation and propagation of fire into the dome or into the waste.

The major hazard associated with FG/RMCS operations in flammable-gas tanks is the existence of flammable material. Consequently, four of the nine accident categories identified in the SA are burn scenarios, which generally result in the highest radiological and toxicological consequences because a dome space deflagration in an single-shell tank (SST) is likely to result in a catastrophic dome failure (see Section 5 of this SA).

To eliminate a fire hazard, either the fuel, the oxidizer, or the ignition source must be eliminated or controlled, and for the safety of FG/RMCS operations, one or more of these factors is controlled under different conditions. Each identified ignition source was analyzed and is discussed in terms of how each is managed by either controls or design safety features. In analyzing the fire risk associated with the proposed FG/RMCS activities, the following multistep approach was used in the following specified order:

1. The most important issue was to develop and implement a spark management strategy that is appropriate for a hazardous flammable gas environment. In summary, the spark-management strategy provides a minimum of two protective system barriers against spark sources (including mechanical sparks) so that no single failure leads to a sparking condition. The details of the spark management strategy are summarized in Appendix B.

2. After implementing the spark-management strategy, the reliability of the equipment used to protect against fire accidents was quantified (Appendix D). Considering the type of operation, failure probabilities on the order of $10^{-4}$ to $10^{-5}$ per activity for the protection systems were used to provide reasonable assurance that all practicable preventive measures would be taken against burn accidents.

3. After completing the first two steps, the probability of a GRE was introduced to assess realistic accident frequencies. In this SA, GRE is defined as any gas release that exceeds the steady-state releases in the SSTs by either volume or rate. The probabilistic model of GREs is discussed in Appendix L.

It is recognized that the order of steps differ from the order one would use to quantify the event trees. Typically, the GRE would be the initiating event and the probability of a burn accident would be the product of the following sequence probabilities:

Burn Probability = (Probability of a GRE causing flammable conditions locally)
x (Failure probability for the protective system)
x (Probability of a spark that can ignite the gas mixture)
x (Probability of flame propagation).

However, in the beginning of the SA process, it was recognized that there is much uncertainty in the magnitudes and probabilities of a GRE for the SSTs as defined in the first term of the above equation, and that design decisions and design controls could not be based on a poorly quantified event probability. Therefore, our initial assumption was that the probability of a large GRE is high, and that flammable gases exist continuously in the areas where potential spark sources are located. Thus, design-changes and design-controls were conservatively developed without taking credit for the GRE probabilities.

After completing the assessment of equipment reliabilities, the GRE probability was evaluated. Based on the analysis provided in Appendix L, it is assumed that GREs would occur during the FG/RMCS operations. However, the frequency of having a resulting flammable-gas concentration exceeding the LFL in the dome space with the dome pressure being positive is estimated as 7.0E-5 per operation. The bounding period of the dome concentration being greater than the LFL limit during the FG/RMCS operations was computed to be <0.12 min./activity, assuming that the ventilation system is continuously operational during a GRE. The time period during which the LFL is exceeded (time-at-risk) divided by the 144-hour mission time of FG/RMCS operations per activity is $1.4 \times 10^{-5}$, which is the probability of a GRE during FG/RMCS activities for accidents involving a random spark. For certain accidents, the GRE probability based on the exposure period to flammable gas is not adequate. These are accidents in which the spark sources are not random in time. In those accidents, the GRE probability of causing the dome pressure to be positive is more appropriate. Thus, depending upon the accident scenario, a GRE probability of 7.0E-5 or 1.4E-5 is used.

The third term in the burn probability equation is the probability of a spark, which is also not easy to evaluate for a general case. It was assumed that the probability of a spark is high, given that flammable conditions exist near nonqualified electrical equipment. Sparks caused by materials with potential electrostatic discharges are also assumed to occur with a probability of 1.0 when the environment is flammable. Ignition as a result of sparks caused by mechanical impacts and drops are, in general, evaluated by performing mechanical ignition tests.

Propagation of a fire from the tank top into the tank dome is assumed to be likely for certain accidents (especially for gas releases through openings at the top of the

tank). The velocity of the released gas could be small enough to allow fire propagation to occur.

In the following subsections, the accidents of concern are quantitatively discussed. In each subsection, the accident, its causes (dominant failures), and mitigation or credited assumptions or controls are defined in evaluating accident frequencies. The accident frequency based on credited assumptions or controls is defined as the MAF. The UAF does not consider the effects of credited assumptions or controls listed in Tables given in the rest of this section. Appendices D and E provide the details of how the UAFs and MAFs are obtained. Appendix E provides two sets of event trees; one for mitigated accidents and one for unmitigated accidents. The mitigated and unmitigated accident frequencies are given in the summary tables and used primarily to identify the level of the controls.

## 4.1. ABOVEGROUND FIRE ACCIDENTS

Accidents in this category include all fire initiators on the top of the tank for which FG/RMCS activities are performed. For this accident scenario, it is postulated that waste-intrusive FG/RMCS operations may cause a large GRE resulting in a flammable-gas environment above the tank through possible leak paths. If a fire occurs at the top of the tank, it could propagate into the tank dome. The fire propagation into the tank may result in structural damage to the tank and in significant material releases.

### 4.1.1. Flammable or Toxic-Gas Release Driven by Gas Release and Burn (Ignition in the Exhauster, Electrostatic and Electrical/Mechanical and Other Spark Sources, Operation, and Removal)

Preinstallation and installation phases do not include waste-intrusive activities. Therefore, a gas-release event is not expected in single-shell tanks during these phases. WHC standard controls require verification that the tank dome does not have flammable gas before starting the installation phase. The preinstallation phase also includes testing of critical alarms.

The exhauster and its safety system, as briefly discussed in Section 2, is required to be operational during FG/RMCS operations, including drilling and sample retrieval activities. Drilling starts by turning the nitrogen purge flow to the drill bit at 30 scfm. Any time the nitrogen purge flow is terminated, a 16-hour, post-drilling exhauster operation is required. During this period, sample retrieval, or other FG/RMCS-related activity could occur. If drilling is resumed during this period, the 16-h requirement must be reestablished after termination of the nitrogen purge flow. The 16-h requirement corresponds to the time in which the equivalent of 4 dome-volumes is circulated at a minimum nominal flow rate of 200 scfm, primarily to remove aerosols and flammable-gas accumulations created during the drilling. To completely circulate the equivalent of one dome volume, the exhauster needs to operate approximately 4 hours. It is expected that the 16-h post-drilling exhauster

operation will remove more than 95% of the accumulated aerosol and flammable gases.

The exhauster must be turned on at least one hour before drilling begins in order to

- Mix any potential flammable-gas pockets,
- Reduce the flammable and toxic-gas concentrations,
- Obtain flammable-gas concentration and pressure data, and
- Perform flammable-gas meter verifications as necessary.

In the current system design, when the flammable-gas detection system detects concentrations higher than those specified in this SA, exhauster operation is continued without interruption while the drilling operations are automatically terminated through a separate interlock. The exhauster will be operational during and after a GRE until the flammable concentration falls below acceptable levels.

There are numerous ways to initiate a fire in the exhauster. The possible ignition sources in the exhauster are as follows:

1. Static electricity from the flexible duct or other parts of the exhauster,
2. A lightning strike to the exhauster,
3. An electrical spark from nonqualified electrical equipment,
4. Mechanical frictional sparks from drops on the exhauster, and
5. Mechanical frictional sparks from the fan and housing contact.

The first four causes are independent whether the ventilation system is active or not.

4.1.1.1. **Static Electricity.** Static electricity in the flexible exhauster duct is managed by grounding the conductive duct and exhauster to the tank using Westinghouse Hanford Company (WHC) standard controls for grounding and bonding. The flexible duct is 1/32 in. thick and made of neoprene over a polyester base, and is conductive from the inner to the outer layer.[2] Vendor information indicates the conductivity of the duct material is 100,000 ohms per square inch, which is within the standards issued by the Institute of Electrical Electronics Engineers (IEEE) 142-1991,[3] paragraph 3.2.6.2, which states that a resistance of 1 Mohms is adequate for static grounding.

Failure to bond/ground the exhauster duct is unlikely because the duct is connected at both ends to the metal flanges of grounded and bonded components. Mechanical failure of grounding also is considered unlikely. The procedural steps requiring a

physical inspection of the ground system before the operation help prevent this failure. Procedural steps requiring the physical inspection of the resistance between the exhauster and the tank are performed by WHC as a standard requirement.

Materials such as plastic bags shall be carefully controlled because of the potential for static sparking.

Based on these considerations, static electricity concerns associated with the exhauster flexible duct are considered to be properly managed and will not cause a burn accident.

**4.1.1.2. Lightning.** Details of a lightning strike and a burn accident initiated by lightning strikes are provided in Section 4.9.1.

**4.1.1.3. Electrical Spark From Nonqualified Electrical Equipment.** Appendix B concludes that the tank dome space should be treated as a Class-I, Div.-1, Group-B environment during active waste-intrusive FG/RMCS operations. The FG/RMCS exhauster flow path has a direct path to the tank and therefore is also treated as a Class-I, Div.-1, Group-B environment.

Emission control requirements for the exhauster are not discussed in this SA, but based on the information provided by WHC, Washington State permits exhauster operation without stack monitoring.[4]

All of the electrical equipment in the exhauster air stream is either intrinsically safe or deenergized. The fan motor is outside the exhauster duct. The shaft between the motor and exhauster fan is purged with nitrogen. The measurement devices for exhauster flow and the differential pressure across the HEPA filter unit are electrical components that have been made intrinsically safe. The exhauster has a heater to prevent condensation in the HEPA filter. The heater was originally an electric heater but has been replaced with a heat exchanger driven with hot water supplied by a heater located in an unclassified area.

Based on these design features, it is believed that an electrical spark in the exhauster is highly unlikely and is not considered a credible initiator of a burn accident.

**4.1.1.4. Mechanical Sparks.** One credible mechanical, frictional spark source can result when heavy equipment or tools are dropped on the exhauster or flexible duct. Generally, WHC has a standard practice of not transferring heavy equipment and tools over the exhauster or other equipment critical to safety. Administrative controls prohibiting the transport of equipment over the exhauster are established in the SA to manage this source of frictional sparking.

The frequency of a fire accident as a result of dropping equipment on the exhauster during operation is determined as 9.5E-12/yr in Appendix E and that value is very low. The accident is caused by failure to terminate the lifting operation, given a high tank dome pressure, hydrogen concentration, or a high rate of hydrogen

concentration increase, failure to observe lift-over-tank control, and a crane load drop and exhauster impact.

Another mechanical spark source is the exhauster fan that is built to the Air Movement Division of the Air Movement and Control Association (AMCA) Standard 99-0401-86.[5] The standard requires the following:

> All parts of the fan in contact with the air or gas being handled should be made of nonferrous material. The hole where the shaft passes through must be made so that ferrous materials could not rub. Steps must be taken to ensure that the impeller, bearings, and shaft are adequately attached and/or restrained to prevent lateral or axial shift in these components. The fan must be so constructed that a shift of the shaft or impeller must not allow two ferrous parts to rub. No bearings, drive components, or electrical devices must be placed in the air or gas stream unless they are constructed or enclosed in such a manner that failure of that component cannot ignite the gas. However, the customer must accept both the type and design with full recognition of the potential hazard and the degree of protection required.

The WHC fire protection engineer has determined that the construction requirements for AMCA Type A adequately address the spark-resistant criteria in NFPA 91. However, there is no requirement to demonstrate that if the fan and housing come into contact because of bearing failure, the contact is not capable of igniting a potential flammable atmosphere. For the frequency of this event, it is assumed that if a bearing fails 10% of the time, it results in contact between the fan and the housing, with a conditional frequency of 6.4E-10/yr.

However, this event is not considered a credible source of ignition because WHC performed an assessment study, including a literature survey, on the possibility of generating sparks as a result of aluminum fan-to-aluminum housing impact.[6] Based on the findings of this study, the following recommendations are made:

- Fan material should be aluminum alloys containing less than 0.8% Mg,
- The housing or any place where impact of fan is possible should not include iron alloys,
- All surfaces should be aluminum, and
- Any lubricant that may cause sparking should not be used on surfaces where impact is possible.

The exhauster fan meets all the conditions recommended above. In addition, Appendix P investigates the possibility of a hot spot for rubbing aluminum surfaces and found no credible evidence to conclude that if the fan mechanically fails and

impacts the housing, sparks capable of igniting hydrogen-air and hydrogen-nitrous oxide mixtures could be created. Although the vendor did not have data to confirm this conclusion, they confirmed that they have no accident reports indicating this type of failure. Consequently, it was concluded that the failure of the fan is not a credible initiator for a burn accident, and the frequency is designated as $<< 10^{-6}$/yr.

**4.1.1.5. Summary of Exhaust Fires.** Table 4-1 summarizes the above discussions. The bounding accident frequency for exhauster fires is 1.1E-10/yr caused by lightning strikes. For bounding consequences, it was conservatively assumed that a fire initiated in the exhauster would propagate into the dome, resulting in a dome collapse accident, as discussed in Section 5 of this SA.

**TABLE 4-1**
**SUMMARY OF FIRE ACCIDENTS IN EXHAUSTER**

| Accident | Frequency of failure 1/year | Dominant Failures | Controls Credited in Calculating UAF and MAF Values |
|---|---|---|---|
| Lightning strike causes dome fire. | MAF and UAF << 1.0E-06 | Random lighting strike hits risers or other equipment on top of tank that connects to tank interior | Do not drill if a lightning strike is observed within a 50-mile radius |
| Drop of equipment from crane onto exhauster leads to dome fire. | MAF and UAF << 1.0E-06 | Equipment is dropped from crane onto exhauster. | No equipment lifts over exhauster. |
| Ignition of flammable gas in the exhauster is caused by fan failure | MAF and UAF << 1.0E-06 | Failure of fan bearings results in fan housing mechanical sparking. | No controls credited |

### 4.1.2. Flammable or Toxic-Gas Release Through Torn duct and Burn (operation)

This event postulates a GRE occurring at a high rate, creating a positive tank pressure, which results in an ignition of flammable gases that have escaped through the torn exhauster duct. The ignition source for this scenario is potentially nonqualified electrical equipment at the exhauster skid and around the exhauster duct.

If the exhauster duct has torn and a GRE occurs, some region around the duct must be assumed as a Class-I, Div.-2 environment, based on the diameter of the leak. The undetected leak diameter is assumed to be $\leq 1$ in. Based on the criteria given in Appendix B, nonqualified equipment with no automatic shut-down features should be 18 in. away from the leak. Therefore, an exclusion zone should be established 18 in. from each side of the exhauster duct, and no equipment with sparking potential should be placed within this exclusion zone. This control protects the tank from fire initiated through a torn duct. All electrical equipment currently on the skid not

meeting Class-I, Div.-1 requirements is protected by enclosures, and most are 18 inches away from the point where the exhauster duct is attached to the metal flange near the heater.

Even though the flexible duct is heavy and difficult to tear,[2] the following requirements are established to prevent duct damage. The flexible duct must be made stationary before operations start to prevent any motion that may result in damage to the duct when there is a strong wind. A control requires the termination of FG/RMCS operations when the sustained wind velocity is greater than 25 mph because of concerns about possible structural failure of the flexible duct. A control to inspect the flexible duct for possible leaks before operations begin also is established, as well as the control to preventing the transport of any equipment or tools over the exhauster or duct.

The MAF is calculated as 1.4E-9/yr, and the UAF is 5.6E-8/yr, as discussed in Appendix E. Note that no credit was taken for the probability of the propagation of fire into the dome. Dominant failures are summarized in Table 4-2. The consequence of this accident is conservatively considered to be the dome collapse discussed in Section 5 of this SA.

**TABLE 4-2**
**ABOVE TANK FIRE ACCIDENTS DUE TO TORN EXHAUSTER DUCT**

| Accident | Frequency of failure 1/year | Dominant Failures | Controls Credited in Calculating UAF and MAF Values |
|---|---|---|---|
| Tear in the exhauster duct exposes flammable gas to nonqualified electrical equipment leading to dome fire. | MAF = 1.4E-9<br>UAF = 5.6E-8 | Big tear occurs in the duct during operation.<br>Tear in the duct is not detected. | Inspect the duct for tears before operation.<br>Locate unqualified equipment at a distance >18 in. from exhauster duct, or provide deflectors/enclosures for equipment located within 18 in. |

### 4.1.3. Flammable-Gas Release Through Open Riser (Or Possible Leak Paths) Driven By Gas Release Event And Burn (Operation and Removal)

This event postulates that a large GRE occurs, releasing flammable gas from openings in the tank, exposing the flammable gas to equipment with possible spark sources, resulting in a fire on top of the tank. This event is of concern during operation and removal phases of FG/RMCS. None of the auxiliary support equipment on top of the tank is qualified to operate in a flammable-gas environment.

Preventing flammable-gas exposure to this equipment is managed in several ways. Open paths from the tank dome to the tank top include the exhauster stack, the breather inlet riser, open risers, drill string riser, and other possible tank leak sources (unsealed risers, pits, etc.). It is assumed that inspection of tank top penetrations for potential leak paths will find leak paths with nominal leak diameters >1 in. Therefore, it is assumed that undetected leak paths with a nominal 1-in. diameter could exist. Therefore, the top of the tank must be examined to identify leaks other than risers used for passive/active ventilation, and when identified, the leaks must be sealed.

A portable stack over the breather inlet HEPA system will be used during waste-intrusive FG/RMCS operations. The portable stack is at least 15-feet tall, has an upper 4-in. diameter, is sealed at the ground level, and is grounded. The purpose of using a portable stack over the breather inlet is two-fold:

- The gas release would be released through stack, resulting in increased atmospheric dilution and reducing the toxicological consequences of a GRE.

- Any nonqualified equipment on the top of the tank around the breather inlet HEPA system would be protected from flammable-gas exposures.

The positioning of the drill truck, the X-ray machine, the light plant or other auxiliary equipment that could be a spark source is based on the criteria given in Appendix B. It is required that any nonqualified electrical equipment must be placed at least 36 diameters away from an open riser during waste-intrusive operations. If a GRE occurs, immediate personnel evacuation is required.

Another control also requires that when the drill truck needs to be parked over an unused, closed riser or pit, the riser or pit must be sealed. Note that the riser or pit considered here is not the riser being sampled but the one that the front part of the truck is parked on. If the truck is parked over an unused riser or pit, the potential spark location is not considered random, and no credit can be taken for the probability of a random placement. However, the leak size from pit or riser is assumed to be no bigger than 1 in. There is at least 3 feet between the top of the pit/riser and any potential ignition sources on the truck. A control was established to make sure the distance between potential ignition sources on the truck and the top of the pit/riser is $\geq$ 36 in. Combining the failure probability to seal the riser/pit and violate the 36 in. distance criteria and the GRE probability that makes the dome pressure positive, the accident frequency is determined as 2.1E-8/yr. This frequency is low. However, the unmitigated frequency becomes 1.4E-4/yr if the control to seal the riser/pit and 36 in. distance criteria are not implemented.

The flammable-gas release could occur from other unused risers if they have undetected leak paths. The control requiring the examination of risers before operations reduces the probability of having an unknown open path. It is assumed

that leaks from threaded junctions, flanges, and cover plates could be identified with an equivalent leak diameter greater than 1 in. If a GRE occurs and nonqualified equipment is located close to these unknown openings, the accident frequency of a above-tank fire becomes 1.8E-7/yr. This frequency includes the probability of a GRE based on exposure time (Appendix L) and the probability of a temporal random spark. It also assumes that 50% of all risers on the top the tank leak after the initial inspection is performed. The existence of a spark on the equipment located around risers is also assumed. The unmitigated accident frequency is 2.8E-5/yr for this accident scenario; therefore, the control requiring limiting the leaks before the FG/RMCS operation is important.

The last accident scenario includes the ignition of a flammable-gas release from an intentionally opened riser during FG/RMCS activities. This may be needed for other daily activities. Appendix E gives the event tree for a fire accident. A control is required not to place any nonqualified equipment within 36 diameters of the riser being opened during waste-intrusive operations. Considering this control and a GRE probability based on exposure time including a temporal random spark, the mitigated accident frequency becomes 4.2E-8/yr. This number is conservative because it was not considered that the riser may be open for only a fraction of the mission time. The unmitigated accident frequency is 1.4E-5/yr.

The combined mitigated frequency of these three events is 2.4E-7/yr. Note that the fire propagation into the dome conservatively is assumed to be 1.0. This number is conservative because it is assumed that nonqualified equipment does include a spark source and the probability of a random spark in time is based on a conservative dome concentration.

Positioning the drilling truck needs special attention. The closest release path to the truck is the drilling riser that can momentarily be open to the environment during installation and removal of FG/RMCS equipment, even though the riser is sealed with a rubber frisbee during operation. However, because some drill rods are fluted, it is likely that the frisbee can be damaged, and a leak can result. A nitrogen purge is provided in the annulus between the drill string and the conductive riser sleeve. This purge flow is designed to provide 5 standard cubic feet per minute (scfm) flow for all postulated tank dome conditions.[7] The purge system has redundant differential-pressure alarms across the flow controller. Necessary controls for this system will be discussed in the dome fires accident category (ignition in the riser).

For a gas release to occur from the riser path, nitrogen purge would have to fail, and a GRE would have to occur. However, even if a 1-in. diameter leak path exists through the frisbee, potential ignition sources on the FG/RMCS truck are at least 3 ft away. There is a direct path from the frisbee to the top of the platform when the shielded receiver or the drill rig are connected to the drill string. However, the spark-generating electrical motors are located at the top of these components and meet the 36-equivalent-leak-diameter distance requirements of Appendix B. This distance is acceptable because the rotating platform also acts as a jet deflector. The

nitrogen instrumentation and piping enclosure have solenoid valves, but they are in an enclosure (not leakproof but reasonably sealed) and protected from direct flammable-gas jet impingement. The major spark contributor is the drill engine and it is at least 3 ft away from the frisbee. In summary, if a leak occurs from the frisbee, the gas would not reach the spark sources on the truck with a flammable concentration.

To further reduce the likelihood of a gas release from the drill string during removal, the drill string must not be removed from the waste without a sampler or a dummy sampler in the string. The drill string and frisbee hole must comply with 36-equivalent-leak-diameter distance requirements during waste-intrusive activities.

The summary of this accident is given in Table 4-3. With the above controls in place it is believed that the ignition from the truck or any other nonqualified equipment is adequately controlled as demonstrated by the low magnitude of the MAF.

#### 4.1.4. Flammable or Toxic-Gas Release through Shielded Receiver (SR) and Ignition in the Shielded Receiver (Operation)

There are two cases for this accident, depending on the operating condition:

- When the shielded receiver (SR) is connected to the drill string during sampler recovery, and
- When the SR is isolated from the drill string while the sampler is being transferred to the X-ray machine or the shielded cask.

This section treats the cases where the SR is isolated from the drill string. The other case is examined in Section 4.3.2 along with drill string fires. Flammable gas may accumulate in the SR either by a gas transfer from the drill string or flammable gas may be released from the sampler into the SR.

For gases to be released into the SR from the drill string, the hydrostatic head must fail. Calculations provided in Appendix J show that as long as the hydrostatic head purge of 0.3 sfcm exists, the flammable gas in the drill string does not diffuse back upstream. There are two sources of hydrostatic head purge while the SR is connected to the drill string. One purge is connected to the SR and one purge is connected to the change-out assembly. Considering the operating procedures, the analysis shows that failure of both purges and not detecting this failure combined with a frequency of a drop of the remote latch unit (RLU) and sampler, which is the only credible spark source in the SR, results in an ignition frequency of 1.9E-6/yr.

TABLE 4-3
ABOVE-TANK FIRE ACCIDENTS CAUSED BY GAS RELEASES FROM OPEN RISERS

| Accident | Frequency of failure 1/year | Dominant Failures | Controls Credited in Calculating UAF and MAF Values |
|---|---|---|---|
| Release of flammable gas from riser/pit that the drilling truck is parked on leading to dome fire. | MAF = 2.1E-8<br><br>UAF = 1.4E-4 | Fail to seal to riser or pump pit.<br><br>Fail to locate potential ignition sources on the FG/RMCS truck within 36 in. of the riser/pit. | Seal the riser or pump pit being parked on.<br><br>Distance between the potential ignition sources on the FG/RMCS truck and the riser/pit is greater than or equal to 36 in. |
| Releases of flammable gas to unqualified electrical equipment from unknown leaks leading to dome fires | MAF=1.8E-7<br><br>UAF=2.8E-5 | Randomly located unqualified equipment is located too close to riser/pit not in use. | Limit leakage from all unused risers/pits to less than 1 in.-effective leak diameter. |
| Releases of flammable gas to unqualified electrical equipment from an intentionally open riser during FG/RMCS waste-intrusive activities leading to dome fire | MAF=4.2E-8<br><br>UAF=1.4E-5 | Equipment located too close to open riser/pit.<br><br>Randomly located unqualified equipment is located too close to open riser/pit. | Restrict location of equipment to greater than 36 diameters from open risers/pits.<br><br>Inlet stack 15 feet tall is installed on high-efficiency particulate air (HEPA) inlet riser. |

The consequences are small when the SR is isolated from the tank, and the quantity of gas in the SR also is small.

Besides being transported from the drill string, the flammable gas can accumulate in the shielded receiver in two other ways:

- Waste accumulation in the SR resulting in a gas accumulation; and
- A gas release from the sampler.

The maximum waste release into the SR is the equivalent of one full sampler (0.39 kg). Gas that could be retained in this amount of waste is small. If the sampler is full of gas at 2.5 atm, the maximum gas volume at atmospheric pressure would be 611 $cm^3$. The volume of the receiver is 120,000 $cm^3$. Thus, the resulting flammable-gas concentration would be less than the LFL, and ignition would not be possible.

There is no incompatible material inside the SR, so that additional gas generation caused by chemical reaction is not a concern.

The SR has a load cell to measure the weight on the cable. This load cell is protected by an intrinsic safety barrier. Therefore, an electrical spark inside the SR is not a concern.

The RLU is based on a mechanical design. A frictional spark caused by RLU motion may be considered as a spark source. The electrical motors controlling RLU use are direct current (dc) pulse width modulated power. The hoist motor for the RLU has a 150:1 worm-gear reduction, and because of the gearbox, the RLU does not freewheel if the motor fails. The normal hoist velocity is less than 1 ft/s. Studies have been done to examine the characteristics of mechanically-produced sparks that lead to the ignition of tank-like gases. Krok and Shepherd[8] carried out frictional spark ignition studies of $H_2$/air and $H_2/N_2/N_2O$/air mixtures in which they used rusted steel and aluminum plates impacted by steel or aluminum bars. A pneumatically-actuated piston made of steel or aluminum was stroked on an inclined, rusted-steel plate. The impact velocity varied from 0.5 to 2.5 m/s (1.64 to 8.2 ft/s). These experiments showed that the frictional ignition in a mixture of 10% or 15% $H_2$ in air at 1 atm was very unlikely. Based on this data, a frictional spark caused by the normal RLU motion is not expected.

Radiation exposures were calculated in Appendix R for possible doses if a full sampler were to be released in the SR. Based on these calculations, measurable quantities of waste would be recorded by manual radiation readings. WHC has radiation controls performed by the health and safety personnel, but an additional radiation control limits the SR dose rate to 100 mrem/h on contact. This radiation monitoring must be performed once per shift during waste-intrusive activities to prevent waste and flammable-gas accumulation in the SR.

One other possibility of frictional spark occurrence is an equipment drop in the shielded receiver. The RLU may be dropped because of a mechanical failure or the sampler may drop from the RLU. The conditional accident frequency is estimated as 3.0E-4/yr in Appendix E and is given in Table 4.4.

Ignition caused by dropping the RLU or the core sampler in the shielded receiver will be investigated by the tests that are conducted at the Bureau of Mines (BOM). Appendix T lists the requirements for the ignition tests performed at BOM. Fire accidents in the shielded receiver are summarized in Table 4-4.

If ignition occurs in the SR with low concentrations, the burn pressure, 1.2 atm, does not exceed failure pressure.[9] The SR maximum design pressure is 52 psia (Ref. 10). The ball valve isolating the SR fails at very high pressures (1100 psia). Therefore, no failure and release is expected if ignition occurs in the SR.

TABLE 4-4
ABOVE-TANK FIRE ACCIDENTS IN SHIELDED RECEIVER

| Accident | Frequency of failure 1/year | Dominant Failures | Controls Credited in Calculating UAF and MAF Values |
|---|---|---|---|
| Flammable gas in drill string (DS)/SR during sampler handling leading to fire in SR.<br>(Fire does not propagate back to the dome.) | Without BOM test results:<br>MAF = 1.9E-6<br>UAF = 2.8E-3<br>With BOM test result:<br>MAF and UAF <<1.0E-6 | Nitrogen purge to both drill string and to SR fails.<br>RLU drops sampler. | Leak test of $N_2$ hydrostatic systems is done for both drill string and for shielded receiver.<br>Unique connections for $N_2$ purge systems for both drill string and SR are used (design feature).<br>Verification of $N_2$ purge supply to both drill string and SR during activation of hydrostatic mode of $N_2$ supply is carried out.<br>Controls over operation of RLU are used. |
| Flammable gas in SR with SR isolated from drill-string results in aboveground fire.<br>(Fire does not propagate back to the dome.) | Without BOM test results:<br>MAF = 3.0E-4<br>UAF = 3.0E-3<br>With BOM test results:<br>MAF and UAF<<1.0E-6 | Waste prevents closure of sampler rotary valve leading to gas release as sample is retrieved and depressurized.<br>Flammable gas is not sniffed or detected.<br>RLU drops sampler. | Controls over operation of RLU are used. |

A control has also been established for a visual inspection of the sampler through the sight glass as it is withdrawn from the drill string. This visual inspection does not directly indicate the failure of the sampler rotary valve, but it may indicate leaking from either the rotary valve or rotary valve seal. An administrative control shall be developed for handling a leaking sampler. An additional control prohibits putting a known leaking sampler into the X-ray machine.

One other concern is the release of gas from the SR. For this accident to occur, the manually operated SR ball valve would have to be opened before it is connected to the X-ray machine, which would be a violation of the procedures. The engine has several potential ignition sources. The likelihood of this event is low because several failures have to occur; inadvertent opening of the ball valve, failure of the rotary ball valve, and dropping the sampler at the same time. In addition, the operator must fail to identify the leak by visual inspection. Besides, the flammable gas may not come from the bottom of the pipe but may accumulate at the top of the

horizontal section of the shielded receiver. Even if flammable gas comes from the valve, the maximum amount of flammable gas that can be accumulated in the receiver is limited to 611 $cm^3$. It is expected that the consequence of the accident is insignificant because of the limited amount of flammable gas present and because there is no entrained waste. The fire can not propagate back to the tank because the shielded receiver is not connected to the drill string. The only concern in terms of material release would be dropping the waste on the ground when the valve is opened. This accident is discussed along with the spill accidents in Section 4.8.

#### 4.1.5. Flammable Gas And Ignition In X-ray or Cask

If the flammable gas were accumulated in the SR, it could be discharged into the X-ray machine or into the shielded cask when the SR is connected to these components. The concern with this scenario is a fire in the cask or X-ray machine with a local release of radioactive material and possible propagation of fire into the tank dome.

If the flammable gas in the SR is discharged into the cask or the X-ray machine, ignition is not expected. No unqualified electrical equipment in a Class I, Division 1 or Class I, Division 2 space exists in the X-ray machine.[11] The cask does not contain a spark source. The only ignition source identified is dropping of the sampler into the plastic X-ray container or the cask. The X-ray container may not produce frictional sparks but rather static electric charges. However, the plastic container is grounded and bonded by a graphite paint as a coating surrounding the interior of the plastic container.

Appendix E examines the probability of ignition in these components. The accident frequencies are found as 2.0E-7/yr and 3.2E-4/yr for the X-ray and the cask, respectively, as indicated in Table 4-5. The X-ray and cask are grounded and bonded through the SR, and the sampler is inspected for external contamination. Even if the ignition occurs, the available flammable gas that can come from the SR or sampler is limited so that the flame would not propagate to the tank. For propagation to the tank to occur, there would have to be hydrogen in the dome and a flammable pathway, which does not exist. Under these conditions, operations would not be conducted.

#### 4.1.6. Flammable Gas Accumulation or Release Caused by the Loss of Electrical Power and Ignition Source (Installation, Operation, and Removal)

In case of loss of electrical power, the FG/RMCS truck is shut down. When the electrical power is lost, the nitrogen shutoff valve closes. If the sampler is being removed or installed, the hydrostatic head purge that keeps the waste from entering the drill string is lost, allowing the drill string to flood. Flammable-gas accumulation in the dome, drill string, drill unit, and shielded receiver is of concern in this scenario. Waste can flood the drill string and release flammable gas into the drill string and the SR. Appendix J shows that the diffusion of hydrogen is

relatively fast. Flammable gases also could be released as a result of depressurization of the waste.

TABLE 4-5
ABOVE TANK FIRE ACCIDENTS IN X-RAY MACHINE AND CASK

| Accident | Frequency of failure 1/year | Dominant Failures | Controls Credited in Calculating UAF and MAF Values |
|---|---|---|---|
| Flammable gas in X-ray machine leads to aboveground fire. (Propagation into dome not possible.) | No fire propagation into the dome:<br>MAF = 2.0E-7<br>UAF = 2.0E-6<br><br>Fire propagation into the dome:<br>MAF and UAF << 1.0E-6 | Waste prevented previous closure of the sampler rotary valve leading to gas release as sample is retrieved and depressurized.<br>Previous sniff in shielded receiver failed to detect flammable gas.<br>RLU drops sampler.<br>Plastic receiver breaks.<br>Isolation barrier volume fails. | Use sealed plastic sampler receiver surrounded by isolation barriers.<br>Controls over operation of RLU. |
| Flammable gas in cask leads to aboveground fire.<br>(Propagation into dome not possible.) | No fire propagation into the dome:<br>MAF = 3.2E-4<br>UAF = 3.0E-3<br>Fire propagation into the dome:<br>MAF and UAF << 1.0E-6 | Waste prevented previous closure of sampler rotary valve leading to gas release as sample is retrieved and depressurized.<br>Operator fails to perform sniff for flammable gas.<br>RLU drops sampler. | Use controls over operation of RLU. |

The management of ignition sources in these components is discussed previously. No attempt was made to evaluate the failure probabilities of the loss-of-power accident. An administrative control must be developed for the startup after loss of power considering the possibility of the presence of flammable gas. A control requiring the purging of the shielded receiver, drill string, and drill unit long enough to evacuate the possible flammable gas in the drill string is established. If the drill string is flooded, the SA requires washing the drill string before the operation is restarted.

### 4.1.7. Propane Release From Refueling Of Nitrogen Trailer Propane Tank and Fire (Installation, Operation, And Removal)

This accident scenario involves a propane spill during the refueling of the propane tank. The main concern is the propagation of fire to the tank being sampled or to

another tank in the farm. The propane tank is kept outside of the tank farm. Drilling on the tank being sampled is prohibited during refueling. This is a typical industrial accident and is not discussed in detail. WHC standard controls already exist to prevent this type of accident.

#### 4.1.8. Flammable Diesel And Gasoline Fuel Fire (Installation, Operation And Removal)

This accident scenario involves a spill of diesel, gasoline, or hydraulic fluid during the refilling of the FG/RMCS equipment. The main concern is the propagation of fire to the tank because the refueling occurs when the truck is already over the tank dome.

The SA requires all engines or motors on affected equipment are shut down during refueling. Exhaust pipes on affected equipment shall be cool. No drilling operations, open risers, or open drill string or non-RMCS activities on affected equipment are allowed on the tank being sampled during refueling. A restricted smoking area is required, and all possible ignition sources need to be kept outside of the refueling area. These controls are established to prevent fire propagation to the tank. In addition, proper fire extinguisher equipment in the vicinity of the drilling truck must be available in case of a local fire.

#### 4.1.9. Collision Caused by Trucks and Other Equipment (Installation, Operation and Removal)

This accident involves frictional sparks created by the collision of trucks or other equipment with the riser. The drill truck and other equipment may be driven on the tank before the installation and after the removal of the drill string. During this period, the riser is closed. However, in the unlikely event that the truck impacts an open riser, all operations must be stopped, and possible gasoline leakage into the tank must be evaluated. The introduction of flammable material into a flammable gas tank may have serious consequences. Thus, the Tank Farm Operations management must be notified and approval must be granted before operations may resume.

Before installation, standard WHC controls are implemented to prevent an unexpected flammable-gas release from the tank dome. Frequent and large natural-gas release events are not expected in single-shell flammable-gas tanks. The tank vapor space must be sampled before installation, and the flammable gas must be less than 25% LFL. If a GRE were to occur, operations would be stopped.

A possible scenario is the flammable-gas accumulation in the dome and failure to detect it before FG/RMCS tank-intrusive activities. If there is flammable gas in the riser, a fire can be initiated by a frictional spark from a collision. During the removal phase, if the exhauster is not operating, the tank dome and drill string shall be sniffed prior to drill string removal and other riser activities. If flammable gas is detected above limits, all operations must be stopped, including drilling. For this

accident to occur the detector systems would have to fail simultaneously with a collision. This event is not considered credible.

Without fire, the consequence of collision is damage to the tank riser. The tank liner is not connected to the riser or to the dome. Thus, the damage would be to the riser, which can be sealed if this accident occurs. Standard WHC safe practice requirements are required to prevent the collision. The likelihood of serious consequences of this type of accident are not considered credible.

### 4.1.10. Summary of Aboveground Fire Accident Category

The total conditional accident frequency for the aboveground fires that lead to a dome fire is 2.4E-7/yr. The dominant contributor to this frequency is gas release to a non-qualified equipment. Randomly located unqualified equipment too close to risers that have an open path results in the highest accident frequency of 1.8E-7/yr. The consequence of an above-tank fire is treated as a dome collapse. Dome collapse consequences are discussed in Appendix I. The total frequency for aboveground fire accidents, 2.4E-7/yr, is added to the other three frequencies considered in the next section to determine the frequency of dome collapse.

## 4.2. Gas Release and Dome Fire Accidents

The postulated accidents in this category consider fires initiated in the dome space of the tank. Most of the cases discussed in this section can occur during the operation phase of the drilling. The flammable gas in the dome is the first necessary condition for a fire scenario to occur. The gas can be released when the drill bit penetrates the crust or waste sludge.

Below, each identified spark source in the dome is examined closely, and the associated control systems are discussed.

### 4.2.1. Ignition Of Flammable Gas As A Result Of A Drill-String Break (Operation)

This accident is caused by a mechanical spark created by the drill string breakage during the drilling. This failure is assumed to occur at a portion of the drill string that is in the dome. The flammable-gas detection system is the primary protection against this accident. This system prevents drilling operations when the flammable-gas concentration is above 25% of the LFL in the dome.

The force applied to the drill string is measured. The force limit, based on drill bit heating (Appendix F), is set to 750 lbf. There are other down force and rotational speed limits caused by structural concerns as discussed in Appendix N. The drill truck has a torque capacity that is more than that required to break the drill string. Several drill-string breakages have occurred in the past. A control is established not to exceed the buckling limit (down force) and not to operate at a rotational speed that could excite the drill string at its natural frequency (Appendix N). The MAF

listed in Table 4-6 for this accident is determined as 3.9E-10/yr (see Appendix E). The UAF is 2.8E-7/yr. Controls to prevent drill-string buckling and resonance are given in Section 4.6.3.

TABLE 4-6
DOME FIRE ACCIDENTS CAUSED BY DRILL-STRING BREAKAGE

| Accident | Frequency of failure 1/year | Dominant Failures | Controls Credited in Calculating UAF and MAF Values |
|---|---|---|---|
| Drill-string break in dome leads to dome fire. | MAF = 3.9E-10<br>UAF = 2.8E-7 | Fail to shut down drill string on detection of $H_2$.<br>Drill string breaks by jamming in waste causing overtorque or buckling. | Drill string automatic trip when high $H_2$ level, high rate of change of $H_2$ level, or high dome pressure occurs. |

### 4.2.2. Ignition of Flammable Gas in the Riser Caused by the Drill-String, Equipment or Tool Drop (Installation and Removal)

This accident is postulated to occur when there is flammable gas in the dome, and equipment, drill string, or tools are dropped into or onto the riser during the installation or removal phase. As discussed previously, the riser condition must be determined before installation to make sure there is no flammable gas in the riser or dome. During the removal, gas may exist in the dome only if the flammable-gas release detectors fail. This accident analysis covers the friction in the riser caused by these drops. The more limiting case is the dropping of the drill string with an impact on the crust; this accident is examined in the next section. The friction in the riser as a piece of equipment falls through the riser is not considered to be a significant contributor and is bounded by the tool drop on the crust in the next section. Nevertheless, Appendix E determines the accident frequency of this scenario as 1.4E-9/yr as given in Table 4-7. The unmitigated frequency is also small, and 2.8E-9/yr. BOM testing also will include frictional spark tests to verify that this accident scenario is not credible (Appendix T).

### 4.2.3. Flammable-Gas Release and Burn Caused by the Drill String or Tool Drop on Crust (Installation, Operation, and Removal)

This accident involves dropping the drill string or other tools that may create frictional sparks on the crust and thus results in ignition of the flammable gas in the vicinity of the crust.

General practice at Hanford site is to use spark-resistant tools during activities around the riser. Riser covers are also grounded and bonded. Standard procedure requires sampling of the dome space when opening a riser. The crust reaction/burn from impact heat is considered separately in the waste burn accident category.

There are several simultaneous conditions required to cause a dome collapse if the drill string is dropped. First of all, there must be a drop, and flammable gas must be present in the dome or in the vicinity of the impact point. Debris is found in the tanks from contaminated or unwanted material being disposed of in the tanks. There must be debris at the impact point, and the impact energy must be large enough to cause a frictional spark. A gas pocket large enough to sustain propagation must exist immediately beneath the surface where impact occurs.

The drill string is held by a pneumatic foot clamp. The drill string is manually inserted into the rubber frisbee by an operator. A lubricant is used to insert the drill string because the inside diameter of the frisbee is smaller than the outside diameter of the drill string. The rubber frisbee creates a frictional force of 200 lbf (Ref. 12). However, this value may go down to 40 lbf when the lubricant is used. As the drill rods are added to the drill string, weight increases and exceeds the frictional force of the rubber frisbee. The maximum drop weight may be as high as 210 lb (Appendix G). The pneumatic foot clamp supports the drill string when it is not supported by the hoist or connected to the drill. The pneumatic foot clamp is designed to fail-close. To open the pneumatic foot clamp, two separate simultaneous operator actions must occur: one operator must activate the foot clamp pedal, while another operator simultaneously activates the pneumatic supply valve. This design feature provides a human failure probability of 9.0E-6 and an accident frequency of 1.8E-5/yr.

The failure probability of the pneumatic foot clamp is investigated in Appendix D. The conditional drop frequency as indicated in Table 4-7 becomes 1.8E-5/yr. The conditional frequency of tool drops on/into a riser is estimated as 1.4E-9/yr. As mentioned above, additional events necessary to cause a local hydrogen burn that could result in a dome collapse must occur simultaneously. Considering these additional probabilities, this accident is concluded to be incredible. However, the possibility of a waste burn is considered in Section 4.4.3.

#### 4.2.4. Ignition of Flammable Gas in the Riser Cause by a Frictional Spark (Installation, Operation, and Removal)

In this subsection, the main concern is the ignition of flammable gas in the riser caused by frictional sparks. There are several ways a frictional spark can be initiated in the riser. These possibilities and their management methods are discussed below.

A flanged, 2.9-in. i.d. (3-in., Sch. 80), and 15-feet-long conductive stainless-steel riser sleeve must be installed in the riser. The installation requires that the piece is bonded. The insertion and removal velocity of the conductive sleeve should be no more than 1 ft/s to prevent frictional sparks in the riser. The riser must be sniffed before insertion of the sleeve as a part of WHC standard control before opening a riser.

TABLE 4-7
DOME FIRE ACCIDENTS CAUSED BY EQUIPMENT AND TOOL DROPS INTO RISER

| Accident | Frequency of failure 1/year | Dominant Failures | Controls Credited in Calculating UAF and MAF Values |
|---|---|---|---|
| Drop of raised drill string onto waste ignites $H_2$ below the crust leading to a dome fire. | Drop frequency:<br>MAF = 3.0E-5<br>UAF = 3.0E-5<br><br>Burn Frequency:<br>MAF and UAF <<1.0E-6 | Foot clamp spuriously fails open. | Pneumatic foot clamp fails, closes upon loss of air. |
| Drop of tool into open riser leads to dome burn. | Drop frequency:<br>MAF = 1.4E-9<br>UAF = 2.8E-9<br><br>Burn frequency with credit from BOM tests:<br>MAF and UAF << 1.0E-6 | Tool is dropped into open riser. | Operator use of spark-resistant tools within 36D of open riser |

The other concern is frictional heating from the drill string rotating in contact with the conductive sleeve, leading to ignition in the riser. This situation is analyzed in Appendix P, and the conclusions are summarized below.

The expected temperature is less than the autoignition temperature for hydrogen in air for the period of the calculation (Appendix P). Given the conservative nature of the problem assumptions, frictional ignition in the tank dome from drill-string-to-sleeve contact is considered unlikely. This determination should be considered in light of the uncertainties in frictional heating calculations and is subject to BOM experimental confirmation, (see the requirements discussed in Appendix T).

A nitrogen purge system is designed to provide flow into the annulus between the riser sleeve and the drill string. This system gives a minimum flow of 5 scfm at any tank pressure. There are two differential pressure detectors for riser sleeve purge gas. Either detector could cause an automatic trip of the drill. The set point is 40 psid across a flow controller sized for 5 scfm. The probability of a GRE pressurizing the dome by 3 in. w.g. is very low. Furthermore, a control is established to stop drilling when the dome pressure increases by 2 in. w.g. The differential pressure across the flow controller is monitored and alarmed to detect a loss of flow. The purge flow also further prevents the hot spot that could occur at the drill string and sleeve

contact point. This system provides the necessary protection to prevent ignition in the riser sleeve.

If the nitrogen purge system fails, the ignition of flammable gases is possible. In order to demonstrate that sparks cannot be generated from drill string and sleeve contact, ignition testing experiments are being performed by the BOM. The test conditions' requirements and acceptance criteria are discussed in Appendix T. The conclusions in this SA are predicated on the assumption that the BOM tests will show that the frictional sparks will not ignite the sensitive flammable mixtures.

Another case considered is the accumulation of hydrogen in the riser, but not in the dome. In this case, flammable-gas detection and the shut-down system could not interrupt drilling. Protection is provided by the riser purge with a failure probability of 6.5E-3 (Appendix E). Based on the sparking tests of the drill against the riser sleeve at the BOM and the calculation that was done for frictional heating, ignition is not expected to occur in this potential pocket of gas. In addition, if it did, the volume would be small and not lead to a dome collapse.

Even though the MAF is small, BOM experiments are needed (Appendix T) because of the uncertainties associated with the GRE probabilities.

**TABLE 4-8**
**DOME FIRE ACCIDENTS CAUSED BY FRICTIONAL SPARKS IN THE RISER**

| Accident | Frequency of failure 1/year | Dominant Failures | Controls Credited in Calculating UAF and MAF Values |
|---|---|---|---|
| $H_2$ in riser during drilling leads to dome fire. | Without BOM test results<br>MAF = 2.5E-10<br>UAF = 2.8E-5 (assumes drill string-sleeve contact may spark)<br><br>With BOM test results:<br>MAF and UAF <<1.0E-6 | Fail to shutdown drill string upon detection of $H_2$.<br>$N_2$ supply to riser sleeve fails. | Drill-string automatically trips when high $H_2$ level, high rate of change of $H_2$ level, or high dome pressure.<br>Leak check of $N_2$ supply to riser sleeve is done.<br>DS trips on loss of $N_2$ to riser sleeve.<br>Unique connector for $N_2$ supply to riser sleeve is required.<br>$N_2$ supply to sleeve during actuation of system is verified. |

### 4.2.5. Ignition of Flammable Gas in the Riser Caused by Electrostatic Spark (Installation, Operation, and Removal) (Rubber and Drill String)

For this event, the concern is with the electrostatic discharge from the rubber frisbee as the drill string rotates on this piece. The rubber frisbee diameter is slightly smaller than the drill-string diameter so that there is always a force exerted by the frisbee on the DS. A lubricant is applied to the drill string in order to ease the rotation and insertion. The use of this lubricant can reduce the probability of the static electricity discharge during drilling. The frisbee is in contact with the grounded DS and washer, and the drill string is connected to the drill unit which is grounded through the drill truck. The riser sleeve is purged with a nitrogen flow. The probability of failure of the nitrogen purge to the riser sleeve is very low; thus, a static discharge is not an issue. However, a control requires the use of the lubricant as a part of the procedure because it also helps to reduce the likelihood of damaging the rubber.

The resistivity of the frisbee is measured, and the findings show that the frisbee is not a good conductor. However, although the frisbee is composed of a non-conductive material, and if the drill string is always grounded by either the foot clamp or the hoist/truck, no credible spark source was identified. Therefore, the SA does not consider a dome fire accident caused by this initiator and does not require the replacement of the frisbee as a mandatory control.

### 4.2.6. Ignition of Flammable-Gas Release Caused by Crust Penetration and Frictional Sparks Caused by the Drill Bit (Operation)

This accident analysis deals with the ignition of flammable gas that could exist in the crust or under the crust during the drill-bit penetration through the crust or waste sludge. The possibility of metal objects at the waste surface or in the crust always exists because it is known that manual tapes, wires, and metal pieces have been dropped through the risers. A frictional spark caused by the drill bit can ignite the hydrogen. The ability of the drill bit to cause a frictional spark when rotating on a steel plate has been observed. In testing discussed by Marusich,[12] the drill bit had carbide teeth and was operated on a steel piece in the dark. Sparks were observed. All carbide teeth are eliminated in later designs. New drill-bit cutting teeth are made of a proprietary sintered bronze with small tungsten chips in the bronze matrix. This material can wear easily when the drill bit is operated on metal objects or hard materials. The core sample drill bits used by FG/RMCS are Longyear (trademark of Longyear Incorporated) Part Number 1001VD/5 (currently used). It is known that the probability of sparks from copper-based materials is not high. Nevertheless, the inability of the drill bit to cause a frictional spark in a bounding flammable-gas mixture needs to be demonstrated by testing.

A series of ignition tests are being conducted to demonstrate that the present drill bit design does not ignite a sensitive flammable-gas mixture. This testing addresses the frictional spark when the drill bit encounters a metal object that could be in the

waste. Tests are designed to simulate the action of drill bit striking a hard object inside a waste tank, such as a piece of structural steel or a rock. Tests are being conducted in a bounding stoichiometric hydrogen oxygen and ammonia nitrous oxide mixture. The detail of the testing procedures are provided in Appendix T.

Controls and automatic shut-down features are used to keep the down force and rotational speed within the limits (750 lbf and 55 rpm) at any time during operations. As long as these limits are not exceeded, the accident frequency is zero, provided that the BOM tests demonstrate no ignition, as discussed in Appendix T. If the controls are exceeded, it is assumed that an ignition could occur if there is enough flammable gas. The frequency of the failures of down force and rotational speed, assuming that the controls are exceeded, is determined in Appendix E and given in Table 4-9. In order to initiate a dome burn when the drill bit is penetrating the crust, other necessary conditions must exist: (a) rocks (or other hard material) must exist at the surface or in the crust, (b) flammable gas with sufficient concentrations must exist, (c) flammable-gas volume must be significantly high to cause propagation into the waste or the dome (propagation to the dome requires flammable gas be in the dome). Because failure frequencies are already small, the consideration of additional probabilities to cause a dome burn makes this scenario incredible. However, the same initiator when the drill bit is in the waste will be considered in Section 4.4 to address the flammable-gas ignition in the waste.

#### 4.2.7. Ignition of Flammable Gas in the Dome (Operation)

This event considers the possibility of an ignition caused by the existence of energized equipment in the dome or domes of connected tanks or connecting ventilation systems. Any activity in the connecting tanks may initiate a fire that may propagate into the tank being sampled. Appendix B requires that all equipment in the dome be rated for operations in a Class-I, Div.-1, Group-B environment or a Class-I, Div.-2, Group-B environment with automatic shutdown. Any equipment that does not meet this requirement must be deenergized during FG/RMCS operations. No other activities in the connecting tanks or on the same tank are allowed during FG/RMCS operations. These controls reduce the likelihood of ignition caused by existing equipment in the tank dome and the domes of connecting tanks. Violation of this control may result in an unanalyzed initiator.

#### 4.2.8. Ignition Of Dust And Flammable Gas In The Dome (Operation, Removal) (Static Electrical Charges And Other Causes)

In this accident scenario, the ignition of aerosols generated in the dome is analyzed. In Appendix H, a bounding analysis is performed to show that the energy contribution of combustible dust is negligible and that the addition of dust in a hydrogen-air mixture would not result in explosion.

#### 4.2.9. Summary of the Dome Fire Accident

The drill string break resulting in a dome fire is the dominant fire initiator in the dome space. The principal contributor to the accident sequence is exceeding the operating limits. The resulting dome fire MAF is 3.9E-10/yr. The UAF is 2.8E-7 and

is low. The consequence of this accident is the dome collapse analyzed in Section 5 of this SA.

TABLE 4-9
DOME FIRE ACCIDENTS CAUSED BY DRILL BIT FRICTIONAL SPARKS

| Accident | Frequency of failure 1/year | Dominant Failures | Controls Credited in Calculating UAF and MAF Values |
|---|---|---|---|
| Excessive drilling rpm leads to ignition of flammable gas resulting in dome collapse. | MAF = 1.4E-5<br>UAF = 2.2E-2<br>With qualification of drill bit, per test specified in Appendix T, UAF<<1.0E-6 | The rpm setting is too high.<br>Drill string fails to trip on high rpm. | Control over speed setting is used.<br>Drill string auto trips on excessive rpm. |
| Excessive down force on drill leads to ignition of flammable gas resulting in dome collapse. | MAF = 9.4E-5<br>UAF = 1.2<br>With qualification of drill bits, per test specified in Appendix T, UAF <<1.0E-6 | Excessive down force is used.<br>Drill string is on excessive force with either force detector or walkdown detector. | Control over down force is used.<br>Auto trip drill string on excessive force is needed: force detector and walkdown detector function for all samples except last, force detector and bottom detector for last sample are needed. |

## 4.3. DRILL-STRING FIRE ACCIDENTS

Drill-string fire accidents consider all possible fire initiators inside the drill string. Each ignition initiator determined for this category is discussed separately. The ignition source may exist as a result of normal as well as abnormal operations.

The consequences of a drill-string fire vary and may end up with small amounts of waste release as well as a dome collapse. Examples of how a drill string fire may propagate to other accidents are discussed in Appendix A. It is assumed that the fire in the drill string (if it occurs) propagates to the tank and results in dome collapse. As explained in the introduction, this assumption is conservative, and there is only one consequence, dome collapse, if a drill-string fire occurs. The conditional frequency of each accident scenario, however, is discussed and the adequacy of preventive features is demonstrated.

### 4.3.1. Flammable-Gas Penetration into the Drill String (Operation)

Section 3 identified the fact that there may be several reasons for hydrogen penetration into the drill string:

- Failure of chevron sampler seal between drill bit and drill string,
- Hydrogen diffusion,
- Waste in the drill string,
- Failure of core sample ball valve on the core sampler,
- Depressurization of waste in the drill string,
- Loss of hydrostatic pressure,
- Incompatible material, and
- Failure to latch the sampler.

The hydrogen can be generated in the drill string if waste exists. A leaky chevron seal may allow waste penetration into the drill string. If the sampler encounters large gas pockets in the waste (although credible evidence for this mechanism is not provided), the sampler could be filled with flammable gas. Failure of the core sampler valve in the drill string could release hydrogen into the drill string. Failure to latch the sampler to the core barrel can cause flooding and gas generation in the drill string. However, as long as hydrostatic pressure during sampler retrieval and nitrogen purge during drilling are available, the hydrogen release into the drill string from the sampler or waste is not of concern because there is enough flow rate to purge or prevent diffusion up the drill string. Appendix J concludes that the minimum flow rate at which hydrogen could diffuse against the flow is 5E-4 scfm, which is lower than a minimum flow rate of 0.3 scfm provided by the purge system.

One other mechanism that can produce flammable gas is the use of incompatible material in the drill-string design. The drill string is made of steel, and steel is known to be compatible with the waste in terms of violent chemical reactions that would result in gas releases or other undesirable consequences. WHC recently reviewed the sampler to ensure there were no incompatible materials used in the construction; in particular, they examined the design for the presence of aluminum. Also, the drill bit and seals used in the design have been used in actual waste and found to be compatible (Ref. 13).

There are three major causes for hydrogen accumulation in the drill string:

1. failure of nitrogen flow during drilling,
2. failure of hydrostatic flow during retrieval, and
3. failure of the chevron seal before the change-out assembly is installed.

The sampler is designed to prevent waste and flammable-gas penetration into the drill string through a chevron seal located at the end of the core sampler. It is a one-

way seal and allows nitrogen flow from the drill string into the tank waste. When the drill string is rotated, the core barrel rotates around the core sampler while the seal is slightly compressed to allow nitrogen flow. When the sampling is finished and the purge flow stopped, the seal provides a barrier between the tank waste and the drill string. Flammable gas may penetrate into the drill string if the seal does not provide an adequate barrier. It is reasonable to assume that the seal may fail partially if not completely before the retrieval of the sampler (as change-out assembly is installed). Calculations (Appendix J) show that hydrogen can diffuse in nitrogen relatively fast.

It is required that the drill string must be purged to evacuate flammable-gas accumulation following a procedure developed by WHC for the following conditions:

- The sampler is left in DS without nitrogen flow or hydrostatic pressure for ≥ 60 minutes, or
- DS hydrostatic head is lost with no sampler in place.

If these conditions occur, the grapple or remote latch unit should not be operated unless the nitrogen purge criteria are met. The hydrostatic head pressures for each sampler need to be calculated before operation.

**4.3.2. Ignition of Flammable Gas in the Drill String Caused by Drops (Operation)** The remote latch unit and the grapple are lowered and raised during the insertion and removal of the sampler. Each unit is driven by an electrical motor through a gear box. Each is mechanically attached to a driving system through a cable. The insertion and removal rates of the remote latch unit and grapple are specified as less than 1 ft/s.

In this section, accidents resulting from frictional sparks in the drill string as a result of dropping the grapple, remote latch unit, and core sampler are considered. In the case that the hoist systems for the grapple and remote latch unit or electrical motors used to raise or lower these units fail, the grapple and remote latch unit may be dropped on the core sampler. The keys or pins connecting the shaft to the drum can be broken as a result of a stuck core sampler, grapple, or remote latch unit. The following are assumed to cause frictional sparks:

- Multiple drive train failures,
- Failure of keys or pins connecting the shaft to the drum, and
- RLU failure.

Studies have been performed to examine the characteristics of mechanically produced sparks that could lead to ignition of hydrogen-nitrous oxide mixtures. Drop velocity could be as high as 19.8 m/s and is well above the range given by Krok

and Shephard's work.[8] Therefore, if the remote latch unit or sampler is dropped in the drill string, it is assumed that an ignition source can be created.

The electric motors driving the remote latch unit and grapple are DC pulse-width modulated power supplies. Their principal operating parameters are given in Section 2. Because of the worm-gear reduction boxes, failure of these motors would not result in a drop. However, a drop accident may occur as a result of the failure of the metal key or pins that is used to attach the shaft to the cable drum. These pins are the weakest points of the system and may fail if the grapple or the RLU is stuck or overweighted because of some unknown reason.

The operation of the RLU is entirely mechanical and is discussed in Section 2. When the RLU is lowered and the sampler comes to rest at the bottom of the drill string, the cable stops when the load cell detects the cable going slack. As the tungsten weights cause the dashpot piston in the RLU to descend, the load cell again engages the downward motion of the hoist.

When the sampler is being raised or lowered in the drill string, the hydrostatic head must be in operation. There are two independent purges, one through the shielded receiver and one through the change-out assembly.

Drops caused by failure of the remote latch unit are possible. For an ignition, flammable gas must be present, which means that the hydrostatic head purges must have failed also. The frequency of this accident is calculated as 1.9E-6/yr in Appendix E. This is the same accident analyzed in Section 4.1.4 for aboveground fires in the SR. This frequency is reported in Table 4.4 and is not reported again in the summary for this section.

Drop tests simulating the drop of the core sampler on the drill bit and drop of RLU on the quadralatch are being performed by the BOM (test description and requirements are given in Appendix T). A prototypical core sampler will be dropped from a height of 60 feet through drill string on the drill bit attached to the lower end of the drill string. The test chamber and drill string will be filled with stoichiometric hydrogen-air mixture. Ignition is not expected because the bottom of the core sampler is made of stainless steel. The tests will be repeated 10 times to confirm this expectation.

Drop tests also will be performed for the RLU-quadralatch-impact related accidents mentioned above. For these tests, a prototypical RLU (stainless steel) will be dropped on a carbon-steel quadralatch from a height of 60 feet for at least 10 times. A long drill string with an open lower end will be used to achieve the drops. A prototypical RLU will be dropped through the drill string onto the stationary quadralatch placed in a test chamber filled with a stoichiometric hydrogen-air mixture. Note that the new quadralatch is made of stainless steel; therefore, these tests are conservative

### 4.3.3. Ignition of Flammable Gas in The Drill String Caused By Assembly/Disassembly of Drill Rods or Drill Rod-Quill Rod Adapter Impact

Ignition of the flammable gas in the drill may be caused by impacts that could be created during drill string or drill string to quill rod assembly or disassembly. The postulated accident can occur when the drill string is in the waste or dome. Accident frequency is different for these two cases because of assumption in regard to the flammable gas. Flammable gas exists in the dome only if a GRE occurs while it is assumed to exist in the waste.

A spark during the disconnecting of the quill rod from the drill string has been observed.[14] The quill rod adapter and drill string were made of carbon steel. Any misalignment between the drill string and quill rod caused by undesired platform movement or operator errors could create a relatively fast impact between the quill rod and drill string when the drill string is disconnected. There is no instrument to detect the misalignment or any stress level on the drill string or quill rod adapter. Therefore, it is very difficult to evaluate the condition of the drill string to quill rod adapter before disconnecting the drill string. Because a spark is observed in the operation, one must assume that the likelihood of this event is high.[14]

The drill string is assembled by adding drill rods. The operator picks the drill rod from the storage location and lifts and screws it onto the drill string by hand. Then the lifting bail is attached to the drill string.

During insertion, drill-rod-to-drill-string impact is very possible. Impact can be caused by dropping the drill string or operator error. Drop height is limited with the drill rod length. However, the operator can also cause a lateral impact. It is determined that a realistic impact velocity is around 10 ft/s. It is not clear that the impact with this velocity would not cause a spark that is capable of igniting the flammable-gas mixtures of concern. A spark is possible because the drill rods are made of carbon steel and assembling/disassembling is performed for each sample.

The cable spray washer is installed after the drill string is disconnected from the quill rod adapter. Dropping the cable spray washer may produce a spark. Next, the change-out assembly is installed on the cable spray washer. Dropping the change-out assembly on the cable spray washer may produce a spark. In order to have an ignition in the drill string, the flammable gas must exist in the drill string. The drill string must be sniffed before it is disconnected from the quill rod adapter.

A drill string fire initiated by a spark caused by the drill-rod-drill-string or the drill-string-quill-rod adapter impact is discussed in this section. Event and fault trees for this scenario are given in Appendix E. Sniffing the drill string before the drill string is disconnected from the quill rod adapter through a port on the quill rod is required. The reliability of the inspection is limited with the reliability of the sniffing equipment, which is on the order of 1.0E-3. If the change-out assembly is installed immediately (within half an hour), no other sniffing is required. If,

however, the drill string is capped and the change-out assembly is installed later, there is a need for a second sniffing from a port on the cap sealing the drill string while the drill string is closed. This is because of the possibility of hydrogen diffusion through the chevron seal (Appendix J).

The chevron seal failure probability is estimated as 3.3E-2. The frequency of operator error causing drill-rod-to-drill-string impact is 0.5/activity. Considering the reliability of sniffing, an accident frequency of 7.6E-5 /activity is calculated if the drill string is left in the waste (note that the probability of hydrogen in the waste is assumed to be 1.0). This frequency is valid for a fire accident caused by drill-string-quill-rod impact. The drill string could be in the dome. In this case, hydrogen must exist in the dome in order to penetrate into drill string. Thus, a GRE is required. Considering the GRE probability, accident frequency becomes low, on the order of 1.1E-9/yr. These frequencies are summarized in Table 4-10. The accident frequency when the drill string is in the waste is high; therefore, laboratory ignition testing is designed to demonstrate that ignition is not possible.

TABLE 4-10
DRILL STRING FIRE ACCIDENTS—DRILL STRING IMPACT

| Accident | Frequency of failure 1/year | Dominant Failures | Controls Credited in Calculating UAF and MAF Values |
|---|---|---|---|
| Spark from assembly/disassembly of drill string sections or drill string to quill rod impact when the drill string is in the waste<br>(does not contribute to the total frequency of dome collapse) | Without BOM test results<br>MAF = 7.6E-5<br>UAF = 1.6E-2<br>With BOM test results<br>MAF and UAF << 1.0E-6 | Failure to perform sniff for flammable gas in the drill string<br>Sampler chevron seal fails. | Sniff enclosed volume for hydrogen in drill string.<br>Presence of sampler with chevron seal in drill string prevents hydrogen movement into drill string. |
| Spark from assembly/disassembly of drill string sections or drill string-quill rod impact when the drill string is in the dome<br>(does not contribute to the total frequency of dome collapse) | Without BOM test results<br>MAF = 1.1E-9<br>UAF = 2.3E-7<br>With BOM test results<br>MAF and UAF << 1.0E-6 | Failure to perform sniff for flammable gas in the drill string<br>Sampler chevron seal fails. | Sniff enclosed volume for hydrogen in drill string.<br>Presence of sampler with chevron seal in drill string prevents hydrogen movement into drill string. |

The following design changes were made to manage the above-mentioned mechanical sparks. First, the quill rod adapter material was changed from carbon steel to stainless steel. Second, all pipe compounds and lubricants used in

FG/RMCS operations were reevaluated.[14] It was found that one of the pipe joint compounds, Bostik Never-Seez Anti-Sieze and Lubricating Compound, showed evidence of enhanced sparking. Necessary procedural changes were made to use only acceptable joint thread compounds listed in Ref. 14. In addition, a series of ignition tests will be performed as described in Appendix T. These tests address the drill-rod-to-drill-string impact, drill-string-to-quill-rod-adapter impact, the change-out assembly-to-cable spray washer impact, and cable-spray-washer-to-drill-string impact.

The first series of tests simulated the carbon-steel drill strings impact by dropping a prototype 19-in. drill string on another vertically oriented prototype drill string from a height of 3 feet. The height of 3 feet corresponds to the impact velocity of 14 ft/s, and impact masses are conserved. Tests are performed 30 times. These tests also address the ignition caused by the drop of the change-out assembly.

The quill rod adapter to drill string impact tests will be performed as follows. A stainless-steel RLU is dropped on the carbon-steel quadralatch from a height of 60 feet for 10 times. The impact velocity is high and considered to simulate the impact between the quill rod and the drill rod. In those cases, ignition is not expected because the quill rod adapter is made of stainless steel.

#### 4.3.4. Ignition of Flammable Gas in the Drill String Caused by Unqualified Electrical Equipment in the Drill Head or Shielded Receiver (Operation)

This accident is concerned with the ignition of the flammable gas by electrical sparks. The SR and grapple box have load cells. These load cells are used to measure the tension on the cable that is attached to the remote latch unit or grapple. The load cells are protected by intrinsic safety barriers. WHC quality assurance requirements ensure that these barriers are certified. Thus, the load cells are not electrical spark sources. The electrical motors are located outside of the grapple box and the SR, which are sealed containers. There is no other equipment in the SR and the drill unit that can cause electrical sparks.

#### 4.3.5. Ignition Of Flammable Gas in the Drill String Caused by Drill-String Failure (Operation)

This scenario is very similar to the event discussed in the dome fire (drill-string break). The difference is this scenario assumes that the fire starts in the drill string (flammable gas is in the drill string, not in the dome). The initiating event is the drill string failure, causing a hot spot in the vicinity of the failure location. This hot spot ignites the hydrogen in the drill string. The propagation of the fire in the drill string into the waste is considered to be possible. Therefore, this postulated accident may result in dome collapse.

Two failures must occur for this scenario to occur; hydrogen in the drill string and failure of the drill string. Hydrogen is not expected to be in the drill string during drilling because it requires a failure of the nitrogen flow and the chevron seal. The conditional frequency of this accident (1.3E-8/yr) is the frequency of the undetected

nitrogen purge failure (1.9E-05), the failure of the chevron seal (3.3E-2) and the frequency of the drill-string breakage (1.0E-2).

#### 4.3.6. Ignition of Flammable Gas in the Drill String Caused by Frictional Sparks (Operation)

This accident scenario considers an ignition of hydrogen in the drill string caused by frictional sparks. Hydrogen can exist in the drill string because of failure to latch a sampler, a leaking chevron seal, etc. The drop cases were treated in Section 4.3.2. The possible sources for mechanical sparks are

- Failure of bearings,
- Frictional sparks caused by operation of the remote latch unit, and
- Frictional sparks resulting from the operation of the grapple,

Acceptance testing verified the operability of bearings. The sampler and these bearings are used only once. The only time the bearing sees relative motion is during rotary sampling at which the time nitrogen purge is present. Waste penetration into the bearings is minimized because they are out of the waste path entering the sampler. Therefore, the failure of bearings resulting in sparks is not credible.

Metal-to-metal sparks are managed by limiting the velocity of movement of the remote latch unit and grapple to no more than ~0.3 m/s (1 ft/s). This velocity is adopted from previous studies[15] concerning a similar hazard of lowering or raising a metal pipe through a riser. It has been shown that mechanically produced sparks that could lead to ignition of tank-like gases is not likely when the frictional impact velocity is less than 2.5 m/s (8.2 ft/s) (Ref. 8).

A gear reducer is used to limit the grapple and remote latch unit motion to 1 ft/s and 0.4 ft/s, respectively. Therefore, the frictional sparks are not likely. The frictional sparks caused by a drop accident are discussed in Section 4.3.2.

A credited design feature controls insertion or removal speed of the grapple, and remote latch unit to no more than 0.3 m/s (1 ft/s). In addition, a purge pressure equal to hydrostatic head pressure before insertion or removal of the grapple or remote latch unit is established. Sniffing the drill string each time the drill string is opened to the atmosphere reduces the possibility of hydrogen accumulation.

#### 4.3.7. Ignition of the Flammable Gas in the Drill String Caused by Frictional Sparks from the Shear Pin Break (Operation)

This accident has been identified during the hazard identification process that considered a design involving a copper pin used to attach the piston to the pintle rod. The pintle rod release mechanism was redesigned to rely on a mechanical release instead of the copper wire shearing, and it is a metal clip. The use of a metal

clip is not expected to produce a spark. During the pintle rod removal operation, the hydrostatic head purge is established, and this provides additional protection.

#### 4.3.8. Detonation in the Drill String and Drill-String Ejection (Operation)

Appendix J discusses the possibility of detonation in the drill string. It assumes that there is hydrogen in the drill string and that it can be ignited. Theoretical detonation pressure for hydrogen-air mixtures in a pipe can be calculated by using a numerical method to solve the differential equation for isentropic compression in the burn gas. From the analysis given in Appendix J, the overpressure and the rate of pressure rise during a burn in the drill string are 630 kPa and 2279.5 bar/s, respectively. During a detonation in the drill string, the overpressure and the rate of pressure rise are 15 bars ($1.5 \times 10^6$ Pa) and $3 \times 10^6$ bar/s, respectively. As explained in Appendix J, the induction distance for the $H_2$-$N_2O$ mixture is short relative to the maximum drill string length. Therefore, a deflagration-to-detonation transition (DDT) may occur in the drill string. The rate of pressure rise is so high ($3 \times 10^6$ bar/s) during the detonation, that the structure of the drill string is expected to fail.

This conclusion is important from the consequence point of view. If the detonation in the drill string causes ignition in the waste with propagation, then a dome collapse would be expected. However, the consequence of dome collapse is not increased by this initiator because the dome collapse accident considered in Appendix I is already conservative and includes bounding waste release amounts. However, detonation may only fail the drill string and result in ejection of the core sampler. In this case, the consequences of this accident may be a release of the waste in the sampler. In Section 5, a waste release of 0.39 kg is considered.

#### 4.3.9. Ignition in the Drill String Caused by Lightning

The lightning strike is discussed in Section 4.1.1. The controls developed to prevent ignition caused by lightning in Section 4.1.1 are applicable to this section as well.

#### 4.3.10. Ignition in the Drill String Caused by Static Electricity Between Seals and Rotating Parts

In this scenario, the concern is the static electric discharge between the seals and the rotating parts in the sampler. The core sampler motion is in the closed space. The rotational or penetration speed is slow, and there is always direct contact with metals.

#### 4.3.11. Summary of Drill-String Fires

All of the initiators previously identified in Section 3 were found not to cause fire in the drill string because of safety design features and experimental results obtained from ignition testing. The accident frequencies of hydrogen penetrations into the drill string are developed in Appendix E and summarized for this category in Table 4-11. The drill string fire accident frequency is 1.3E-8/yr.

TABLE 4-11
DRILL STRING FIRE ACCIDENTS-CONDITIONAL FREQUENCIES OF HYDROGEN PENETRATION INTO THE DRILL STRING

| Accident | Frequency of failure 1/year | Dominant Failures | Controls Credited in Calculating UAF and MAF Values |
|---|---|---|---|
| Drill string break leads to a fire in the drill string. | MAF = 1.3E-8<br>UAF = 6.6E-4 | Drill String fails to shut down on loss of nitrogen purge.<br>Drill string breaks by jamming in the waste causing overtorque or buckling. | Drill string automatically trips when the nitrogen purge to the DS is lost. |
| $H_2$ in drill string/shielded receiver during sampler handling leading to waste fire.<br>(does not contribute to the total frequency of dome collapse) | Without BOM tests results<br>MAF = 1.9E-6<br>UAF = 2.8E-3<br><br>With BOM test results<br>MAF and UAF <<1.0E-6 | $N_2$ hydrostatic systems to both drill string and to shielded receiver fails.<br>RLU drops sampler. | Leak test of $N_2$ hydrostatic systems for both drill string and for shielded receiver are done.<br>Unique connections for $N_2$ hydrostatic systems for both drill-string and shielded receiver are used.<br>Verification of $N_2$ hydrostatic supply to both drill-string and shielded receiver during activation of hydrostatic mode of $N_2$ supply is made.<br>Controls over operation of RLU are used. |

## 4.4. WASTE FIRE ACCIDENTS

Accident sequences considered in the waste fire category include waste ignition as well as flammable-gas ignition in the waste. The waste in single-shell flammable-gas tanks includes organics. Below, the initiators that could result in waste fire accidents are discussed.

### 4.4.1. Waste Fire Caused by Drill Bit Over-Temperature (Operation)

Wastes including mixtures of sodium nitrate and sodium nitrite with organic compounds can produce violent exothermic reactions (Appendix G). Increasing the temperature of the waste in the vicinity of the drill bit can cause a thermal runaway. There are several hazards that are associated with a local thermal runaway, and they are discussed in Appendix G. Two major important hazards are the ignition of the flammable gas and the initiation of a self-propagating exothermic reaction in the

waste. Reactions in mixtures containing relatively small amounts of organic compounds can result in temperatures greater than the autoignition temperature of hydrogen mixtures, so the ignition of flammable gases is the more limiting condition. However, a self-propagating reaction would produce very high temperatures, which would cause structural damage to the tank. The consequences of a self-propagating reaction could be severe.

Because the possibility of a flammable-gas mixture cannot be eliminated, the approach used in this Safety Assessment is to take all practical measures to eliminate ignition sources. A local runaway reaction is a potential ignition source, so the requirement that there be no local runaway reaction is consistent with the philosophy used in this SA. Preventing a local thermal runaway is also protection against a propagating exothermic reaction, and it eliminates the possibility of generating additional flammable gas as a result of elevated temperatures. Appendix G discusses runaway reactions and waste ignition in great detail. Basic conclusions of Appendix G are that local runaway reactions can be prevented by establishing waste temperature limits. The following temperature limits are established:

- The temperature of small waste fragments produced at the drill tip must not exceed 180°C.
- The temperature of the drill bit and the average temperature of the waste affected by drilling must not exceed 160°C for more than 10 minutes.

Because the consequences of a propagating exothermic reaction are severe, FG/RMCS should not be performed in tanks in which a propagating exothermic reaction may occur.

New envelope testing has been performed by WHC to determine the operating parameters, rotational speed, down force, and nitrogen purge flow to comply with the safety criteria given above. Appendix F discusses the details of testing and the results obtained.

As a summary, results of envelope testing and their analysis showed that the drill bit surface temperature correspondingly the waste substrate temperature can be kept below 160°C, including an uncertainty of 10°C, if the following limits are applied: Down force <750 lbf, rotational speed <55 rpm, minimum nitrogen flow >30 scfm, and penetration rate >0.75 in./min. The chip temperatures under these conditions are also limited to 180°C as required. If a trip is initiated when one of the set points for these four parameters is exceeded, drilling must be stopped. After a shutdown there must be a waiting period of 10 minutes before drilling can continue. The waiting period of 10 min. is based on the experimentally determined cooling time. The testing and the analysis included plugged holes on the drill bit.

The minimum purge flow must be greater than 30 scfm; however, it is possible that necessary cooling to the drill bit would not be provided if there were a leak from the

nitrogen purge system between the flow measurement location and the drill bit. WHC determined that the leak from the truck is within the uncertainty range of instrumentation. As indicated in Table 4.12, the leak rate from the nitrogen system must be measured once every 6 months. This control requires that the leak rate must be within the uncertainty range of instrumentation or less than 2% of the nominal flow.

Drill rods are threaded to each other. An O-ring is used to provide a seal. The leaks are possible if the O-rings are left out. WHC[16] determined the possible leak rates could not be higher than 0.3 scfm when the O-rings are not used. This is less than 1% of a nominal flow of 30 scfm and negligible. With the use of O-rings, the leak rate also was measured and was shown to be negligible. Therefore, O-rings on the drill rod are not required, and the nitrogen purge flow for drill bit cooling is sufficient when set to a minimum of 30 scfm.

There is one event that would include an unknown leak path as a result of failure of the drill string during drilling. If the drill bit or string becomes embedded in the waste momentarily because of debris in the waste, torque could continue to be applied to the drill string at a constant rate. If such a condition occurs, there is a possibility that the drill string could partially fail. Continuing to operate with a partially failed drill string could result in a nitrogen flow bypass through the failed area. This concern is assessed below.

Appendix N examines the possibility of over-torquing the drill string. The drill string is considered as having torque applied from the upper end, but the rotation of the lower end is not allowed. Appendix N presents two methods to determine the time necessary to break the drill string. Linear elastic methods are applied as a first approximation to obtain the lower bound failure estimate. Second, strain-energy methods are used to determine an upper bound by assuming that the ultimate shear strain in the drill rod is proportional to the shear modules. It is estimated that failure would occur in less than 15 seconds for all rotational speeds. Note that Appendix N did not take any credit for the threaded drill rods. Experience shows that the drill string always fails at the threaded sections. The real failure time is expected to be in a few seconds because of the stress concentration factor for threaded sections. Therefore, it is concluded that a drill string tear without a break is very unlikely.

Envelope testing measured the rate of increase in the drill-bit surface temperature when nitrogen flow is terminated at steady-state operating conditions. The test results are summarized in Appendix F. Results showed that an average heat-up rate of 2°C/s is observed in the time period of 0 to 20 seconds after the nitrogen flow is shut down. This rate corresponds to a temperature increase of 30°C in 15 seconds in which the drill string would be broken when overtorqued. Envelope testing established the operating parameters so that the drill bit and waste temperature is less than 150°C. Considering a 30°C heat-up of the drill bit for this accident, the drill

bit/waste temperature would be 180°C. Appendix G argues that the waste temperature would be allowed to be at the minimum exothermic-reaction temperature of 180°C for a short period of time because the induction time of reaction is expected to be much larger than 10 to 20 seconds. Therefore, it is concluded that if the drill fails because it is over-torqued it would fail in a time period in which the waste in the vicinity of the drill bit would not experience runaway reactions.

**4.4.1.1. Summary of Controls for Drilling Operation.** Envelope testing suggests that a maximum drill-bit temperature corresponding to the maximum waste substrate temperature increase is limited to $\Delta T=60°C$ when the rotational speed, down force, and nitrogen purge flow are 750 lbf, 55 rpm, and 30 scfm, and there is good penetration (penetration rate is higher than 0.75 in./min). These parameters consider a partially plugged drill bit and ensure that waste chip temperatures are bounded by the safety limit of 180°C. In order to meet the safety criteria established in this SA, the down force and the rotational speed must not exceed 750 lbf and 55 rpm. The minimum nitrogen flow rate must not be lower than 30 scfm. The penetration rate must not be less than 0.75 in./min. The probability of having a hard layer in the waste is 0.1 that is obtained with the assumption that 20% chance for a need for rotary drilling in an activity and 50% chance of hard layer in rotary mode drilling.

When a trip value is reached in one of the three parameters, down force, rotational speed, and nitrogen purge flow, the drilling must be stopped within the time period that data acquisition activates the shut-down signal. The alarm set point may be chosen lower than the trip values. If the alarm set points are set to trip values, 750 lbf, 55 rpm, and 30 scfm, the programmable logic controller (PLC) sends a shutdown signal to the drill engine upon receipt of a valid shutdown signal with no additional programmed-delay. It is understood that the determination of a valid alarm signal requires approximately 2 seconds. The penetration rate is alarmed at 0.75 in./min and shut down occurs with a 60 second cumulative time in any three-minute period. This gives a chance for the operator to penetrate a thin, hard layer (if encountered), provided that the force, rotational speed, and nitrogen purge controls are not violated. There must be at least a 10-minute waiting period following the trip prior to the continuation of drilling.

The nitrogen inlet temperature to the drill string must be maintained between 10°F to 140°F.

**4.4.1.2. Accident Frequency Of Waste Ignition.** Failure to shut down the drilling when limiting operating parameters are exceeded is assumed to cause runaway reactions in SSTs. The reliability of the nitrogen purge system and control system for the rotational speed and down force are examined in Appendix D. In Table 4-12, conditional accident frequencies are given. The accident frequencies caused by loss of cooling, excessive rotational speed, down force, and low penetration rate are

estimated as 3.8E-5, 1.4E-5, 9.4E-5, and 7.4E-5/yr. These numbers consider the use of a bottom detector or walkdown option to shutdown. These frequencies are added to obtain the conditional frequency of a waste fire accident caused by drilling operations. The combined frequency is 2.3E-4/yr.

TABLE 4-12
WASTE FIRE CAUSED BY FRICTIONAL HEATING FROM THE DRILL BIT

| Accident | Frequency of failure 1/year | Dominant Failures | Controls Credited in Calculating UAF and MAF Values |
|---|---|---|---|
| Loss of drill-bit cooling leads to waste fire. | Without probability of reactive waste<br>MAF=3.8E-5<br>UAF=2.0<br><br>With consideration of probability of reactive waste for selected tanks (Appendix G)<br>MAF <1.0E-6 | $N_2$ cooling holes in the drill bit are partially blocked, there is no trip of the drill string on low $N_2$ flow, and there is localized overheating of sections of drill bit. | Auto trip of the drill string on low $N_2$ purge gas flow<br>Annunciation of high $N_2$ purge gas temperature is required.<br>$N_2$ purge system is tested for bypass leakage.<br>Test results show that $N_2$ leakage from drill string with section O-rings not installed is acceptable.<br>Analysis shows that a drill string tear without a break is very unlikely. |
| Excessive drilling rpm leads to waste fire. | Without probability of reactive waste<br>MAF=1.4E-5<br>UAF=2.2E-2<br><br>With consideration of probability of reactive waste for selected tanks (Appendix G)<br>MAF <1.0E-6 | The rpm setting is too high.<br>Failure to trip drill string on high rpm. | Control over speed setting is used<br>Drill string auto trips on excessive rpm |

TABLE 4-12
WASTE FIRE CAUSED BY FRICTIONAL HEATING FROM THE DRILL BIT
(CONT'D)

| Accident | Frequency of failure 1/year | Dominant Failures | Controls Credited in Calculating UAF and MAF Values |
|---|---|---|---|
| Excessive down force on drill leads to waste fire. | Without probability of reactive waste<br>MAF=9.4E-5<br>UAF=1.2<br><br>With consideration of probability of reactive waste for selected tanks (Appendix G)<br>MAF <1.0E-6 | Excessive down force is used.<br>Drill string on excessive force with either force detector or walkdown detector. | Control over down force used<br>Auto trip drill string on excessive down force: force detector and walkdown detector function for all samples except last; force detector and bottom detector for last sample.<br>The drill bit type tested by BOM is used. |
| Slow penetration rate results in waste fire. | Without probability of reactive waste<br>MAF=7.4E-5<br>UAF=0.2<br>With consideration of probability of reactive waste for selected tanks (Appendix G)<br>MAF <1.0E-6 | Operator fails to act. | Provide a 1 of 1 system for detection of penetration rate. Auto trip on slow penetration rate.<br><br>One minute is available for operator to recognize slow penetration conditions and stop drilling. |

### 4.4.2. Waste Fire As A Result Of Exothermic Reaction Caused By Incompatible Materials (Installation, Operation And Removal)

Aluminum, bronze, and teflon are known to be incompatible, at least with the waste in Tank 101-SY. The existence of an exothermic chemical reaction between aluminum material and the waste has been observed. The reactions can produce large quantities of flammable and toxic gas, and heat. This material must not be used inside the waste tank. Inadvertent placement of this material in the waste tank environment presents itself as one of the more logical sources of an accident initiator. Use of this material in the drill-string column could lead to rapid chemical reaction.

All that is required for this accident to occur during the core-sampling phase is for the sampler seal to leak waste into the drill string. Personnel exposure to this hazard occurs when the drill string is opened to add a section. At this point, the pressure balance across the seal provided by the nitrogen gas has been removed, and the string is at atmospheric pressure. This allows the waste to rise up into the column. When the waste encounters incompatible aluminum material, an exothermic reaction occurs.

To mitigate this hazard, the materials used in the FG/RMCS and drill string were chosen to be compatible with the contents of the tank so that neither chemical action nor materials failure is expected as a result of expected or accidental contact with the waste. WHC performed compatibility study on seal components as well as for the drill bit using an ammonia-saturated environment. Additionally, these materials have been used in actual waste. No significant degradation was observed. Study results summarized in Ref. 13 confirm these observations.

Using aluminum tools around the open risers could have a potential for a drop accident. Administrative controls and work plans must be enforced to ensure that personnel near an open riser do not use waste incompatible tools.

To minimize the potential for exothermic chemical reaction, aluminum pans and containers shall not be used in contact with significant quantities of tank waste.

The drilling truck has some aluminum parts around the rotating platform. However, the tank waste is not normally handled above these parts.

A review of the compatibility of aluminum with the tank gases has been conducted and determined to be without detrimental effect and is therefore not considered further.[17]

Based on Ref. 14, pipe compounds, lubricants and tapes in contact with the DS or tank waste that contain spark-inducing or waste-incompatible materials shall not be used.

**4.4.3. Crust Burn Due to Drop Impact (Installation, Operation, Removal)**

In this section, the drop of the drill string or tools on the crust or waste surface is analyzed. The frictional spark aspect of this accident has already been discussed. In this section, crust reaction and the possibility of waste ignition are discussed. The drill string impact is a bounding impact accident.

Appendix G assesses the possibility of crust ignition and propagation following a drop of the drill string. Based on the analysis summarized in Appendix G, the maximum crust temperature produced by impact is 126°C, which is much less than the limit of 160°C given in Section 4.4.1.1 for preventing local exothermic reactions. Therefore, no local exothermic reactions are expected.

It is concluded that with the limited energy input possible and with the crust-burning characteristics, propagation is impossible.

#### 4.4.4. Flammable-Gas Ignition Under The Waste Surface Caused By Friction From The Rotation Or Penetration Of The Drill Bit (Operation)

One of the safety concerns of sampling with the rotary-mode drill in flammable gas tanks is the ignition of the flammable gas in the waste by the frictional sparks created by the drill bit. The condition of waste in terms of hardness is not known before the operation. A possibility of penetrating a very hard waste layer in a tank exists. In addition, there may be some metal debris lost or dropped from the riser in the past. Hard materials such as rocks or metals can also exist in the waste. Thus, it is likely that the drill bit may strike against metal and other hard objects during drilling.

Ignition caused by frictional sparks is evaluated by performing ignition testing in bounding conditions. Appendix T discusses the ignition testing requirements and acceptance criteria. The objective of the tests is to demonstrate that the operation of rotary core drilling in a bounding frictional environment with bounding gas composition does not cause an ignition. Testing is being performed by the WHC and BOM personnel.

The conditional frequencies of a fire accident resulting from exceeding the rotational speed and down force are estimated as 1.4E-5 and 9.4E-5/yr as indicated in Table 4.12. Controls are established to trip the drilling operation when the rotational speed and down force exceed 55 rpm and 750 lbf. There is no delay time for the trip except the delay time from the data acquisition system. If needed, the alarm points will be set at lower values. However, drilling must stop when the trip value is reached. The FG/RMCS operations must use only the drill-bit type tested according to the requirements listed in Appendix T.

Some of the early tests performed at the BOM showed some interesting results. First series of tests were conducted at a down force of 1360 lbf and rotational speed of 65 rpm. Frictional tests performed with metal objects did not ignite the hydrogen-oxygen mixture. An ignition was observed while testing an experimental bit which had carbon steel pins embedded in the tooth region against rocks. No ignition was observed using a bit where the carbon steel pins were not in the tooth region. The tooth region is defined as the material beneath the carbon steel blank. Therefore, this SA requires that no spark-inducing materials be located in the tooth region. Because the drill bit base also is made of carbon steel, an additional control requires that the drill bit must be replaced if drilling is shutdown four times consecutively as a result of low penetration rate, and if the cumulative penetration is <0.3 in. for the last three attempts (subject to confirmation by BOM testing).

During frictional ignition tests using the current bit with assorted rocks and with a test period of 3 minutes, no ignition was observed. The last test was run to failure. Ignition occurred in the hydrogen-oxygen mixture within the sixth minute. It was postulated that the ignition occurred because the autoignition temperature at the teeth surface was reached. The test was repeated and ignition was observed at

almost the same time. The bit teeth were not worn significantly to cause the carbon steel blank to be exposed to the rock. Additional tests without flammable gas were performed to determine the interface temperature. In one of the tests, a thermocouple was placed 1/8 in. beneath the assorted rock. The rock was not worn significantly therefore the temperature just beneath the rock could be measured. The rock temperature 1/8 in. beneath the surface was 236 °C 6 minutes in testing. An infrared temperature probe was also use to determine the teeth surface temperature. Four minutes into the test, temperatures up to 400 °C were observed. These tests indicate that the autoignition temperature would be reached between 4 and 6 minutes.

The analytical and experimental program described in Appendix T will provide the data to verify that the ignition observed in these tests was indeed caused by the interface temperature reaching the autoignition temperature.

A penetration control is established in order not to operate in the frictional mode of cutting that results from worn teeth. However, this control is established for the substrate temperature to be within the limits. In order to cause a hot spot on a substrate, the penetration rate control must be violated. Appendix F shows that with reasonable penetration, the substrate temperature is less than 160°C. Appendix F also concludes that as long as a nitrogen purge flow of 30 scfm is provided, down force is less than 750 lbf, or rotational speed is less than 55 rpm, the substrate temperature does not increase above 160°C. Therefore, to reach a autoignition temperature of hydrogen nitrous oxide ammonia mixtures, a triple failure needs to be obtained; penetration rate and purge flow; penetration rate and force; or penetration rate and rotational speed (see Table 4-13). However, these results must be verified by using rocks in the envelope testing discussed in Appendix F.

**TABLE 4-13**
**FLAMMABLE-GAS IGNITION UNDER THE WASTE SURFACE CAUSED BY FRICTION FROM THE ROTATION OF THE DRILL BIT**

| Accident | Frequency of failure 1/year | Dominant Failures | Controls Credited in Calculating UAF and MAF Values |
|---|---|---|---|
| Drill bit hits a rock and spark leads to ignition of flammable gas and consequently waste fire. | Without BOM data:<br>MAF=6.6E-7<br>UAF=0.2<br><br>With BOM Data<br>MAF and UAF <1.0E-6 | Contact rocks in the waste.<br><br>Penetration rate detector fails | Auto trip on slow penetration rate and a loss of or low $N_2$ drill string purge gas flow. |

### 4.4.5. Summary of Waste Fire Accidents

The waste fire accidents considered various initiators. The overheating of waste or drill-bit and the ignition of flammable gas by friction that could be created by drilling are the dominant initiators. Experiments are being conducted to define safe operating parameters at which these two initiators could not cause ignition. The critical operating parameters are down force, rotational speed, nitrogen purge flow, and penetration rate. Failure to control these parameters could result in dome collapse. The total accident frequency is found to be 2.3E-4/yr.

The analysis of the waste ignition did not account for the probability of encountering a waste layer where the burn propagation is expected. The proportion of the reactive waste in each SST is considered in Appendix G. As shown in Appendix G, only some tanks satisfy the low fraction of reactive waste criterion. The accident frequency for these tanks become less than 1.0E-6/yr.

## 4.5. CHEMICAL REACTIONS AND CRITICALITY ACCIDENTS

### 4.5.1. Criticality Caused by Drilling (Operation And Removal)

The criticality issues associated with the FG/RMCS operations are addressed in Appendix R. The analysis given in Appendix R concludes that nuclear criticality within the single-shell flammable gas tanks could not occur as a result of FG/RMCS.

### 4.5.2. Water Addition And Temperature Limits (Operation, Removal)

These accidents address the possibility of excessive water additions to the tank that would cause the level to rise above what is allowed by safety controls. It also addresses the effect of the water addition on the waste temperature and gas releases. In the limit, flooding could result from the release of tank materials into the environment caused by hydrostatic failure of the tank. Flooding from natural events is considered in Section 4.9.

Also, water addition can have several effects: (1) changes of the waste temperature, (2) release of gases, (3) changes in pH level, and an increase in radiolysis activity. Appendix O discusses the effect of water additions. It is concluded that, if done within the specified limits, water addition does not cause a safety concern.

### 4.5.3. Waste Ignition And Melting (Operation)

Waste ignition as a result of exothermic chemical reactions is discussed in the waste fire accident category. In this section, the waste melting hazard is addressed. The estimation of the melting temperature of waste depends upon the waste composition. A mixture of sodium nitrate, sodium nitrite, and sodium acetate melts at 175°C (Ref. 18). In addition to these components, the waste contains sodium hydroxide, sodium aluminate, sodium carbonate, sodium sulfate, sodium phosphate, and a host of minor components. Adding additional salts lowers the melting point. Therefore, the melting point of waste is expected to be much lower than the 175°C observed for mixtures of sodium nitrate, sodium nitrite, and sodium acetate. The maximum allowable drill-bit temperature is 160°C, which is probably

above the melting point of the waste. Thus, waste melting may occur during drilling.

One consequence of melting could be a gas release, but it is not expected that the gas release will be significant. At worst, the FG/RMCS perturbs the temperature in the neighborhood of the drill bit. Thus, the affected volume is small. Much larger gas releases are considered in the consequence analysis.

Melting has been proposed as a necessary precursor to runaway exothermic reactions. Melting would cause different chemical components to be brought into contact with each other. Although melting may be necessary for a runaway reaction, it is not the only consideration. Appendix G discusses the temperature limit to prevent runaway exothermic reactions based on experiments conducted on simulants, real wastes, and waste surrogates. These experiments already include the melting phenomenon. Therefore, melting as an initiator of runaway reactions is not considered as a separate hazard.

The drill bit holes can become totally or partially plugged during drilling. Such a scenario could cause overheating of the drill bit, resulting in waste ignition. Envelope testing discussed in Appendix F includes testing with plugged holes. It is demonstrated that the plugging would not cause overheating within the bounds of the operating parameters controlled in Section 6 of this SA.

#### 4.5.4. Energy Addition to the Tank (Operation)

As discussed in Appendix O, energy additions or nitrogen cooling during FG/RMCS operations do not cause a safety concern, provided the operations are performed within the specified limits.

#### 4.5.5. Impact Sensitive Compounds

The presence of impact sensitive explosive materials was evaluated by Martin[19] and Beitel.[20] It was concluded that impact-sensitive compounds are not considered to be credible initiators for chemical reactions.

### 4.6. CONTAINMENT BREACH ACCIDENTS

A loss of confinement of the toxic and radioactive waste from a structural failure of the tank liner is an important safety issue. Installation, removal, and/or decontamination operations potentially constitute hazards to the structural integrity of the tank. The following subsections discuss the assessment made of these situations.

#### 4.6.1. Excessive Static and Dynamic Tank Dome Loading (Installation, Operation and Removal)

Appendix N examines static and dynamic dome loading and its consequences. The static load capacity of the tank dome is monitored carefully, and an overload state that could precipitate a structural failure must be avoided. The equipment required

on the surface of the tank to support FG/RMCS sampling operations qualifies as a live load (see Appendix N). The tank loads study permits a 50-ton live load on the tank dome. Even though the weight of all FG/RMCS equipment exceeds 50 tons, not all of the equipment is placed on the tank dome at one time. Therefore, the dome loading must be controlled by the dome loading limits for SSTs as specified in OSD-T-151-00013 (Ref. 21).

The dome would be subjected to dynamic dome loads if a truck were to fall from the hydraulic jack or from a platform. Appendix N considers this scenario and analyzes the consequences of the dynamic loading caused by dropping the truck. It is concluded that the dome could withstand the impact force of the 30,000-lb truck dropping on it from the 3-ft-high platform.

Excessive vacuum in the dome is another accident identified as a result of exhauster operations. The exhauster design prevents the occurrence of excessive vacuum because the shutoff head is 14 in. w.g. A dome collapse would not occur until -15 in. w.g. Also, the inlet high-efficiency particulate air (HEPA) filter has a vacuum breaker to prevent excessive negative tank pressure. The vacuum breaker is set at about -4 in. w.g.

#### 4.6.2. Penetration of Tank Bottom, Drill String Drop, and Drilling against the Liner (Installation, Operation and Removal)

The drill string is restrained from falling and impacting the tank bottom by the pneumatic foot clamp. After numerous sections of the drill string have been added, the suspended weight could cause the drill string to fall if the clamp is released because the force of gravity exceeds the frictional forces of the frisbee. Initially, the frictional force developed at the riser seal interface exceeds the string weight. The frictional force is produced by the rubber seal that girths the outside diameter of the drill string. This constant force eventually is overcome by the column weight as the drill rods are added. The drill string extending nominally halfway into the tank poses the largest hazard to the integrity of the tank bottom from an impact. The impact force that would occur if the drill string were released was evaluated.[22]

Appendix N includes a ballistic impact analysis for different drop heights. The resulting stress level is expected to challenge the ultimate strength of the liner material despite the inherent ability of the carbon-steel liner to withstand higher stresses under high strain rate conditions. Because this accident can lead to a breach of the waste confinement, it is a major concern and must be avoided through the application of administrative controls. The very low expected accident frequency associated with this drop significantly ameliorates the hazards. This mitigating consideration is discussed next.

The pneumatic foot clamp provides a positive grip around the string due to gravity and interference fit. Even when deenergized, the clamp provides positive restraint to prevent the string from falling. Although gravity and the interference fit prevent the string from falling under gravity, it does not preclude upward motion. Several

events must occur for the drill string to fall and impact the tank bottom. Appendix E determines that the frequency of a DS drop impacting the tank bottom is 7.0E-5/yr. The consequence of this drop of the drill string is damage to the bottom liner resulting in a radioactive liquid release into the ground.

Sampling near the bottom of the tank introduces the possibility of contacting the tank bottom. Precautions are taken in setting up the drill string simply by recording the string depth during installation. Nonetheless, in the rotary-mode sampling method, the drill string can produce an axial force of 750 lb. The force produced on the drill string by hydraulic action neither causes the drill string to penetrate the tank liner nor threatens the tank's structural integrity in any way. The drill string is a very long, slender column when fully extended to the tank bottom. This column buckles at a load less than the ram capacity force of 5370 lb. As an added protective feature, the FG/RMCS incorporates a bottom-contact sensor that reverses the hydraulic ram pressure used in the drill string operation. The pressure reversal causes the sampling operation to cease and pulls the drill bit away from the tank bottom.

Because the axial forces that can be produced by the FG/RMCS during sampling are significant, contacting the tank liner may pose an unacceptable risk to the tank's structural integrity. Therefore, a control is established not to drill closer than 3 in. from the tank bottom (see Appendix N for the basis of this control). Note that the failure probability of the walkdown and force plus the hydraulic bottom detector protection systems to detect the bottom are low and are estimated as 7.0E-5/activity.

#### 4.6.3. Failure of the Drill String (Installation, Operation, and Removal)

The failure of the drill string during drilling is evaluated as a fire hazard. A torque and axial load are applied to the drill string during drilling. Buckling of the drill string from the application of axial force and torque as well as excitation of the drill string with natural frequency could yield drill string failure. The down force is limited to prevent drill bit overheating. The other limit on the down force should be based on the buckling limit. Appendix N discusses the structural buckling limit under various boundary conditions. The buckling limits as a function of the drill string length are given in Fig. N-1 of Appendix N.

Appendix N concludes that the drill string could not be excited with natural frequency as a result of torque only. Figure N-4 of Appendix N plots the first and second mode-resonance rotational speed as a function of the drill string length. The suggested range of rotational speeds are tabulated in Table N-2.

When the drill string length is less than 45 ft, down force must be limited to 750 lbf and rotational speed is limited to 55 rpm. When the drill strength length is > 45 ft, administrative controls shall be established to limit the speed to 40 rpm, and down force to a maximum of 650 lbf.

Buckling loads and rotational speed to prevent resonance are established as required controls in Section 6. The frequency of the exceeding force limits is 9.4E-5/yr (Appendix E). The consequences of drill string breakage are several. The major concern is to cause a hot spot resulting in a fire in the dome (assumes that a failure occurs in the dome space and coincides with the existence of flammable gases). In Section 4.2.1, the fire accident caused by the drill string breakage was discussed. The other concern is the operational difficulty of removing the broken drill string. This SA does not address the removal of damaged drill strings.

#### 4.6.4. Riser Damage (Installation, Operation and Removal)

The risers in the SSTs, although differing in diameter and overall length, share common support features. Each riser is anchored into the concrete tank dome with horizontal studs. The risers are not welded to the primary tank liner because the primary liner does not cover the tank dome. Failure of these studs conceivably would result in the riser being driven into the tank space. This prospect is an unlikely event for small-diameter risers.

Riser loads have been investigated by Miller.[23] The stress produced in the riser from this impact is directly proportional to the square root of the falling body's kinetic energy, the material modules of elasticity, and is inversely proportional to the riser volume. Thus, stress buildup in the riser pipe is not only influenced by the riser cross-sectional area but also by pipe length.

The drill string is to be placed on and removed from the riser during installation, operation, and removal activities. The new drill rods are lifted manually and threaded to the drill string. Even if they are dropped, their weight is only about 7 lb. An analysis of the drop height performed by Miller shows that a maximum height exists that depends upon the mass of the object to be dropped. The analysis further indicates that the scaling of the mass is a linear function of the ratio of the masses. Miller calculated 1.7 in drop height to fail the studs if an object with 363 kg (800 lb) is dropped. Using this information and the weight of a drill string, the scaling ratio is 800/7, or 114.3. The maximum lift height associated with a drill rod is 5.0 m (16.4 ft). This height is larger than the distance between the rotary platform and the riser. Considering all of the arguments above, riser damage from a drill-rod drop is not expected.

During operation, the drill string rotates in the conductive sleeve installed in the riser. Because the riser would be subjected to lateral loading, excessive stresses could be introduced on the riser's lower lip, upper flange, the drill string, or to the conductive sleeve, causing either or both to fail. Lateral loads can result from many factors, including misalignment or excessive lateral movement of the drill string, wasteberg impact on the submerged portion of the drill string, or attempts to remove a bent drill string. The failure of the riser lower lip has no consequence other than a possible sparking source as it plastically deforms from the load application, while failure of the upper flange results in a breach of confinement from an inability to properly close the riser. The failure of the drill string has other

consequences, including portions of the unit falling into the tank or deformation of the drill string so that it cannot easily be removed from the riser. Removal of a stuck drill string is not in the scope of this SA. Dropping of a broken drill string could only occur when the drill string is submerged into the waste. There are controls on the downward load requiring it to be less than the buckling limit. If the control is violated and this results in a failure, the drill string would not sink because the high load would not cause penetration. Therefore, the only consequence from this type of event is that the riser could become unusable and need to be sealed.

During operation, the hydraulic capacity of the drill head and shielded receiver can also apply a vertical load to the foot clamp and the riser when the foot clamp is closed. This sequence can result in riser damage, such that the riser may become unusable and need to be sealed.

Riser damage is a more likely event in the preinstallation phase. In this phase, the vehicles are positioned on the tank top and could inadvertently run into the riser, resulting in damage to the riser. This type of accident is considered as an industrial accident, and standard WHC controls prevent this accident.

Riser damage resulting in ignition of flammable gas is prevented by cessation of all activities upon receipt of a flammable gas alarm.

Heavy equipment, such as casks, exhauster skids, etc., are positioned on the tank top using cranes. Failure of the cranes during the positioning would cause riser damage. WHC safe practice standards provide the necessary protection for the proper handling of components.

#### 4.6.5. Tank Wall Penetration (Operation)

A tank-wall penetration accident addresses the cases in which the drill string could damage the vertical section of the tank liner. This accident is considered to be incredible. Appendix N presents a calculation to estimate the bounding horizontal load to break the drill string at the riser. It was found that the drill string could be broken if a 610 lbf is applied. The deflection of the drill string is estimated as 5.7 in. Thus, before the drill string reaches the tank wall it should be broken already. When the drill string is broken, the debris would not cause a threat to the side wall because the waste in single-shell, flammable-gas tanks is very viscous. Both the consequences and the frequency of this accident are bounded by the bottom penetration accidents.

## 4.7. GAS RELEASES WITHOUT BURN

### 4.7.1. Toxic-Gas Releases (Installation, Operation, Removal)

The toxic gases of interest are ammonia and nitrous oxide. The consequences of toxic-gas releases are divided into anticipated, unlikely, and very unlikely bins and are discussed in Section 5 of this SA.

### 4.7.2. Unfiltered Releases

The consequences of unfiltered waste releases associated with the gas-release events also are discussed in Section 5 of this SA. The consequences are analyzed in anticipated, unlikely, and very unlikely accident bins, consistent with the toxic-gas release accidents.

### 4.7.3. Steam Release and Moisture Removal From Tank (Operation)

Mass removal by evaporation caused by drill bit heating and by ventilation operations are discussed in Appendix O. Water can also be evaporated as a result of an energy release by local exothermic reactions. However, operating parameters prevent the drill bit temperature being close to the critical reaction temperature. The analysis shows that water removal during FG/RMCS operations is not a safety concern.

### 4.7.4. Undetected Gas Release (Operation)

In this accident, the concern is an undetected release path at the top of the tank. The consequences of this accident may be a fire as considered in the above tank fire accident category. Toxic-gas releases are bounded by the releases from the riser.

### 4.7.5. Nitrogen Additions (Installation, Operation, Removal)

Nitrogen gas is added to the tank during the normal FG/RMCS operation. Nitrogen is added to waste at the rate of 0.3 to 100 scfm. Nitrogen addition to the waste is discussed in Appendix M. Although very unlikely, a nitrogen addition may cause a gas-release event. The exhauster must be operable during drilling.

## 4.8. SPILLS, RELEASES, AND HAZARDOUS MATERIAL AND RADIATION EXPOSURES

Because the tank waste contains toxic, radioactive, and hazardous materials, it is possible that workers or the environment could be exposed to harmful levels of hazardous materials.

It is possible that personnel could be exposed to toxic or hazardous materials in activities that require handling potentially contaminated components. This accident scenario does not consider exposures associated with a GRE or with fires, both of which have been discussed. The subject of this section is the potential for exposure associated with contaminated components and equipment and aerosol releases from spills.

**4.8.1. HEPA Releases as a Result of Excessive Loading and HEPA Failures (Operation and Removal).**

Appendix R evaluates the HEPA particulate loading based on results reported by Francis.[24] The total mass from out of the riser and to the HEPA filter is reported as 901 g, a value based on continuous operation of the exhauster, total drilling depth of 266 in., and a schedule of 40 min of drilling (19 in.) followed by a 60 min delay before starting the next drilling period. The results take into account settling of the aerosol created.

If the HEPA filters fail, it is assumed a 1% release as given by Voice[25] who gave some experimental values for the release fractions of blowout incidents. The experimental estimated values are smaller than 1%. The release from HEPA would be less than 9 gr.

Differential pressures across the HEPA filters are measured. Failure to detect high HEPA loading and failure to shut down the exhauster may result in HEPA failure. The frequency of this accident is estimated as 1.6E-5/yr. (Appendix E, Table 4-14).

**4.8.2. Exhauster Continuous Release after Filter Failure (Operation, Removal)**

This accident is considered in the unfiltered release accidents in Section 4.7.2. addresses the failure of HEPA filters following a continuous release with a flow rate of 250 scfm.

**4.8.3. Inlet Duct Failure (Operation, Removal)**

This accident addresses the release of aerosol from the riser where the breathing HEPA filter is installed. It is assumed that a HEPA filter fails, and a GRE occurs. The consequence of this accident is bounded by the gas releases from an open riser as discussed in Section 4.7.1.

**4.8.4. Releases from Core Sampler Drops (Operation)**

This accident addresses the releases to the atmosphere if the failed sampler (ball valve is open) is dropped from the shielded receiver. The maximum amount of waste in one sampler is 0.39 kg. A conservative airborne release fraction of 2E-4 is used (Appendix S). The aerosol release is 0.08 g for this accident. A control is established to inspect the sampler during sampler retrieval. The ball valve cannot be closed if the sampler is not inserted completely in the shielded receiver when held by the RLU.

The frequency of an accident depends upon the failure rate of the rotary ball valve and the probability of a drop or inadvertent opening of the ball valve. The frequency of this accident is determined as 8.6E-9/yr (Appendix E) as shown in Table 4.14. There are two administrative controls that are credited in obtaining this frequency.

## TABLE 4-14
## SPILL ACCIDENTS CONTROLS

| Accident | Frequency of failure 1/year | Dominant Failures | Controls Credited in Calculating UAF and MAF Values |
|---|---|---|---|
| Radioactive aerosols are released from the HEPA filter blowout. | MAF = 1.6E-5 (not a dome fire)<br>UAF = 1.6E-5 | Excessive differential pressure | No controls credited. |
| Spill results from dropped sampler in shielded receiver.<br>(Similar accidents are spills from drops of sampler in X-ray machine or in cask but they are of lower frequency.) | MAF = 8.6E-9 (not a dome fire)<br>UAF = 0.02 | RLU drops sampler.<br>Sampler rotary valve fails given drop of sampler.<br>Ball valve in shielded receiver is inadvertently left open. | Controls over operation of RLU are used.<br>Control to close ball valve in shielded receiver is used. |
| Waste from contaminated drill string interior is released aboveground. | MAF = 6.2E-7 (not a dome fire)<br>UAF = 2 | $N_2$ hydrostatic systems fail to both drill string and shielded receiver.<br>Contamination is not detected during removal of drill string sections. | Leak test $N_2$ hydrostatic systems for both drill string and for shielded receiver is used.<br>Unique connections for $N_2$ hydrostatic systems for both drill string and shielded receiver are used.<br>Verification of $N_2$ hydrostatic supply to both drill string and shielded receiver during activation of hydrostatic mode of $N_2$ supply is done.<br>Monitoring for radioactive contamination during removal of drill string sections is done. |
| Waste from contaminated drill string exterior is released aboveground. | MAF = 4.4E-6 (not a dome fire)<br>UAF = 2.0 | Wash of drill string exterior surface is ineffective before removal of drill string.<br>Contamination is not detected during removal of drill string sections. | A water wash of the drill string exterior surface is done before removal of drill string.<br>Monitoring is done for radioactive contamination during removal of drill string sections. |

minutes of time because it is based on an average mass flow rate. Controls are established to survey the radiation level from HEPA filter housing each shift during waste-intrusive operations.

4.8.8.2. **Radiation doses from the shielded receiver.** Appendix R represents the radiation calculation from a full sample when it is in the shielded receiver (SR). The bounding value of exposure calculated is 211 mrem/h at 1 cm from the surface of the receiver. It would be expected that there would be no samples that would actually produce this value because the samples would contain liquid that has a lower source strength. In addition, the source strength used here is the maximum found in any waste sample.

Administrative controls are established to survey radiation levels from the SR per WHC procedures.

4.8.8.3. **Radiation From the X-ray Machine.** The requirements for operating the X-ray machine are explained in the document entitled "Requirements for Mobile Core Sample X-Ray Systems Number 2, 3, and 4" that the WHC provided.[26] Some of the safety requirements for shielding are listed below (taken from the reference). Radiation Shielding and Safety Requirements satisfy all the safety requirements dictated in American National Standards Institute (ANSI) N43.3, 21, CFR Section 1020, Chapter 246-243 WAC.[27]

The maximum allowable dose rate at any accessible area 5 cm from the outside surface of the enclosure must not exceed 0.5 mrem/h. This is demonstrated or measured using calibrated equipment before final acceptance of the system. Particular attention is placed on the dose rate at the Kamlok® adapter coupling. The rest of the safety requirements are available in the above-mentioned document.

4.8.8.4. **Excessive Radiation Exposure as a Result of Personnel Being in a Direct Line of Sight to the Tank Waste (Installation and Removal).** Ionizing radiation from inside the tank caused by radioactive waste produces a nearly constant radiation field when viewed from an open riser. The maximum radiation field at the throat of an open 4-in. riser has been determined to be in excess of WHC limits for areas not considered to be high in radiation. Controls are required to ensure that workers do not receive excessive exposure during installation and removal, during which a direct line of sight to the tank wastes is possible. Because the FG/RMCS essentially fills the riser, there is little chance for workers to be exposed to a direct line of sight during operation. Only through the failure of workers to follow procedures limiting the exposure or through improper development of work plans can workers be exposed to excessive levels of waste on the FG/RMCS if the decontamination system is not effective. This issue is discussed in the next section.

4.8.8.5. **Excessive Personnel Radiation Exposure during FG/RMCS Decontamination.** The FG/RMCS may be contaminated by tank waste during removal or operation phases. The amount of waste on the FG/RMCS can increase

**4.8.5. Open Sampler-Spills (Operation)**
The concern is the spill of 0.39 kg of waste from the core sampler. For this to occur, the rotary ball valve needs to fail with the inadvertent opening of the shielded receiver valve. The release fraction is estimated as 2.0E-4 (Appendix S), and the release to the atmosphere would be 0.08 gr. The frequency of this accident is the same as for the previous accident and is estimated as 8.6E-9/yr (Appendix E).

**4.8.6. Spill from Accumulated Waste in Core Barrel**
If waste collects inside the core barrel or drill rods, handling could cause a release. The decontamination system would not be helpful because water is injected outside of the drill string. Even though accumulated waste may be discovered by radiological monitoring, this would only aid workers in preparing to catch the spill that could follow removal. This release would be a spill. Considering that the length of the core barrel is 1.1 m (40 in.), and the diameter is 5.08 cm (2 in. i.d.), there could be 3.3 kg (7.3 lbm) of waste. The release fraction is recommended as 2.0E-4 (Appendix S). Thus, the material release would be 0.66 gr.

The frequency of this accident is dominated by failure of the nitrogen hydrostatic system and failure to detect contamination as indicated in Table 4.14. The frequency of spill is estimated as 6.2E-7/yr.

**4.8.7. Ineffective Decontamination and Drop of Drill String**
If decontamination is not effective and cannot be made effective, some spilling of contamination from the drill rod could be expected. The quantity of material on the exterior of the drill string can be no more than 0.37 kg assuming a 3-mm waste film on a drill rod. The frequency of spill is calculated by considering a failure to detect the contamination and an ineffective wash as indicated in Table 4.14. A spill of the maximum quantity of material assumes no provisions to catch and contain the spill once the failed decontamination system is discovered. For conservatism, the spill quantity is assumed to be the maximum possible, however. The frequency of the ineffective decontamination and drop is estimated as 4.4E-6/yr. A release fraction of 2.0E-4 (Appendix S) gives 0.75 gm of waste to be released.

**4.8.8. Radiation Exposures (Installation, Operation, Removal)**
It is possible for personnel to be exposed to excessive levels of radiation in association with proposed operations for the FG/RMCS. Several accidents are posed and discussed below. It is important to remember, however, that the exposure calculations are performed using the bounding nuclide inventory for all the SSTs (see Appendix R). Thus, such high exposure levels are not expected in any given SST.

**4.8.8.1. Exposures from HEPA filters.** Appendix R represents a calculation for possible radiation doses from HEPA filters. Using the code MicroShield (Appendix R), a filter geometry of 24 in. x 24 in. x 11.5 in. containing $SiO_2$ at a density of 0.1 $g/cm^3$, it is found that the exposure at 1 cm from the surface is 317 mrem/h at the end of 100 minutes of operation. This exposure may be scaled with units of 100

the radiation caused by tank shine. Workers are required to aid in the assessment of decontamination effectiveness during removal actions. Therefore, workers could be exposed to the combined fields of tank waste on the drill string and tank shine.

A hand-held radiation monitor is used by radiological health technicians to ensure that radiation levels are acceptable for unrestricted work. Protective equipment and other work limitations (such as work duration) are specified by tank radiological and industrial health authorities, according to established procedures. All open-riser work requires respiratory protection, as indicated in Section 6 of this SA.

The likelihood that workers could be exposed to this high level of radiation depends on whether the decontamination system and handling procedures are effective. WHC has experience with other similar activities,[28, 29] and what can be expected for the FG/RMCS should not result in increased personnel risk. In general, the water decontamination method is successful in removing hazardous levels of waste from the exterior surfaces of components, particularly if the components are designed to facilitate decontamination, as in the FG/RMCS.

In summary, workers could be exposed to high levels of radiation; however, this is a very unlikely occurrence because the controls are strictly enforced and monitored, and workers are highly trained in both radiation protection techniques and the types of exposure possible at the tank farm.

## 4.9. EXTERNAL EVENTS

In this section, the accidents associated with external events are evaluated. It is concluded that the risk associated with lightning, wind, fire, earthquake, tornado, flood, volcanoes, and dust devils are acceptable as long as the activities are performed in accordance with the available administrative controls. Before and periodically during FG/RMCS operations, at the discretion of the person in charge (PIC), external event status shall be verified with meteorological stations or appropriate authorities. WHC is required to identify an acceptable meteorological station and acceptable verification authority.

### 4.9.1. Lightning

The Hanford Site is not a major thunderstorm area. On average, only ~10 thunderstorm days per year are recorded at the Hanford Site, although this number has varied from a low of 3 to a high of 23 thunderstorm days per year. Thunderstorms theoretically can occur during any month of the year; however, they occur most frequently from April through September. The largest number of thunderstorm days recorded in a single month is eight, a number of days that has occurred in both June and August. Large differences in electric potential can occur during thunderstorms, which in turn can lead to lightning strikes. In general, ~20% of lightning strikes are cloud-to-ground/ground-to-cloud discharges. Lightning

strikes in the summer occasionally have ignited range fires in the Hanford Site region.

A lightning strike could initiate a hydrogen burn during FG/RMCS operations. Lightning is a generic source for all the fire accident categories analyzed in this section. Lightning strikes are discussed in this section only, and this section will be referred to when discussing the same issue in other parts of Section 4.

Lightning hazards have been extensively treated by Cowley.[30] For background and detailed treatment, the reader is referred to this reference. Relevant features of that analysis that are pertinent to the FG/RMCS operations are discussed below.

- Lightning strikes at Hanford have a frequency of 1 per $km^2/yr$.
- A rough rule of thumb is that a grounded vertical rod attracts any lightning that would have struck the ground in a circle around the rod with a radius equal to the height of the rod.

Conclusions from the analysis are

- Where the object struck is not directly attached to a tank riser, the lightning could not be an ignition source for flammable-gas mixtures in the tank.
- Strikes to control panels/enclosures, power lines, backup supplies, structures, and ventilation systems result in accident situations that are insignificant, covered by interim operational safety requirements, or analyzed in the interim safety basis (ISB).
- Strikes to tank risers or equipment attached to tank risers require further study, which is the subject of the Umman report, (Appendix A of Ref. 30).

Umman says that the structure of an SST, the large quantity of rebar in the concrete, and the fact that the tank is buried gives an SST some of the properties of a Faraday cage. However, the lack of a complete steel inner liner makes the SST less effective than a double-shell tank (DST) as a Faraday cage. Construction drawings do not indicate that any effort was made during construction to make electrical connections between the risers on the SSTs and the rebar in the concrete. Therefore, there are electrically noncontinuous paths through the tank that can result in arcing. The paths are:

- Arcing between inadequately bonded equipment extending through risers and the risers.
- Arcing between the riser or equipment and the rebar in the concrete dome.
- Arcing between an equipment item and the waste surface.

- Arcing at bolted flanges.
- Ohmic heating of the waste by conduction of a current into the waste by an equipment item such as a thermocouple (TC) tree.

In his report, Cowley assumes that any lightning strike on a riser or riser-mounted equipment will have enough energy to ignite a flammable mixture. To minimize the probability of a lightning strike, all FG/RMCS equipment (including the drill string) must be bonded to the riser or inserted into the tank, and must be grounded, using existing or an alternate grounding methods consistent with the principals outlined in Cowley's report (Ref. 30). WHC must develop, revise, and implement appropriate grounding/bonding procedures. Equipment not attached to the riser or inserted into the tank must be grounded following adequate WHC grounding and bonding controls consistent with the NFPA requirements.

Lightning could strike the exhauster or any other auxiliary system or drill truck during a thunderstorm. This cannot be prevented. Therefore, no FG/RMCS waste-intrusive activities can proceed during thunderstorms, or when thunderstorm activity or lightning strikes are reported or predicted within a 50 mile radius. This reduces the likelihood that drilling would cause flammable-gas conditions in the dome when there is a high probability of a lightning strike. The drill string could be left in the riser for different reasons. When it needs to be left in the riser, and the truck is not manned, the drill string needs to comply with the grounding requirements developed by WHC.

Grounding systems, and bonding needs to be verified as being adequate before initiation of operations. If the strike occurs, a fire is assumed to result. Assumptions and event trees in estimating the frequency of fire accidents caused by lightning are given in Appendix E.

The low probability of a lightning strike during a GRE and during FG/RMCS operations combine to make a lightning-induced burn frequency beyond extremely unlikely.

#### 4.9.2. Wind

At the Hanford Site, the severe-weather phenomenon that occurs most frequently and has the greatest impact is dust storms (Ref. 31). The maximum recorded peak gust at 15.24 m (50 ft) above the ground was 35.8 m/s (80 mi/h), which occurred in January 1972. A 100-yr return period peak gust of 38.4 m/s (86 mi/h) has been calculated at the 15.24-m (50-ft) elevation.

Procedures governing FG/RMCS operations constrain operations to be performed only when the sustained wind velocity is less than 11.1 m/s (25 mi/h). This limit reduces the risk of wind-caused accidents.

### 4.9.3. Fire

The tank farm area has been subject to range fires in the past. Procedures governing FG/RMCS operations involving installation, operation, and removal prevents operations if a range fire is within 8.0 km (5 mi) of the tank being sampled. The FG/RMCS operation may be terminated very quickly once a fire is detected within an 8-km (5-mi) radius. In addition, procedures require limitations on flammable material in the vicinity of the tank, and fire extinguishers need be on hand before beginning installation or removal operations.

### 4.9.4. Earthquake

An earthquake occurring during FG/RMCS installation and removal operations does not change the risk assessed in this SA significantly because the operation period of FG/RMCS is short. The low probability of a large earthquake occurring during FG/RMCS installation, operation, and removal operations is acceptable risk, and accidents that could result as a consequence of this initiator are not considered in this report.

The design-basis earthquake has a return period of 7500 yr (frequency > 1 x $10^{-4}$/yr). SSTs are designed to withstand a 0.2-g zero-period acceleration (ZPA), but there is a high probability that a stronger earthquake with a magnitude exceeding 0.2 g may produce structural failure of the dome.

### 4.9.5. Tornado

Tornadoes are very rare in the vicinity of the Pasco Basin and, on average, the state of Washington experiences just over one tornado each year. As specified by Ref. 32, and "Design and Evaluation Guidelines for Department of Energy Facilities Subjected to Natural Phenomena Hazards"[33] are used for natural phenomena loadings for nonreactor facilities. This document states that tornadoes are not considered a viable threat or hazard at the Hanford Site and are eliminated as an external initiating event. Nevertheless, in Section 6 of the SA, a control restricts FG/RMCS activities when tornado activity has been predicted within the next 8 hours within a 50 mile radius.

### 4.9.6. Flood and High Rainfall

Reference 33 describes probable maximum flooding of the 200-West Area—streams, rivers, surge and seiche flooding, flooding from ice dams, tsunamis, and flooding from dam failures. The worst-case flood was found to be caused by a hypothetical catastrophic failure of the Grand Coulee Dam. In this case, it was concluded that the floodwaters (elevation ~140.2 m (460 ft) would be well below the elevation of the 200-West Area [elevation ~213.4 m (700 ft)]. Thus, flooding was eliminated as an external initiating event.

### 4.9.7. Volcanism

Volcanic hazards of the 200-West Area were examined in Ref. 33. In this report, it is stated that there is no evidence of lava flows, ash flows, or mudflows from Cascade Range volcanoes having reached the Pasco Basin during the Quaternary period.

The nearest Cascade Range volcano is more than 96.5 km (60 mi) from the Hanford Site. With the exception of mudflows and airborne ejecta, most eruption products remain within 48.3 km (30 mi) of Cascade volcanoes. At increasing distances from the eruptive vent, flows of lava, debris, and mud tend to become more confined to existing drainage channels. Because no streams flow directly from the Cascade Range volcanoes to the Hanford Site, this type of volcanic product is not considered likely at Hanford.

A volcanic ashfall event is considered to be a potential natural phenomenon occurrence at the Hanford Site. The design criterion for ashfall loading on Hanford Safety Class I (SC I) structures, systems, and components is an uncompacted ashfall of 11.4 cm (4.5 in.). This ashfall should cause no undue additional loadings on critical structures.

The low probability of a volcanic event, combined with the minor consequences of an ashfall, are not considered to pose a significant hazard to the proposed operations. The installation and removal procedures contains a requirement to suspend operations in the event of volcanic activity that could lead to an ashfall.

### 4.9.8. Dust Devils

A dust devil is a localized wind pattern that moves in a circular motion which spawns and decays quickly and travels at relatively low velocities. Dust devils occur frequently in the Hanford Site areas during the daytime in the summer months. Wind speeds are believed to be in the low tens of miles per hour. The major concerns related to dust devils entering the site are (1) the effects on lifting of the equipment, (2) control of contaminants during installation and removal, and (3) the effect on personnel around an open riser from contaminant dispersal. It is difficult to predict the effect of a dust devil moving over the open riser because the dust devil wind speeds are unknown and because of the variety of operations being performed. To prevent adverse effects from dust devils, FG/RMCS activities shall be suspended at the discretion of the PIC when there is observable dust devil activity.

## 4.10. REFERENCES

1. A. D. Swain, "Accident Sequence Evaluation Program Human Reliability Analysis Procedure," US Nuclear Regulatory Commission report NUREG-CR-4772 (February 1987).

2. J. Robinson, "Description of Conductive Flexible Hose for Exhauster," Westinghouse Hanford Company letter to J. Darby (January 31, 1996).

3. "Standard Reliability Data," IEEE Standard 500, Published by the Institute of Electrical and Electronics Engineering, Inc. (1984).

4. J. E. Rasmussen, "Approval Requested for New Potential-to-Emit for the Rotary Mode Core-Sampling System Exhauster," Westinghouse Hanford Company letter (enclosure WHC Environmental Compliance Document, WHC-CM-7-5, Rev. 1) to Mr. A. W. Conklin and Mr. Jerry Leitch (December 1995)

5. Air Movement and Control Association, Standard 99-0401-86 (1986).

6. R. N. Johnson "Sparking Potential of Aluminum vs. Aluminum," Pacific Northwest National Laboratory letter to J. Robinson (February 10, 1996).

7. J. Smalley, Westinghouse Hanford Company, "Design Review Meeting for Purge Gas System," Purge Gas Pneumatic Diagram, H-2-690009 (December 1995).

8. J. C. Krok and J. E. Shepherd, "Electrical and Frictional Spark Ignition of $N_2O$-$H_2$-$N_2$-Air Mixture," Los Alamos National Laboratory report LANL-WT-800 (June 1993).

9. C. Unal, "Burn in the Shielded Receiver," Los Alamos National Laboratory Calc-Note TSA10-CN-WT-SA-TH-099 (January 1996).

10. J. Smalley, Westinghouse Hanford Company personal communication, (November 1995).

11. R. A. Huckfeldt, "NFPA Barriers," Westinghouse Hanford Company internal memorandum 75230-96-006, to D. Hamilton, Characterization Equipment Design Project (February 27, 1996).

12. R. M. Marusich, "Safety Assessment for Push-Mode Core Sampling in Tank 101-SY," Westinghouse Hanford Company report WHC-SA-WM-SAD-008, Rev. 0-A (May 10, 1991).

13. A. J. Kostelnik, "Rotary Mode Core Sample Truck Material and Component Compatibility with Tank Waste," letter (attachment Westinghouse Hanford Company internal memo, 75230-96-001 R2) to Dennis Hamilton (February 5, 1996).

14. L. F. Ermold, "Actions in Response to Spark Reported During Work on Tank 241-U-109," Westinghouse Hanford Company letter WHC-9650352, (enclosure WHC Occurrence Report, RL-WHC-TANKFARM-1996-0009) to S. Burnam (January 23, 1996).

15. H. Sullivan, et al., "A Safety Assessment for Proposed Pump Mixing Operations to Mitigate Episodic Gas Releases in Tank 242-SY-101," Los Alamos National Laboratory report LA-UR-92-3196, Rev. 14 (1995).

16. J. F. McCormick, "Test Report For Drill String Seal Pressure Test," WHC-SD-WM-TRP-DRAFT, Rev. 0 (January 1996).

17. C. Shepard and L. Pederson, "Reaction of Aluminum with Gases Released by Wastes in Tank 101-SY," Los Alamos National Laboratory memorandum LANL-WT-1152, to Troy Stokes (April 11, 1994).

18. D. Scheele, R. Shell, J. Sobolik, and L. Burger, "Organic Tank Safety Project: Preliminary Results of Energetics and Thermal Behavior Studies of Model Organic Nitrate and/or Nitrite Mixtures and a Simulated Organic Waste," Pacific Northwest National Laboratory report PNL-10213 (August 1995).

19. E. C. Martin, "Complexant Stability Investigation Task 2-Organic Complexants," Pacific Northwest National Laboratory report PNL-5453 (1985).

20. G. A. Beitel, "Exothermic Potential of Sodium Nitrate Salt Cake," Atlantic Richfield Hanford Company report ARH-LD-163 (1977).

21. V. C. Boyles, "Operating Specifications for Single-Shell Waste Storage Tanks," Westinghouse Hanford Company report OSD-T-151-00013, Rev. D-4 (1994).

22. W. O. Miller, "Retained Gas Sampler Drill String Drop Analysis," Los Alamos National Laboratory Calc-Note TSA-6-CN-WT-SA-075 (November 30, 1994).

23. W. O. Miller, "Riser Impact Loads," Los Alamos National Laboratory Calc-Note TSA6-CN-WT-SA-ST-063 (March 1994).

24. P. M. Francis, "Aerosol Study for the Rotary Mode Exhauster," Westinghouse Hanford Company report WHC-SD-WM-ES-225, Rev. 0 (1993).

25. J. D. Voice, "Tank Farm Accelerated Safety Analysis; Tank Ventilation System," Westinghouse Hanford Company report WHC-SD-WM-SARR-018, Rev. 0 (June 29, 1994).

26. "General Safety Standard for (ANSI NBS 114) Installations Using Non-Medical X-ray and Sealed Gamma-Ray Sources, Energies up to 10 MeV," ANSI N43.3 (American National Standards Institute, Inc., New York, 1993).

27. "Section Performance Standard for 1020-1991 Ionizing Radiation Emitting Products," Code of Federal Regulations (CFR), 21 CFR

28. Westinghouse Hanford Company report WHC-SD-WM-HSP-022, Rev. 0A (April 12, 1993).

29. "Hanford Site Tank Farm Facilities Interim Safety Basis," Westinghouse Hanford Company report WHC-SD-WM-ISB-001, Rev. 0 (August 1, 1993).

30. W. L. Cowley, "Evaluation of Hazards From Lightning Strikes to Tank Farm Facilities," Westinghouse Hanford Company report WHC-SD-WM-SARR-027, Rev. 0 (June 29, 1994).

31. D. I. Herborn, et al., "Hanford Waste Vitrification Plant Preliminary Safety Analysis Report," Westinghouse Hanford Company report WHC-EP-0250, Rev. 0 (May 1991).

32. "General Design Criteria," US Department of Energy Order 6430.1A (1989).

33. Kennedy, et al., "Design and Evaluation Guidelines for Department of Energy Facilities Subjected to Natural Phenomena Hazards," Department of Energy report UCRL-15910 (1990).

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Title/Desc:
A SAFETY ASSESSMENT OF ROTARY MODE CORE SAMPLING IN FLAMMABLE GAS SST HANFORD SITE RICHLAND WA [SEC 2 OF 3 PAGE 5-1 TO H-4]

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**Document number:** SD-WM-SAD-035

**Section** 2 **of** 3

**Title:** A Safety Assessment of Rotary Mode Core Sampling in Flammable Gas Single Shell Tanks; Hanford Site, Richland, Washington

**Date:** 4/15/96 **Revision:** 0

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# 5.0. CONSEQUENCES OF ACCIDENTS

In this section, the consequences of accidents are discussed for the installation, operation, and removal of rotary-mode core sampling (RMCS) equipment in single-shell tanks (SSTs) on the Flammable Gas Watch List (FGWL) or those tanks recommended by the contractor to be included on the FGWL, hence referred to as FG/RMCS operations. Section 5.1 presents the Risk Guidelines (RGs). Section 5.2 contains a summary of bounding accidents identified in Section 4. In Sections 5.3 through 5.5 the bounding consequences of different accidents are quantified. The consequences are then compared with the RGs in Section 5.6.

Long-term radiological and toxicological consequences of material releases into the soil are not quantified in this safety assessment (SA). Accidents that may lead to a containment breach and to a release of material into the soil are identified and discussed in Section 4. The mitigative features of such accidents also are included in the discussion provided in Section 4. Environmental risk associated with the rotary mode core sampling operations in flammable tanks (FG/RMCS) is not further discussed in this section.

## 5.1. Risk Guidelines

This section defines the RGs used for comparing the consequences of the accidents analyzed in this SA. These criteria are divided into two major areas: radiological committed effective dose equivalent (CEDE) and toxic material exposure.

### 5.1.1. Radiological Risk Criteria

The RGs used in this SA for radiological consequences are obtained from Ref. 1. Ref. 1 requires that the radiological RGs contained in Revision 3 of Ref. 2 be used. Revision 4 of Ref. 2 recommends a less conservative set of radiological RGs. Presently, Department of Energy, Richland (DOE-RL) has not made a ruling on the set of radiological RGs that must be used in this SA. Thus, the more conservative set proposed in Ref. 1 and in Revision 3 of Ref. 2 were used. This choice is primarily predicated on the fact that the use of the more conservative set prevents a major reanalysis if DOE-RL chooses to implement the more restrictive guidelines contained in Ref. 2. If the alternative radiological RGs are implemented by DOE-RL, the findings of this SA would be bounding and an SA revision will not be necessary.

To use the RGs, a frequency and consequence for the particular accident must be analyzed. The best estimates of the frequencies are given in Section 4, and the basis of the frequencies is discussed in Appendixes D, E and L. The present analysis was performed using conservative modeling assumptions, and the conservative consequences have been judged using best estimates for the frequencies. Ref. 1 provides the frequency-dependent, radiological dose limits shown in Table 5-1a. Also, Ref. 1 specifies that if a specific single-point frequency is used, the guidelines are to be applied as curves. However, if a qualitative frequency ranking is used, the

corresponding consequence limit (in rem) must be used equal to the lowest value for that frequency range.

The less restrictive alternative guidelines contained in Ref. 2 are shown in Table 5-1b for comparison purposes. Note that the guidelines in Ref. 2 are to be applied as a step-function.

### 5.1.2. Toxicological Risk Guidelines

Toxicological acceptance criteria have been developed from the guidelines presented in Ref. 2. In the referenced material, the onsite and offsite concentration limits are given in terms of Emergency Response Planning Guidelines (ERPGs) and Permissible Exposure Limit—Time-Weighted Average (PEL-TWA). The toxicological RGs are summarized in Table 5-2.

ERPG-1 is the maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to 1 h without experiencing anything other than mild transient adverse health effects or perceiving a clearly defined objectionable odor.

ERPG-2 is the maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to 1 h without experiencing or developing irreversible or other serious health effects or symptoms that could impair an individual's ability to take protective action.

**TABLE 5-1a**
**RADIOLOGICAL RISK GUIDELINES (REF. 1)**

| Frequency Category | Frequency Range ($yr^{-1}$) | On-site CEDE (rems) | Off-site CEDE (rems) |
|---|---|---|---|
| Anticipated | $10^{-1}$ to $10^{-2}$ | 1 to 5 | NA |
| Anticipated | 1 to $10^{-2}$ | NA | 0.01 to 0.5 |
| Unlikely | $10^{-2}$ to $10^{-4}$ | 5 to 25 | 0.5 to 4 |
| Extremely Unlikely | $10^{-4}$ to $10^{-6}$ | 25 to 100 | 4 to 25 |

**TABLE 5-1b**
**RADIOLOGICAL RISK GUIDELINES (REF. 2)**

| Frequency Category | Frequency Range ($yr^{-1}$) | On-site EDE * (rems) | Off-site EDE (rems) |
|---|---|---|---|
| Anticipated[a] | 1.0 to $10^{-2}$ | 5 | 0.5 |
| Unlikely | $10^{-2}$ to $10^{-4}$ | 25 | 5 |
| Extremely Unlikely | $10^{-4}$ to $10^{-6}$ | 100 | 25 |

* EDE: effective dose equivalent

TABLE 5-2
TOXICOLOGICAL RISK GUIDELINES

| Frequency Category | Frequency Range ($yr^{-1}$) | On-site Limit | Off-site Limit |
|---|---|---|---|
| Anticipated | 1 to $10^{-2}$ | ≤ ERPG-1 | PEL-TWA |
| Unlikely | $10^{-2}$ to $10^{-4}$ | ≤ ERPG-2 | ≤ ERPG-1 |
| Extremely Unlikely | $10^{-4}$ to $10^{-6}$ | ≤ ERPG-3 | ≤ ERPG-2 |

ERPG-3 is the maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to 1 h without experiencing or developing life-threatening effects.

When specific values for PEL-TWA and ERPGs are not available, alternative concentration guidelines also are included in Ref. 2.

Based on Ref. 2, these guidelines are applied using a step-function within the specified frequency range. In this SA, the following RGs are used:

Ammonia: Ammonia ($NH_3$) is a corrosive or irritant and it is known to exist in large quantities in the waste gas.

Nitrous Oxide: Nitrous oxide ($N_2O$) is a central nervous system depressant, and it is known to exist in large quantities in the waste gas.

Waste Material: The human reception of solid/liquid waste material results in systemic toxicity and corrosive effects. Various accidents analyzed in this SA (unfiltered releases, burns, spills, etc.) result in a wide range of waste release quantities. Note that all the releases that result in radiological consequences also yield toxicological consequences as a result of an exposure to the same material.

The results of the vapor space sampling program were reviewed.[3] Major toxic gases that are found in the dome space of the presently defined flammable-gas tanks are ammonia and nitrous oxide. Other gases are found in trace quantities and do not pose a concern. However, it was recognized that the data contained in Ref. 3 are limited, and all tanks of interest are not covered. Consequently, the toxic gas evaluation was made a checklist item (Section 7). Thus, it is required that the potential for toxic gases other than ammonia and nitrous oxide must be re-evaluated before FG/RMCS operations may be initiated in a specific tank.

Also, combustion products were not considered in this SA. Major combustion products that must be considered for their toxic effects are nitrogen oxides ($NO_x$). As

discussed in Ref. 4, large quantities of $NO_x$ may be produced if a large volume of waste gases is burned. However, such a large burn in the single-shell tanks (SSTs) also result in releases of large quantities of waste material (see the dome collapse accidents). Under these circumstances, the contribution of the $NO_x$ releases to the total toxic consequences of a burn is very small and well within the uncertainties of the toxicological consequence calculations.

Table 5-3 provides the PEL and ERPG values for the toxic gases considered in this SA. To determine the acceptance limits for liquid/solid waste material, Westinghouse Hanford Company (WHC) uses different types of composite waste for different tank grouping.[5] The risk associated with waste releases is divided into three categories: particulate, toxic effects and corrosive effects. The chemical species in the composite waste is divided into toxic and corrosive bins. Within each bin, the allowable releases are computed using the "sum of the fractions" methodology. The minimum among the three categories (particulate, toxic, corrosive) is chosen in each frequency range. For further details of the methodology used in determining the maximum acceptable waste releases, the readers are referred to Ref. 5. The

**TABLE 5-3**
**ESTABLISHED RISK GUIDELINES FOR SPECIFIC GASES**

| Species | PEL-TWA | ERPG-1 | ERPG-2 | ERPG-3 |
|---|---|---|---|---|
| $NH_3$ | 17 mg/m$^3$ (25 ppm) | 17 mg/m$^3$ (25 ppm) | 140 mg/m$^3$ (200 ppm) | 680 mg/m$^3$ (1000 ppm) |
| $N_2O$ | 90 mg/m$^3$ (50 ppm) | 270 mg/m$^3$ (150 ppm) | 18,000 mg/m$^3$ (10,000 ppm) | 36,000 mg/m$^3$ (20,000 ppm) |

**TABLE 5-4**
**MAXIMUM ACCEPTABLE WASTE MATERIAL RELEASES[6]**

| | SST LIQUID RELEASES | | | |
|---|---|---|---|---|
| | ONSITE | | OFFSITE | |
| Freq. ($yr^{-1}$) | Puff (L) | Continuous (L/s) | Puff (L) | Continuous (L/s) |
| $10^{-2}$ - 1 | $3.57 \times 10^{-4}$ | $1.04 \times 10^{-4}$ | $7.69 \times 10^{+1}$ | $1.85 \times 10^{-1}$ |
| $10^{-2}$ - $10^{-4}$ | $4.55 \times 10^{-3}$ | $1.33 \times 10^{-3}$ | $7.69 \times 10^{+1}$ | $1.85 \times 10^{-1}$ |
| $10^{-4}$ - $10^{-6}$ | $1.75 \times 10^{-2}$ | $5.00 \times 10^{-3}$ | $1.01 \times 10^{+2}$ | $2.38 \times 10^{+0}$ |
| | SST SOLID RELEASES | | | |
| $10^{-2}$ - 1 | $9.09 \times 10^{-5}$ | $2.56 \times 10^{-5}$ | $6.67 \times 10^{+0}$ | $1.59 \times 10^{-2}$ |
| $10^{-2}$ - $10^{-4}$ | $1.67 \times 10^{-4}$ | $5.00 \times 10^{-4}$ | $1.92 \times 10^{+1}$ | $4.55 \times 10^{-2}$ |
| $10^{-4}$ - $10^{-6}$ | $3.45 \times 10^{-3}$ | $1.02 \times 10^{-3}$ | $3.70 \times 10^{+1}$ | $9.09 \times 10^{-2}$ |

resulting maximum acceptable releases for SST liquid and solid releases are shown in Table 5-4. Note that the values reported in Table 5-4 represent the release quantities at the source because the atmospheric dispersion coefficients already are accounted for in deriving these magnitudes.

## 5.2. Accident Consequences

The accidents for the FG/RMCS operations identified in Section 3 are analyzed in Section 4. The radiological and toxicological consequences of these accidents are analyzed in this section. Not all the accidents have unique consequences; the bounding consequences for all the burn accidents are analyzed as a dome collapse. Section 4.4 discusses that the waste burn resulting in a dome collapse is highly unlikely given the controls introduced by this SA. Consequences of a local waste burn are not currently analyzed and assumed to be bounded by a dome collapse. Table 5-5 summarizes how the accidents analyzed in Section 4 are mapped into the consequence analysis contained in this section.

Accidents resulting in environmental contamination are identified in Section 4. However, long-term radiological and toxicological consequences of environmental contamination are not analyzed in this SA.

In Section 5.6. all the consequences are summarized and graphically compared with the RGs.

## 5.3. Consequences of Dome Collapse Accidents

In SSTs, burn accidents result in unacceptable consequences because even a small pressurization in the dome may result in dome failure potentially followed by a catastrophic collapse. Because of large radiological and toxicological consequences (especially onsite) of a dome collapse accident, one must demonstrate that such accidents have a frequency of less than $10^{-6}$/yr. However, burn accidents are not the only accidents that may result in dome failure.

The design basis earthquake (DBE) has a return period of 7500 yr (frequency > $1 \times 10^{-4}$/yr). SSTs are designed to withstand a 0.20-g zero-period acceleration (ZPA). Because they are independent of the RMCS activities, structural consequences of seismic events are not analyzed in this SA.

The frequency of the dome collapse as a result of dome space deflagration is obtained by summing the frequency of the first 3 accident categories shown in Table 5-5. Thus, the unmitigated accident frequency for the dome collapse during FG/RMCS operations is > 1.0E-4/yr/tank.

Taking credit of the controls discussed in Section 4 and listed in Section 6, the frequency of the dome collapse accident (denoted as mitigated frequency) is lowered to less than 2.5 E-7/ yr/tank.

TABLE 5-5
SUMMARY OF CONSEQUENCE ANALYSIS

| Accident Category | Bounding Consequence | Frequency | Radiological Consequences | Toxicological Consequences |
|---|---|---|---|---|
| Above Ground Fires (Sec. 4.1) | Dome Collapse (Sec. 5.3) | MAF = 2.4E-07<br>UAF = 1.8E-04 | Sec. 5.3.1. | Sec. 5.3.2. |
| Dome Fires (Sec. 4.2.) | Dome Collapse (Sec. 5.3) | MAF = 3.9E-10<br>UAF = 2.8E-07 | Sec. 5.3.1. | Sec. 5.3.2. |
| Drill String Fires (Sec. 4.3.) | Dome Collapse (Sec. 5.3) | MAF = 1.3E-8<br>UAF = 6.6E-4 | Sec. 5.3.1. | Sec. 5.3.2. |
| Waste Fires (Sec. 4.4.) | Dome Collapse (Sec. 5.3) | MAF < 1.0E-06<br>UAF ~ 3.7 | Sec. 5.3.1. | Sec. 5.3.2. |
| Chemical Reactions (Sec. 4.5.) | Environmental Contamination | NA | NA | NA |
| Containment Breach (Sec. 4.6.) | Environmental Contamination | NA | NA | NA |
| GRE (no burn) (Sec. 4.7) | Toxic Gas Release (Sec. 5.4.1.) | Qualitative | Sec. 5.4.1.2 | Sec. 5.4.1.1 |
| | Unfiltered Material Release (Sec. 5.4.2.) | Qualitative | Sec. 5.4.2.1. | Sec. 5.4.2.2 |
| Spills, etc (Sec. 4.8). | HEPA Blowout (Sec. 5.5) | MAF = 1.6E-5<br>UAF = 6.0E-3 | Sec. 5.5.1 | Sec. 5.5.2 |
| | Sampler Drop (Sec. 5.5) | MAF = 8.6E-9<br>UAF = 2.9E-6 | Sec. 5.5.1 | Sec. 5.5.2 |
| | Core barrel drop (Sec. 5.5) | MAF = 6.2E-7<br>UAF = 2.0 | Sec. 5.5.1 | Sec. 5.5.2 |
| | Drill String Drop (Sec. 5.5) | MAF = 4.4E-6<br>UAF = 2.0 | Sec. 5.5.1 | Sec. 5.5.2 |
| External Events (sec. 4.9) | Seismic Induced Dome Collapse (Sec. 5.3) | 1.0E-04 | Sec. 5.3.1. | Sec. 5.3.2. |

MAF = Mitigated accident frequency
UAF = Unmitigated accident frequency
HEPA= High-efficiency particulate air (filter)

The material releases as a result of dome collapse are discussed in Appendix I. Based on the calculations provided in Appendix I, the conservative amount of prompt respirable material release during a dome collapse in an SST is obtained as 62.5 L. The long-term respirable release from the crater left after the dome collapse is obtained as 12.5 L/wk.

### 5.3.1. Radiological Consequences

Appendix R provides the on-site and off-site receptor doses for a 1 L release for solid and liquid waste. Because the surface of the SST waste may be quite dry and the solid waste may result in larger doses than the liquid waste, it is assumed that all the

short-term and long-term releases correspond to solid waste. Using the unit doses provided in Appendix R, the on-site and off-site radiological doses are obtained as shown in Table 5-6. As shown in Table 5-6, the long term doses are much lower than the prompt doses and are well within the uncertainty of the prompt doses. Also shown in Table 5-6 are the doses corresponding to RGs. Note that assuming that a fraction of the release is liquid lowers the doses.

TABLE 5-6
BOUNDING RADIOLOGICAL CONSEQUENCES OF
DOME COLLAPSE ACCIDENT

| | | Receptor Dose (rem) |
|---|---|---|
| ONSITE | Prompt | 17250 |
| | Long-Term 1 wk | 193 |
| OFFSITE | Prompt | 9.3 |
| | Long-Term 1 wk | 0.1 |

**5.3.2. Toxicological Consequences**
The toxicological consequences of waste and toxic gas releases are discussed below.

**5.3.2.1. Waste Material.** For waste material, the release volume of 62.5 L must be compared with the puff release limits given in Table 5-4. The long term release of 12.5 L/wk ($2 \times 10^{-5}$ L/s) may be compared to continuous release limits given in Table 5-4. The prompt release volume (if assumed to be solid waste) exceeds the offsite RGs even for a very unlikely accident.

**5.3.2.2. Toxic Gases.** The toxic gases of interest (ammonia and nitrous oxide) are flammable. Thus, they will be totally or partially consumed during the burn event and the consequences of toxic gas releases during a burn are bounded by the consequences of a gas-release event (GRE) without a burn (Section 5.4.1.). As discussed previously, the combustion products are not considered.

## 5.4. GRE without a Burn

A large gas release event that pressurizes the dome space is of concern because of the potential toxic gas and unfiltered material releases.

**5.4.1. Toxic-Gas Releases.**
This section considers the release of toxic gases (ammonia and nitrous oxide) through the open risers, frisbee, and the exhaust and inlet stacks.

As bounding magnitudes, the maximum ammonia fraction in the waste gas is set to 60%, and the maximum nitrous oxide fraction in the waste gas is set to 75% (Appendix C). Only the toxicological consequences of ammonia are discussed in this section because if ammonia releases meet the RGs, the nitrous oxide releases also

will meet the RGs. While the maximum nitrous oxide fraction is 125% of the ammonia fraction, the guidelines for nitrous oxide are always more than twice the ammonia guidelines for all the accident frequencies (see Table 5-3).

The peak ammonia concentrations in the dome are provided in frequency bins in Appendix L. In this section, the peak concentration as well as the release rate are needed. For the purpose of this consequence assessment, the total release volume of waste gas is obtained by multiplying the peak concentration by the dome volume at a given frequency bin. The results are shown in Table 5-7. The toxicological guidelines are given in terms of 1-h average values (Section 5.1.2.). For added conservatism, the total release is postulated to occur in less than 15 minutes, and the average release rate is obtained by dividing the volumes shown in Table 5-7 by 15 minutes. The release to the atmosphere is assumed to occur at this release rate with the peak ammonia concentration. This simplification is conservative because the expected gas-release rates are much lower than the magnitudes obtained by this simple approach (see Appendix L). If the actual release is faster than 15 min. (which is very unlikely based on the discussion in Appendix L), the proposed approach still yields the correct time-averaged release rate over a 15-min. period.

**TABLE 5-7**
**ANTICIPATED AND UNLIKELY GAS-RELEASE EVENTS**

| Event Probability | Q-Prompt Release, ($ft^3$) | Peak $NH_3$ Conc. (%) |
|---|---|---|
| ≥1.0 E-2 | ≤1000 | 1.2 |
| ≥1.0 E-4 | ≤ 5000 | 6 |
| ≥1.0 E-6 | ≤ 10,000 | 12 |

The dome peak ammonia and nitrous oxide concentrations then become 1.2%, 6%, and 12% for the anticipated, very unlikely, and extremely unlikely gas-release events. The releases are not expected during installation because the installation is not a waste-intrusive activity. However, gas releases could be induced during the operation or removal phase. Postulated gas releases are listed in Table 5-8. Note that release rates given in Table 5-8 is based on 15-minute average releases.

The first three accidents may occur during removal when the riser is open for a period of much less than 8 hours. The conservative 8-hour open riser period relative to mission time is considered in the frequency determination, resulting in a gas-release probability of 8/144 = 5.6E-2. The third accident will not be considered further because the frequency is low. Accidents 4-6 consider gas releases from the frisbee. The riser sleeve is protected with nitrogen purge. This system prevents any gas penetration between the riser sleeve and the DS. Thus, the gas release from the frisbee could occur only if the nitrogen purge fails. Accidents 5 and 6 are beyond extremely unlikely. Accident scenarios 7 to 9 are gas releases through the drill string. This accident can occur when the drill string is disconnected from the drill unit if the seal between the sampler and drill bit fails or if the sampler fails to latch

before drilling. Accidents 8 and 9 are beyond extremely unlikely. The last 6 accidents considered only the GRE from the exhauster and inlet stack during operations.

TABLE 5-8
SUMMARY OF GAS-RELEASE ACCIDENTS

| Accident Condition | Frequency (yr) | Gas Concentration & Release Rate |
|---|---|---|
| 1-Anticipated-GRE and open riser (removal) | 1.1E-3<br>(0.01x5.6E-2x2) | 1.2% $NH_3$ in the dome,<br>66 scfm* |
| 2-Very unlikely-GRE and open riser (removal) | 1.1E-5<br>(1E-4x5.6E-2x2) | 6% $NH_3$ in the dome,<br>333 scfm* |
| 3-Extremely unlikely-GRE and open riser (removal) | 1.1E-7<br>(1E-6x5.6E-2x2)<br>Beyond extremely unlikely | 12% $NH_3$ in the dome,<br>666 scfm* |
| 4-Anticipated-GRE and open frisbee (operation)(nitrogen purge to riser sleeve fails) | 3.2E-6<br>(2x0.01x1.6E-4) | 1.2% $NH_3$ in the dome,<br>66 scfm* |
| 5-Very unlikely-GRE and open frisbee (operation) (nitrogen purge to riser sleeve fails) | 3.2E-8<br>(2x1.0E-4x1.6E-4)<br>beyond extremely unlikely event | 6% $NH_3$ in the dome,<br>333 scfm* |
| 6-Extremely unlikely-GRE and open frisbee (operation) (nitrogen purge to riser sleeve fails) | 3.2E-10<br>(2x1.0E-6x1.6E-4)<br>beyond extremely unlikely event | 12% $NH_3$ in the dome,<br>666 scfm* |
| 7-Anticipated-GRE and drill string open at the top with sampler in the drill string | 2.6E-5<br>(2x0.01x1.3E-3) | 1.2% $NH_3$ in the dome,<br>66 scfm* |
| 8-Very unlikely-GRE and drill string open at the top with sampler in the drill string | 2.0E-7<br>(2x1.0E-4x1.3E-3)<br>beyond extremely unlikely event | 6% $NH_3$ in the dome,<br>333 scfm* |
| 9-Very unlikely-GRE and drill string open at the top with sampler in the drill string | 2.0E-9<br>(2x1.0E-6x1.3E-3)<br>beyond extremely unlikely event | 12% $NH_3$ in the dome,<br>666 scfm* |
| 10- Anticipated-GRE from exhaust and inlet stack (operation) | 0.02<br>(2x0.01) | 1.2% $NH_3$ in the dome,<br>66 scfm* |

TABLE 5-8
GAS-RELEASE ACCIDENTS (CONT.)

| Accident Condition | Frequency (yr) | Gas Concentration & Release Rate |
|---|---|---|
| 11-Very unlikely-GRE from exhaust and inlet stack (operation) | 2.0E-4 (2x1.0E-4) | 6% $NH_3$ in the dome, 333 scfm* |
| 12-Extremely unlikely-GRE from exhaust and inlet stack (operation) | 2.0E-6 (2x1.0E-6) | 12% $NH_3$ in the dome, 666 scfm* |
| 13-Continuous releases from exhauster after an anticipated-GRE | 0.02 (2x0.01) | 1.2% $NH_3$ in the dome, 250 scfm** |
| 14-Continuous releases from exhauster after an very unlikely-GRE | 2.0E-4 (2x1.0E-4) | 6% $NH_3$ in the dome, 250 scfm** |
| 15-Continuous releases from exhauster after an extremely unlikely-GRE | 2.0E-6 (2x1.0E-6) | 12% $NH_3$ in the dome, 250 scfm** |

* Averaged over 15-minute period
** Maximum exhauster flow rate

**5.4.1.1. Toxicological Consequences.** The toxic-gas concentrations at the on-site and off-site receptor locations are calculated using Eq. (K-2) given in Appendix K. Atmospheric dispersion factors for ground and stack releases are summarized in Table K-3 of Appendix K. Table 5-9 gives the calculated on-site and off-site ammonia concentrations for ground and stack releases. Numbers given in parentheses are acceptable concentrations for ammonia.

In the first nine accidents given in Table 5.8, the GREs are treated as ground releases because they involve an opening at the top of the tank. Note that there are still inlet and exhaust stacks where approximately 2/3 of the release occurs. It is clear from Table 5-9 that the on-site RGs are not exceeded (accidents 1, 2, 4, 7 in Table 5.9) for accidents involving ground releases.

Accidents 10 to 15 do not involve ground releases. For these accidents, the results of both ground or stack releases are given in Table 5.9. Accidents 11, 12, 13, and 14 result in exceeding RGs if they were considered as ground releases. However, the exhauster has a 15-ft height stack with a 4-in. internal diameter. This SA requires the use of an inlet stack with the same exit diameter and height as the exhaust stack. For gas releases of 66, 330, and 250 scfm, the velocity of released gas in these stacks become 3.8 m/s, 19.2 m/s, and 7.3 m/s, respectively. With these velocities and the consideration of the height of the stacks, the plume effective emission height increases as a result of momentum effects. Dispersion coefficients for these conditions are smaller than those given for ground releases, as shown in Appendix K. Consideration of the stack height reduces the on-site concentrations 6 to 7 times. To be conservative, credit is taken only for the height of the stack. A point source at a 15-ft height is considered. With this assumption, the ammonia concentrations at

the on-site and off-site receptor locations meet the RGs as shown in Table 5-9. The consideration of the velocity and diameter of the stack further decreases ammonia concentrations. Furthermore, the flammable-gas monitors will alarm at concentrations much lower than those postulated in these conservative estimates, providing adequate time for workers and nearby individuals to take protective measures. Response procedures for a GRE must be developed, assuming that the release contains a large fraction of ammonia (flammable-gas monitors cannot differentiate between hydrogen and ammonia).

TABLE 5-9
AMMONIA CONCENTRATIONS AT ON-SITE AND OFF-SITE RECEPTORS FOR GROUND AND STACK RELEASES FOR ALL GAS RELEASE ACCIDENTS

| | | Ground Release | | Stack Release | |
|---|---|---|---|---|---|
| Accident | Freq. (1/yr) | Onsite (ppm) | Offsite (ppm) | Onsite (ppm) | Offsite (ppm) |
| 1-Anticipated-GRE and open riser (removal), 1.2% $NH_3$, 66 scfm | 1.1E-3 | 13 (200) | 0.01 (25) | NA | NA |
| 2-Very unlikely-GRE and open riser (removal), 6% $NH_3$, 633 scfm | 1.1E-5 | 324 (1000) | 0.18 (200) | NA | NA |
| 4-Anticipated-GRE and open frisbee (operation) (nitrogen purge to riser sleeve fails), 1.2% $NH_3$, 66 scfm | 3.2E-6 | 13 (1000) | 0.01 (200) | NA | NA |
| 7-Anticipated-GRE and drill string open at the top with sampler in the drill string, 1.2% $NH_3$, 66 scfm | 2.6E-5 | 13 (1000) | 0.01 (200) | NA | NA |
| 10-Anticipated-GRE from exhaust and inlet stack (operation),1.2% $NH_3$, 66 scfm | 0.02 | 13 (25) | 0.01 (25) | 2 (25) | 0.01 (25) |
| 11-Very unlikely-GRE from exhaust and inlet stack (operation), 6% $NH_3$, 333 scfm | 2.0E-4 | 324 (200) | 0.18 (25) | 48 (200) | 0.18 (25) |
| 12-Extremely unlikely-GRE from exhaust and inlet stack (operation), 12% $NH_3$, 666 scfm | 2.0E-6 | 1297 (1000) | 0.72 (200) | 193 (1000) | 0.72 (200) |
| 13-Continuous releases from exhauster after a anticipated-GRE, 1.2% $NH_3$, 250 scfm | 0.02 | 49 (25) | 0.03 (25) | 7 (25) | 0.03 (25) |
| 14-Continuous releases from exhauster after an very unlikely-GRE, 6% $NH_3$, 250 scfm | 2.0E-4 | 244 (200) | 0.13 (25) | 36 (200) | 0.13 (25) |
| 15-Continuous releases from exhauster after an extremely unlikely-GRE, 12% $NH_3$, 250 scfm | 2.0E-6 | 487 (1000) | 0.27 (200) | 72 (1000) | 0.27 (200) |

**5.4.1.2. Radiological Consequences.** The radiological consequences of gas release is a concern when the riser is open. If the release is through HEPA filters, there is no particulate release. Open riser particulate releases are discussed in the next section.

**5.4.2. Unfiltered Material Releases.**
This section discusses the unfiltered waste releases associated with the GREs. Releases from spill accidents are considered in the next section. Unfiltered releases can occur during operation and removal. During installation, a GRE is not expected; thus, only the operation and removal phases involve unfiltered material releases. Accidents for unfiltered releases are listed in Table 5-10. Release amounts are determined in Appendix M.

Appendix M gives the release amounts for unfiltered releases through an open riser. The waste releases from the open riser become 12 g, 60 g, and 120 g for gas release amounts of 1000, 5000, and 10,000 $ft^3$, respectively. Accidents 1 and 2 in Table 5-8 are considered for unfiltered releases through the open riser. The third accident given in Table 5.8 is beyond extremely unlikely. In the fourth scenario, it is conservatively assumed that waste material is released from an opening between the frisbee and the drill string if the nitrogen purge fails, the frisbee fails and a GRE occurs. Credit was not taken for the failure of the frisbee. The frequency includes the failure probability of a nitrogen purge while drilling. Accidents 5 and 6 are not considered for unfiltered releases because they are beyond extremely unlikely events. The seventh scenario addresses a release through the drill string with a failed chevron seal. It is assumed that the internal surfaces of the drill string are contaminated. If there is a 0.5-mm layer inside the surface of the drill string with a maximum length of 395 in., the total waste could be estimated as 1280 g. Assuming a 10% release fraction (because velocities could be high in the drill string), a release amount of 128 g for both anticipated and unlikely GREs can be estimated. Accidents 8 and 9 (Table 5.8) are not considered for unfiltered releases because they are beyond extremely unlikely events. Accidents 10 to 12 given in Table 5.8 do not involve unfiltered releases because they are through HEPA filters. The last scenario involves releases through the exhauster if the HEPA filters fail. The frequency of this accident is 1.6E-5/yr and it is same for anticipated or unlikely GREs. The maximum flow rate is 250 scfm. Based on a dome loading of 950 g, the solid flow rate is 0.08 g/s. These accidents cover the cases 13 to 15 of Table 5.8 with the assumption that the HEPA filter fails.

There is another case in which a GRE during removal with a contaminated drill string occurs. Failure of the decontamination procedures and the seal or the sampler latching is assumed. The frequency of this accident is very small because a contaminated drill string must occur during removal and coincide with a GRE.

A non-GRE unfiltered release occurs if the riser is open and the tank-dome pressure becomes positive. Ventilation system failure combined with open-tank conditions has been identified as one of these conditions. Controls are established to help ensure that this kind of release is minimized. No waste-intrusive activities can be

started if the ventilation system is not working properly. However, the ventilation system can fail during the periods when the riser is open. In comparison to other releases driven by GREs, this release is small, and the frequency of this accident is also small.

TABLE 5-10
UNFILTERED WASTE RELEASE ACCIDENTS

| Accident | Freq. (1/yr) | Release Type |
|---|---|---|
| Anticipated-GRE and open riser (removal) (1)* | 1.1E-3 | 12 g material release |
| Very unlikely-GRE and open riser (removal) (2) | 1.1E-5 | 60 g material release |
| Anticipated-GRE and open frisbee (operation) (nitrogen purge to riser sleeve fails) (4) | 3.2E-6 | 12 g material release |
| Anticipated-GRE and drill string open at the top with sampler in the drill string (7) | 2.6E-5 | 128 g material release |
| Continuous releases from exhauster after a HEPA filter fails (NA) | 1.6E-5 | 0.08 g/s |

* Numbers in parentheses correspond to accident numbers in Table 5-8.

The controls derived from these analyses are as follows:

- Existence of a decontamination system operation and the decontamination of the sleeve and drill string are required when the radiation level exceeds the allowable limits.
- RMCS operations must be shut down if the dome flammable gas concentration is above 5000 ppm hydrogen equivalent. Based on currently available calibration data, this set point gives protection for ammonia concentrations of ~10,000 ppm if the gas is purely ammonia.
- Risers shall not be opened within four hours after drilling.
- The riser shall be open no more than eight hours.
- Evacuation is necessary if a gas release occurs.

**5.4.2.1. Radiological Consequences.** Radiological doses at the onsite and offsite receptor locations are summarized in Table 5-11. All the accidents listed in Table 5.11 meet the radiological on-site and off-site RGs.

TABLE 5-11
RADIATION DOSES AT ON-SITE AND OFF-SITE RECEPTORS FOR GRE ACCIDENTS

| Accident Condition | Frequency (yr) | Onsite (rem) | Offsite (rem) |
|---|---|---|---|
| Anticipated-GRE and open riser (removal), 12 g. (1)* | 1.1E-3 | 2.04 (10) | 0.001 (2) |
| Very unlikely-GRE and open riser (removal), 60 g. (2) | 1.1E-5 | 10.2 (49) | 0.006 (10) |
| Anticipated-GRE and open frisbee (operation) (nitrogen purge to riser sleeve fails), 12 g. (4) | 3.2E-6 | 2.04 (70) | 0.001 (15) |
| Anticipated-GRE and drill string open at the top with sampler in the drill string, 128 g. (7) | 2.6E-5 | 21.8 (38) | 0.012 (10) |
| Continuous releases from exhauster after a HEPA filter fails, 0.08 g/s. (NA) | 1.6E-5 | 12.4 (40) | 0.007 (10) |

* Numbers in parentheses correspond to accident numbers in Table 5-8.

**5.4.2.2. Toxicological Consequences.** The off-site and on-site consequences are measured at the release source. For a GRE and open riser or a GRE and open frisbee the volume release rates are 8.3E-6 L/s for an anticipated GRE and 4.2E-5 L/s for a very unlikely GRE. For an unfiltered release and failed chevron seal, the volume released is 9.0E-5 L/s. HEPA filter failure can cause a release of 0.08 g/s (5E-5 L/s). The waste-release rates are compared with the RGs in Table 5-12.

Toxic waste release rates are based on 15 minute continuous releases. Acceptable release rates at the source are obtained from Table 5-1 and are shown in parentheses in Table 5-12. The consequences meet the on-site and off-site RGs.

## 5.5. Spill Accidents

Spill accidents are summarized in Table 5-13. The frequencies of the second and third accidents in Table 5-13 are small, and these accidents are beyond extremely unlikely events.

### 5.5.1. Radiological Consequences.

The calculated on-site and off-site radiation doses for HEPA filter blowout and waste spill from drill string accidents are given in Table 5-14 with the acceptable dose amounts given in parentheses. HEPA filter blowout does not result in exceeding on-site and off-site RGs. On-site and off-site radiological consequences of spill meet the radiological RGs.

TABLE 5-12
ONSITE AND OFFSITE TOXIC SOLID WASTE RELEASES

| Accident | Freq. (1/yr) | Onsite | Offsite |
|---|---|---|---|
| Anticipated-GRE and open riser (removal), 12 g. (1)* | 1.1E-3 | 8.3E-6 L/s (5E-4 L/s) | 8.3E-6 L/s (4.55E-2 L/s) |
| Very unlikely-GRE and open riser (removal), 60 g. (2) | 1.1E-5 | 4.2E-5 L/s (1.02E-3 L/s) | 4.2E-5 L/s (9.09E-2 L/s) |
| Anticipated-GRE and open frisbee (operation) (nitrogen purge to riser sleeve fails), 12 g. (4) | 3.2E-6 | 8.3E-6 L/s (1.02E-3 L/s) | 8.3E-6 L/s (9.09E-2 L/s) |
| Anticipated-GRE and drill string open at the top with sampler in the drill string, 128 g. (7) | 2.6E-5 | 9E-5 L/s (1.02E-3 L/s) | 9E-5 L/s (9.09E-2 L/s) |
| Continuous releases from exhauster after a HEPA filter fails, 0.08 g/s. (NA) | 1.6E-5 | 5E-5 L/s (1.02E-3 L/s) | 5E-5 L/s (9.09E-2 L/s) |

* Numbers in parentheses correspond to accident numbers in Table 5-8.

TABLE 5-13
SUMMARY OF SPILL ACCIDENTS

| Accident | Frequency (1/yr) | Release (g) |
|---|---|---|
| Radioactive aerosols are released from HEPA filter blowout. | 1.6E-5 | 9 |
| Spill results from dropped sampler in shielded receiver. | 8.6E-9 beyond extremely unlikely | 0.08 |
| Waste from contaminated drill string interior is released above ground. | 6.2E-7 beyond extremely unlikely | 0.66 |
| Waste from contaminated drill string exterior is released above ground. | 4.4E-6 | 0.75 |

### 5.5.2. Toxicological Consequences.

The off-site and on-site consequences are measured at the release source. For the short term release for HEPA failure the volume released is 5.63E-3 L. A spill from drill string yields 4.7E-4 L of material. Release amounts and acceptable release amounts to meet the ERPG values are given in Tables 5.14a. Spill releases meet the off-site RGs. The on-site RGs are exceeded for HEPA filter blowout accidents. However, in deriving allowable limits, the atmospheric dispersion coefficients for ground releases were used.[5]

TABLE 5-14
ONSITE AND OFFSITE RADIOLOGICAL DOSES FOR SPILLS

| Accident | Freq. (1/yr) | On-site Dose (rem) | Off-site Dose (rem) |
|---|---|---|---|
| Radioactive aerosols are released from HEPA filter blowout. | 1.6E-5 | 1.53 (43.4) | 8.3E-4 (2) |
| Waste from a contaminated drill string exterior is released aboveground. | 4.4E-6 | 0.13 (64) | 7.0E-5 (4) |

TABLE 5.14a
ONSITE AND OFFSITE TOXIC SOLID WASTE RELEASES FOR SPILLS

| Accident | Freq. (1/yr) | On-site | Off-site |
|---|---|---|---|
| Radioactive aerosols are released from HEPA filter blowout. | 1.6E-5 | 5.63E-3 L (3.45E-3 L) | 5.63E-3 L (37 L) |
| Waste from contaminated drill string exterior is released aboveground. | 4.4E-6 | 4.7E-4 L (3.45E-3 L) | 4.7E-4 L (37 L) |

HEPA filter blowout would be an elevated release with a factor of 6 reduction in the dispersion coefficient. Thus, the receptor doses will be 1 x $10^{-3}$ L and within the allowable limits.

## 5.6 Comparison of the Accident Consequences with the RGs

Section 5.6 presents the comparison of the consequence calculated in Section 5.5 to the RGs presented in Section 5.1. The comparison is broken into the following sections,

- Section 5.6.1 - Comparison to on-site and off-site radiological dose.
- Section 5.6.2 - Comparison to on-site and off-site toxic gas releases.
- Section 5.6.3 - Comparison to on-site and off-site toxic waste release.

In order to perform the comparison, the frequency of the accidents on a per-year basis must be computed. It is assumed in Section 4 that there will be two FG/RMCS activities per year per tank. The accident frequencies are calculated based on this assumption. The risk computed is on a per-tank basis and is not a site-wide risk, where the site-wide risk is defined as the cumulative risk of FG/RMCS operations over multiple tanks in a given year. The information contained in this SA cannot be easily converted to a site-wide risk because of the following:

- The SA uses bounding tank parameters for a hypothetical worse-case tank;
- The SA uses 95% meteorology data to compute the consequences;

Appendix Q discusses this issue in detail. The discussion in Appendix Q demonstrates that the use of the bounding tank consequences computed in this SA is not adequate to obtain site-wide risk. This approach is expected to grossly overestimate the risk.

On the other hand, this SA should not be interpreted as only being applicable to a single tank in a given year. This SA does not place any restrictions on the number of tanks that can be sampled in a given year, and multiple tanks can be sampled under the present safety basis.

This interpretation is in agreement with the general concept of RGs and the Safety Assessment approach and does not contradict the guidance provided in Ref. 2. However, the guidance provided by Ref. 2 on how to combine the risk from different activities and from different tanks is not very explicit and is subject to interpretation.

### 5.6.1. Accidents with Radiological Consequences

All accidents (except the dome collapse accidents and other accidents which are beyond extremely unlikely events) resulting in radiological consequences are summarized in Table 5-15. Comparison with the on-site and off-site RGs is shown in Figs. 5-1 and 5-2. The numbers next to the data points correspond to the accident numbers given in Table 5.15. As shown in Fig. 5-1 and 5-2, all the conservative doses fall below the RG using best-estimate frequencies.

### 5.6.2. Toxic-Gas Releases

All gas-release accidents (except the accidents which are beyond extremely unlikely events) with toxicological consequences are summarized in Table 5.16. The computed ammonia concentrations shown in Table 5.16 are plotted in Figs. 5.3 and 5.4 in comparison with the RGs. As shown in these figures, all conservatively calculated ammonia concentrations at the on-site and off-site receptor locations fall below the RGs using best-estimate frequencies. This conclusion is valid also for nitrous oxide releases because the calculated bounding nitrous oxide concentrations are slightly higher than the ammonia concentrations shown in these figures, but the RGs for nitrous oxide are much larger.

### 5.6.3. Toxic Liquid/Solid Releases

All of the accidents (except the dome collapse accidents and other accidents which are beyond extremely unlikely events) resulting in material release are listed in Table 5-17. Release rates are given over a 15-minute release period. The first five accidents are continuous releases, and the last two are puff releases. Table 5-17 lists the frequency each of accident and the release rates at the release point.

TABLE 5-15
SUMMARY OF ALL ACCIDENTS RESULTING IN RADIOLOGICAL RELEASES

| Accident Condition | Frequency (yr) | Onsite (rem) | Offsite (rem) |
|---|---|---|---|
| 1-Anticipated-GRE and open riser (removal), 12 g. | 1.1E-3 | 2.04 | 0.001 |
| 2-Very unlikely-GRE and open riser (removal), 60 g. | 1.1E-5 | 10.2 | 0.006 |
| 3-Anticipated-GRE and open frisbee (operation) (nitrogen purge to riser sleeve fails), 12 g. | 3.2E-6 | 2.04 | 0.001 |
| 4-Anticipated-GRE and drill string open at the top with sampler in the drill string, 128 g. | 2.6E-5 | 21.8 | 0.012 |
| 5-Continuous releases from exhauster after a HEPA filter fails, 0.08 g/s. | 1.6E-5 | 12.4 | 0.007 |
| 6-Radioactive aerosols are released from HEPA filter blowout. | 1.6E-5 | 1.53 | 8.3E-4 |
| 7-Waste from the contaminated drill string exterior is released aboveground. | 4.4E-6 | 0.13 | 7.0E-5 |

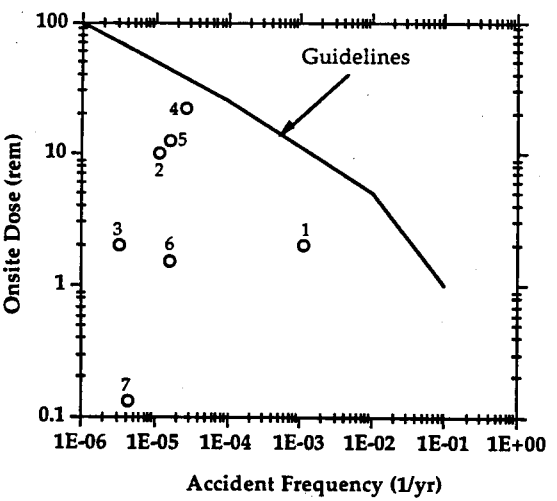


**Fig. 5-1. Comparison of calculated radiological doses with the on-site RGs.**

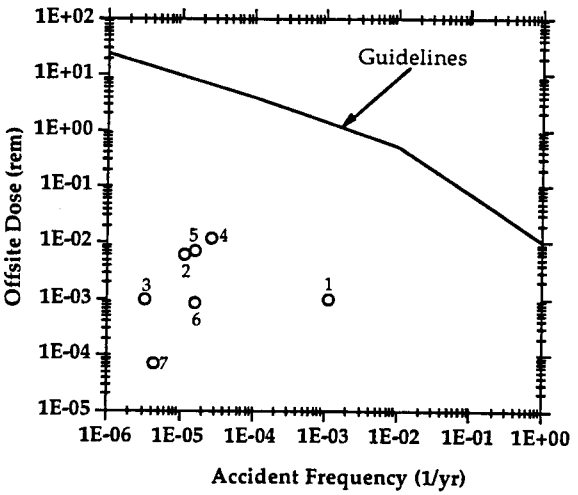


**Fig. 5-2. Comparison of calculated radiological doses with the off-site RGs.**

The computed waste-release rates at the source of releases shown in Table 5-17 are plotted in Figs. 5-5 and 5-6 in comparison with the RGs. The RGs in these figures are given in terms of the release amount or release rate at the release point. As shown in these figures, all the conservative waste release rates at the on-site and off-site receptor locations fall below RGs using best-estimate frequencies, except for Accident 6. Accident 6 is the HEPA failure accident. Total release is estimated as 9 g. The onsite acceptable release amount is 5.5 g. To minimize a significant particulate accumulation at the HEPA filters, a radiation survey control is established. The radiation rate is limited with 100 mrem/h. This rate corresponds to waste amounts much less than 900 g that is assumed to accumulate in the HEPA filters. This control was not credited in obtaining the frequency of 1.6E-5. Furthermore, in deriving allowable limits, the atmospheric dispersion coefficients for ground releases were used.[5] A HEPA filter blowout would be an elevated release with a factor of 6 reduction in the dispersion coefficient. Thus, the receptor doses will be within the allowable limits.

## TABLE 5-16
## SUMMARY OF GAS-RELEASE ACCIDENTS

| Accident | Freq. (1/yr) | Onsite (ppm) | Offsite (ppm) |
|---|---|---|---|
| 1-Anticipated-GRE and open riser (removal), 1.2% $NH_3$, 66 scfm | 1.1E-3 | 13 | 0.01 |
| 2-Very unlikely-GRE and open riser (removal), 6% $NH_3$, 633 scfm | 1.1E-5 | 324 | 0.18 |
| 3-Anticipated-GRE and open frisbee (operation) (nitrogen purge to riser sleeve fails), 1.2% $NH_3$, 66 scfm | 3.2E-6 | 13 | 0.01 |
| 4-Anticipated-GRE and drill string open at the top with sampler in the drill string, 1.2% $NH_3$, 66 scfm | 2.6E-5 | 13 | 0.01 |
| 5-Anticipated-GRE from exhaust and inlet stack (operation),1.2% $NH_3$, 66 scfm | 0.02 | 2 | 0.01 |
| 6-Very unlikely-GRE from exhaust and inlet stack (operation), 6% $NH_3$, 333 scfm | 2.0E-4 | 48 | 0.18 |
| 7-Extremely unlikely-GRE from exhaust and inlet stack (operation), 12% $NH_3$, 666 scfm | 2.0E-6 | 193 | 0.72 |
| 8-Continuous releases from exhauster after a anticipated-GRE, 1.2% $NH_3$, 250 scfm | 0.02 | 7 | 0.03 |
| 9-Continuous releases from exhauster after an very unlikely-GRE, 6% $NH_3$, 250 scfm | 2.0E-4 | 36 | 0.13 |
| 10-Continuous releases from exhauster after an extremely unlikely-GRE, 12% $NH_3$, 250 scfm | 2.0E-6 | 72 | 0.27 |

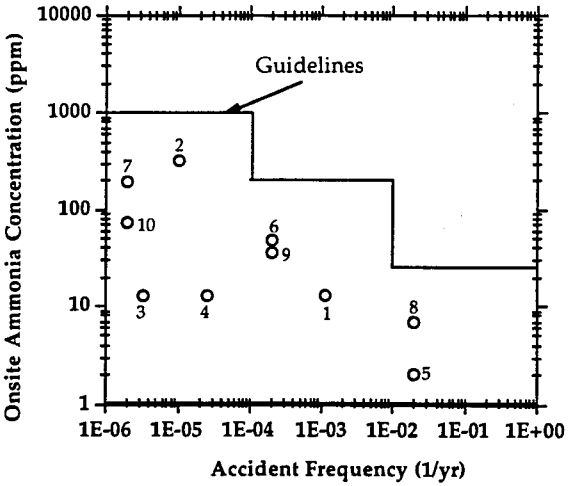


**Fig. 5-3. On-site ammonia concentrations for gas release accidents.**

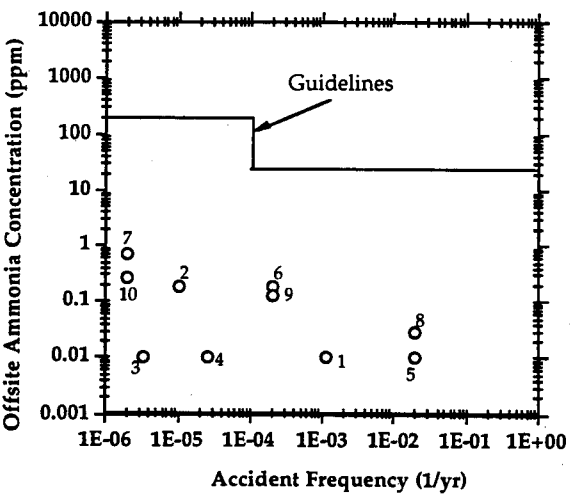


**Fig. 5-4. Off-site ammonia concentrations for the GRE accidents**

**TABLE 5-17**
**SUMMARY OF TOXIC SOLID WASTE RELEASES**

| Accident | Freq. (1/yr) | On-site | Off-site |
|---|---|---|---|
| 1-Anticipated-GRE and open riser (removal), 12 g. | 1.1E-3 | 8.3E-6 L/s | 8.3E-6 L/s |
| 2-Very unlikely-GRE and open riser (removal), 60 g. | 1.1E-5 | 4.2E-5 L/s | 4.2E-5 L/s |
| 3-Anticipated-GRE and open frisbee (operation) (nitrogen purge to riser sleeve fails), 12 g. | 3.2E-6 | 8.3E-6 L/s | 8.3E-6 L/s |
| 4-Anticipated-GRE and drill string open at the top with sampler in the drill string, 128 g. | 2.6E-5 | 9E-5 L/s. | 9E-5 L/s |
| 5-Continuous releases from exhauster after a HEPA filter fails, 0.08 g/s. | 1.6E-5 | 5E-5 L/s | 5E-5 L/s |
| 6-Radioactive aerosols are released from HEPA filter blowout. | 1.6E-5 | 5.63E-3 L | 5.63E-3 L |
| 7-Waste from contaminated drill string exterior is released aboveground. | 4.4E-6 | 4.7E-4 L | 4.7E-4 L |

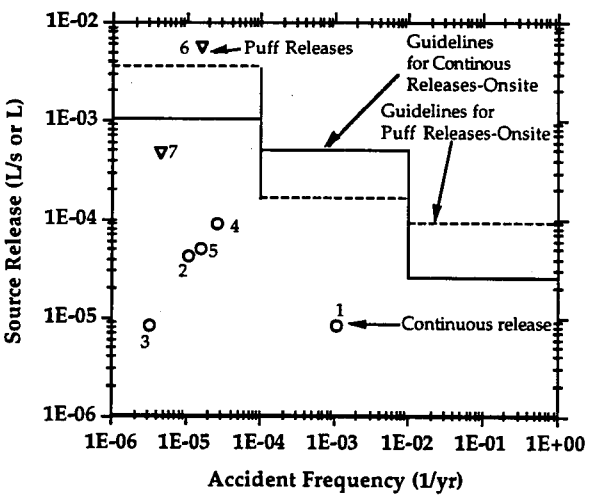


**Fig. 5-5. Consequence of toxic waste releases at the on-site receptor location.**

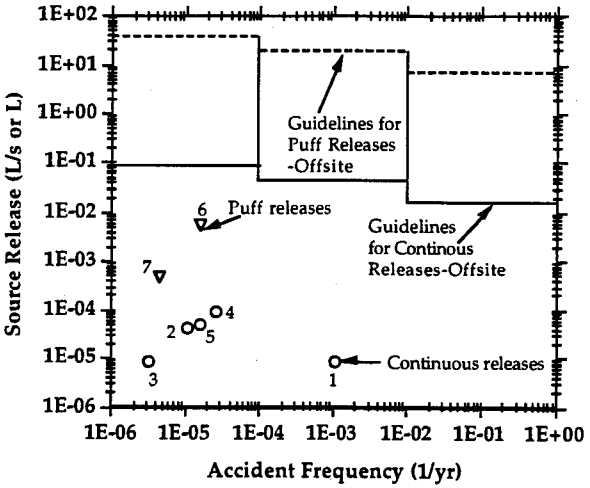


**Fig. 5-6 Consequence of toxic waste release at the off-site receptor location.**

## 5.7. REFERENCES

1. A. B. Sidpara, "Risk Acceptance Criteria for Tank Farm Operation," Department of Energy/Richland Operations, letter, 95-TOP-063 to the President of Westinghouse Hanford Company (June 14, 1995).

2. Westinghouse Hanford Company, "Safety Analysis Manual," Westinghouse Hanford Company report WHC-CM-4-46 Rev. 4 (September 30, 1995).

3. J. L. Huckaby, H. Babad, and D. R. Bratzel, "Headspace Gas and Vapor Characterization Summary for the 43 Vapor Program Suspect Tanks," Westinghouse Hanford Company report WHC-SD-WM-ER-514, Rev. 1A (September 1995).

4. W. L. Kubic, "Production of Nitrogen Oxides During Burn Accidents in Tank 241-SY-101," Los Alamos National Laboratory Calc-Note TSA10-CN-WT-SA-GR-040 (September 1995).

5. Westinghouse Hanford Company, "Toxic Chemical Considerations for Tank Farm Releases," Westinghouse Hanford Company report WHC-SD-WM-SARR-011 Rev. 1 (October 1995).

# 6.0. CONTROLS

In this section, the comprehensive list of all credited design features, and procedural and administrative controls imposed on the installation, operation, and removal of rotary-mode core sampling (RMCS) equipment in single-shell tanks (SSTs) on the Flammable Gas Watch List (FGWL) or those tanks recommended by the contractor to be included on the FGWL, hence referred to as FG/RMCS operations, are described.

## 6.1. Administrative Controls

This section provides the controls to be used for all phases of FG/RMCS activities in: (1) pre-installation and installation activities; (2) drilling and sample retrieval; and (3) removal and decontamination. The controls have been grouped for each phase of the FG/RMCS activities for clearer and easier procedures development, and have been developed based on the results, assumptions, and initial conditions of this SA, in conjunction with existing WHC controls. Those WHC standard controls important to the activities have been repeated in this SA for clarity; however, the set of controls listed in this SA is intended only to supplement the WHC standard controls, not replace them.

Westinghouse Hanford Company (WHC) standard controls include a series of WHC documents that define the safety envelope for the tank farm, waste transfer activities, and waste storage activities. The primary document is the WHC Health and Safety Plan[1], although other documents include the Safety Assessment for Push- and Rotary-Mode Core Sampling in Ferrocyanide Tank,[2] Safety Analysis for the Push Mode and Rotary Mode Core Sampling,[3] and the Interim Safety Basis Document.[4] During the development of the procedures for each of the activities, the current operational safety requirements (OSRs), interim operational Safety requirements (IOSRs), and operational safety documents (OSDs) must be considered. The safety envelope established by the analyses shall not be changed unless approved by the Department of Energy (DOE). The controls provided in this section can be modified if the appropriate organization grants approval.

Most of the controls presented in this section are based on the analyses conducted for this safety assessment (SA). These controls have been designed to ensure that the analysis assumptions and initial conditions are maintained throughout each phase of the activities. In several cases, the controls have been developed to add an additional safety margin, consistent with a philosophy of defense-in-depth. Therefore, the controls should be an integral part of the procedure development process to maintain the level of safety demonstrated in this SA.

Administrative controls are the requirements that shall be followed to ensure that the activity stays within the bounds of the SA. As such, this set of administrative controls shall be used during the development of the procedures for each activity.

Sections 6.4 through 6.8 provide the specific controls in tabular format to be used for the activities covered by this SA. Of these activities, FG/RMCS operations are the most complex. Therefore, more controls have been instituted for the operational phase than for other processes. Because of the complexity of the FG/RMCS operation, these controls have been divided into three levels. Each control level requires a different level of approval for modification and for restarting operations after abnormal shut downs.

FG/RMCS operation controls are designated as either Level 1, Level 2, or Level 3. This graded approach reflects the importance of a particular control, the level of approval required for modification, and the level of approval required to restart operation if a particular limit is exceeded.

Level 1 controls are the most important, they are under the most stringent management supervision and are equivalent to OSRs (see Section 6.2.). Level 1 controls ensure that the most important bounds, established in the SA, are maintained at all times, as demonstrated by the appropriate analyses for both potential prompt effects and post-operation effects. Changes to the Level 1 controls, if required, will be developed by Characterization/RMCS support personnel, and approved by the Plant Review Committee (PRC), WHC management, and DOE/RL. The WHC Design Authority is responsible for approval of all aspects of equipment design.

Level 2 controls are the next level in importance. The PRC must approve modifications to Level 2 control parameters and notify WHC Management and DOE/RL of the modifications and the technical bases for the modifications.

Level 3 controls are the lowest level in importance. Changes to the Level 3 controls will be approved by the PRC. WHC Management and DOE/RL will be notified of the changes and their technical bases.

The PRC may charter a separate technical review group to perform the review and approval responsibilities of the PRC.

All changes to any of the controls or equipment credited in this safety assessment, and any special tests, must be screened for unreviewed safety questions, in accordance with DOE Order 5480.21, and in accordance with WHC policies and procedures.

An automatic shutdown as defined in the following administrative control tables is not considered a violation of the control. Restart of any FG/RMCS activity shall be commensurate with its designated level, and with DOE and contractor procedures.

## 6.2. Level Designation Process

The designation of the control levels was performed using the following methodology. Mitigated and unmitigated accident frequencies and consequences were estimated for each individual accident scenario discussed in Section 4 by considering the application of the controls (mitigated) or without the controls (unmitigated).

In general, controls were designated Level 1 when the control prevented the mitigated consequence of an accident scenario from exceeding the offsite Risk Guidelines.

Level 2 was assigned to controls when the accident was considered to result in consequences that exceed the onsite Risk Guidelines, based on unmitigated accident frequencies.

A control was designated Level 3 if the unmitigated accident frequency was lower than 1.0E-6, or if it enhanced the defense-in-depth arguments even when the accident consequences are within the Risk Guidelines.

Certain controls appeared in multiple accident scenarios. In these cases, the most conservative level was designated for that control.

### 6.3. FG/RMCS Safety Design Features

Principal safety criteria have been established to ensure safe operations during rotary-mode core sampling activities. Design features within the FG/RMCS equipment and procedures have been established to comply with these safety criteria.

The safety equipment list with design classifications, as approved by the WHC Design Authority and plant management, is provided in Ref. 5. Reference 6 lists the qualitative safety design features to prevent the identified hazards. Table 6-1, which identifies those credited design features used in this SA, is based on new design features added to the FG/RMCS trucks, and Refs. 5 and 6.

Table 6-1 identifies design features credited for mitigation of "offsite" or "onsite" consequences. Combinations of design features and administrative controls were used to meet "offsite" and "onsite" Risk Guidelines (RG). Appendix E describes how the design features and administrative controls are combined to meet the guidelines. No modifications to the design features identified in Section 6 are required to meet the RGs. Therefore, classification of a design feature as "offsite" would not require the modification of a design feature to increase its reliability beyond that credited in Appendix E. For example, redundant sensors, beyond that specified in Section 6, would not be necessary for a detector system identified as "offsite."

## TABLE 6-1
## FG/RMCS CREDITED DESIGN SAFETY FEATURES

| | |
|---|---|
| **General Features** | |
| Material compatibility (Onsite) | Materials used in FG/RMCS activities and the drill string components are compatible with the waste stored in single-shell tanks to prevent chemical action or material failures resulting from expected or accidental contact with the wastes.[7,8] |
| Spark-resistant tools (NA) | Spark-resistant tools are used at all times around open risers or the sampled riser to mitigate mechanical sparking. |
| Grounding and bonding (NA) | The FG/RMCS equipment is grounded and bonded to mitigate electrical sparking and mitigate the buildup of static electricity. |
| Radiological controls (NA) | The area around the riser is radiologically monitored, and the exhauster HEPA filter housing is monitored to prevent exposure of personnel to hazardous radiological conditions as set by WHC ALARA controls. |
| **Riser Adapter Features** | |
| Riser sleeve (Offsite) | A conductive sleeve is inserted into the riser to be sampled to mitigate frictional sparking. In addition, the sleeve is provided with a manually controlled nitrogen purge system to prevent flammable gas accumulation in the riser sleeve. |
| Drill string spray washer (NA) | A hot-water spray washer is provided on the riser adapter to reduce the contamination of drill rods as they are removed from the tank. Check valves and a positive displacement pump are provided on the system to restrict back flow. |
| Frisbee/DS interface lubricant (NA) | The frisbee/DS interface is lubricated with a non-spark inducing, waste-compatible material to decrease the friction between the rubber seal and the drill string, and thereby mitigate damage to the seal. |
| Pneumatic foot clamp (Offsite) | The pneumatic foot clamp is designed to fail closed to prevent the drill string from falling into the tank when the drill truck or platform hoist are not connected. Two, independent, simultaneous operator actions are required to open the foot clamp. |

| Drill String Features | |
|---|---|
| Drill bit configuration and material<br>(Offsite) | The drill bit is made of a waste-compatible material, and must be qualified commensurate with the requirements provided in Appendices F, G and T of this SA. |
| Drill centering spike<br>(NA) | The first rotary-core sampler shall be equipped with a centering spike on initial use to prevent random bit motion when first entering the waste. |
| Chevron seal between drill bit and sampler<br>(NA) | The chevron seal between the drill bit and sampler provides a barrier between tank waste and the drill string. This seal allows one-way flow of nitrogen purge from the drill string into the tank, but does not allow waste or waste gas to flow back into the drill string. |
| Core sampler and drill string components<br>(Offsite) | The core sampler and drill string components must meet the requirements specified in Appendix T to prevent sparking. |
| Sniffing ports<br>(NA) | Sniffing ports are provided to allow measurement of flammable gas from a contained environment. |
| Change-out assembly<br>(NA) | The change-out assembly is provided with a ball valve to isolate and maintain pressure within the drill string during sampler exchange. |
| Cable spray washer<br>(NA) | The hot-water cable spray washer connects to the drill string to wash cables and samplers that are contaminated. |
| **Drilling Features** | |
| Purge flow limitation<br>(Offsite) | In FG/RMCS operations, the drill string is purged with a minimum of 30 scfm of nitrogen to prevent drill bit overheating and to remove cutting-products from the drill bit. Purge flow is initiated just before drilling begins.<br>With a loss of nitrogen purge, drilling is automatically terminated with no delay to maintain drill bit temperature within the defined limits. |
| Rotational speed limitation<br>(Offsite) | In FG/RMCS operations, the maximum rotational speed of the drill string is 55 rpm to maintain the drill bit temperature within the defined range.<br>Drilling is automatically terminated with no delay if the speed exceeds 55 rpm. |
| Down force limitation<br>(Offsite) | In FG/RMCS operations, a maximum down force of 750 lbf shall be imposed on the drill string to maintain drill bit temperature within the defined range.<br>When the rotational speed is greater than 2 rpm, the set point is selected at 750 lbf upon which shutdown will be initiated.<br>Drilling is automatically terminated with no delay if the down force exceeds 750 lb. |
| Drill string penetration rate<br>(Offsite) | In FG/RMCS operations, a minimum penetration rate of 0.75 in./min is limited to < 60 seconds to maintain drill bit temperature within the defined range.<br>Drilling automatically terminates when the penetration rate is <0.75 in./min. for a cumulative time of 60 seconds in any 3 min. period. |

| | |
|---|---|
| Hydraulic bottom detector (Offsite) | The hydraulic bottom detector detects the increased resistance during the last sample to prevent increasing the downward force and penetrating the tank bottom by reversing ram motion upward. Two operators are needed to enable the hydraulic interlock system to ensure activation redundancy. The hydraulic interlock system has a pressure-relief valve to control overpressure and check valves to prevent inappropriate flow reversal. |
| Walk Down Function (Offsite) | The walk down function automatically limits down force by controlling lower ram pressure. |
| Hydrostatic head (NA) | Hydrostatic head pressure is maintained and monitored during sample retrieval to prevent drill string flooding. |
| **Sampling Truck Features** | |
| Truck position (Offsite) | All truck ignition sources are greater than 3-ft. from the frisbee or protected with a barrier to separate potential sources and flammable gases leaking from the frisbee. |
| Stabilizing jacks (NA) | The sampling truck is provided with stabilizing jack locking collars to prevent truck movement in case of hydraulic failure. |
| Quill rod adapter (Offsite) | The quill rod adapter shall be fabricated of a waste-compatible, spark-resistant material. |
| **Grapple Hoist Assembly Features** | |
| Grapple hoist assembly (Offsite) | The grapple hoist assembly is designed to meet NEC requirements as defined in this SA to allow operation in a flammable gas environment. |
| Grapple (sample actuator) (Offsite) | The mechanical design of the grapple (sample actuator) mitigates electrical and mechanical sparking. |
| Grapple insertion (NA) | The design of the grapple hoist assembly limits grapple insertion and removal rates to $\leq$ 1 ft/s to minimize frictional sparking. |
| Grapple hoist cable tension (NA) | The grapple hoist assembly measures cable tension during sampling to prevent grapple hoist damage. |
| **Shielded Receiver Assembly Features** | |
| Shielded receiver assembly (Offsite) | The shielded receiver assembly is designed to meet NEC as defined in this SA to allow operation in a flammable gas environment. |
| SR tube (NA) | Shielding materials are used in the SR to protect against sampler radiation. |
| SR view port (NA) | The SR view port provides a means to inspect the sampler during retrieval to control the spread of contamination. |
| SR hoist cable tension (NA) | The SR hoist assembly measures cable tension during sample retrieval to prevent damage to the SR hoist assembly. |
| Remote latch unit (Offsite) | The mechanical design of the remote latch unit mitigates electrical and mechanical sparking. |
| RLU insertion (NA) | The design of the SR assembly limits RLU insertion and removal rates to $\leq$ 1 ft/s to minimize frictional sparking. |

| | |
|---|---|
| RLU position indicator (NA) | The position of the RLU is monitored to ascertain whether the core sampler is completely raised into the SR, or inserted into the drill string. |
| **Exhauster Features** | |
| Exhauster Operation (Offsite) | The exhauster continues to operate, as described in Appendix L, but terminates drilling upon detection of flammable gases or dome pressure rise exceeding the specified limits to protect personnel and equipment during a potential gas-release event. |
| Exhauster intrinsic safety (Offsite) | All electrical equipment within the exhauster flow stream, including the exhauster fan and instrumentation, is qualified to operate in a NEC Class-1, Division-I, Group B environment to allow operation in a flammable gas environment. |
| Exhauster PLC (Offsite) | An exhauster programmable logic controller processes out-of-tolerance alarm signals to activate the alarm strobe and indicator lights, and sends a signal to the shut-down logic to initiate drill engine shutdown for all operating parameters listed in the administrative control table. |
| Exhauster duct (Offsite) | The exhauster duct is made of a conductive material and is grounded to mitigate static sparking. In addition, the duct is attached to the exhauster to prevent damage from wind. |
| Exhauster heater (Offsite) | The heat exchanger is designed for operation in a flammable gas environment. |
| Exhauster fan and motor assembly (Offsite) | The exhauster fan and motor assembly as defined in this SA is qualified for operation in a flammable gas environment. |
| Inlet breather stack (Offsite) | The tank inlet breather stack shall be at least 15-ft tall with a nominal 4-in. i.d. to reduce toxicological consequences and to protect non-qualified equipment on the tank dome during GRE. |
| Tank pressure detection (Offsite) | The exhauster is equipped with a tank pressure detection system to prevent low tank pressure. |
| **Flammable Gas Detection** | |
| Flammable gas detector (Offsite) | The flammable gas detection system, with redundant sensing systems, is provided to meet the functional requirements and performance acceptance criteria as defined in Appendices C and U to terminate FG/RMCS operations in the event of a GRE.<br>Tank pressure is also measured to provide GRE detection and diversity. |
| **Mobile X-ray System Feature** | |
| X-ray containment (NA) | The mobile X-ray system has a sealed, conductive-tube enclosure and redundant sleeve to separate waste and waste-generated flammable gases from the electrical components of the system. |
| **Nitrogen System Safety Features** | |
| DS nitrogen purge supply (Offsite) | The DS nitrogen purge supply is provided to prevent drill bit overheating. Automatic termination of drilling operations on low purge flow is provided to prevent drill bit overheating. |
| Nitrogen hydrostatic head supply (NA) | Maintaining the hydrostatic equilibrium in the drill column with hydrostatic head nitrogen is controlled by a flow controller to ensure that excessive amounts of nitrogen are not injected into the waste. |

| | |
|---|---|
| Riser sleeve nitrogen purge supply (NA) | The riser sleeve nitrogen purge flow is provided to prevent flammable gas accumulation in the annulus between the riser sleeve and drill string. Automatic termination of drilling operations occurs on loss of flow. |
| Unique connections (NA) | Unique connections are provided for both the DS and riser/sleeve annulus nitrogen purge systems, as well as the hydrostatic head systems for the DS and SR, to prevent incorrect connections. |
| **Instrumentation, Control, and Interlock Features** | |
| Truck PLC (Offsite) | The truck programmable logic controller processes out-of-tolerance alarm signals to activate the alarm strobe, horn, and indicator lights and to send a signal to the shut-down logic to initiate drill engine shutdown for all operating parameters listed in the administrative control table. |
| Audible and visual annunciation (NA) | Audible and visual annunciation is provided to alert the operator to out-of-tolerance alarm conditions as listed in the administrative control table. |
| Shut-down interlock (Offsite) | The shut-down interlock accepts signals from the PLC to shut down the drill rig engine ignition. |

## 6.4. FG/RMCS Controls

The control tables in this section are discussed in terms of the applicable phases, the descriptions of the columns and several definitions that are pertinent to accurately interpreting the controls.

### 6.4.1. FG/RMCS Controls Phases

All of the controls developed for FG/RMCS activities have been categorized into one of the following 5 phases:

- All Phases—these controls will apply to all phases of FG/RMCS operations. See Section 6.6, Table 2.
- Pre-installation Phase—controls in this phase are focused at the activities necessary to prepare the site, acquire and set up equipment, and perform grounding and bonding activities. See Section 6.7, Table 3.
- Installation Phase—these controls are directly related to all activities associated with opening and preparing the riser, and inserting the drill string. See Section 6.8, Table 4.
- Operations Phase—this phase contains all of the controls related to sampling operations and sampler handling. See Section 6.9, Table 5.
- Removal Phase—this final phase includes the decontamination of the drill string, breaking down the equipment and restoring the site. See Section 6.10, Table 6.

### 6.4.2. Control Table Columns

Each of the tables has the following columns:

- System or condition—defines the situation or equipment for which the control is being developed.
- Safe operating condition—defines the levels or conditions under which safe operation occurs.
- Surveillance or monitoring method—defines the surveillance or monitoring method used to check the operation condition.
- Administrative controls—defines the controls for the given system or equipment in terms of operation or performance.
- Level—defines the Level 1, 2 or 3, as described in Sections 6.1 and 6.2.
- Basis for Control—defines the reason behind or necessity for the control.
- Safe Shutdown Definition—defines the conditions and actions necessary if the control requirements are not met.

## 6.5. REFERENCES

1. "Tank Farm Health and Safety Plan," Westinghouse Hanford Company report WHC-SD-WM-HSP-002, Rev. 0A (September 28, 1993).

2. "Safety Assessment for Push- and Rotary-Mode Core Sampling in Ferrocyanide Tanks," Westinghouse Hanford Company report WHC-SD-WM-SAD-013, Rev 3-A (November, 1993).

3. "Safety Analysis for the Push Mode and Rotary Mode Core Sampling," Westinghouse Hanford Company report WHC-SD-WM-SARR-031, Rev. 2 (July, 1995).

4. C. E. Leach, "Hanford Site Tank Farm Facilities Interim Safety Basis," Westinghouse Hanford Company report WHC-SD-WM-ISB-001, Rev. 0 (August 1, 1993).

5. J. E. Corbett, "Rotary-mode Core Sampling Safety Equipment List, WHC-SD-WM-SEL-032, Rev. 0 (February 16, 1994).

6. R. L. Koontz, "Hazards Identification and Evaluation for Waste Tank Core-Sampling Equipment," Westinghouse Hanford Company Report, SD-WM-SAR-007, (June 1985).

7. "Rotary Mode Core Sample Truck Material and Component Compatibility with Tank Waste," Westinghouse Hanford Company Internal Memo 75230-96-001 R2 (February 5, 1996).

8. L. H. Sullivan et al., "A Safety Assessment for Proposed Pump Mixing Operations to Mitigate Episodic Gas Releases in Tank 241-101-SY: Hanford Site, Richland, Washington," Los Alamos National Laboratory report LA-UR-92-3196 (October, 1992).

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
|---|---|---|---|---|---|---|
| **6.6. Table 2. All Phases** | | | | | | |
| **6.6.1. Use of FG/RMCS Controls** | | | | | | |
| 6.6.1.1. Control Applicability | Approved checklist | Checklist evaluation | This Safety Assessment and its controls shall be applicable to single-shell tanks (SSTs) on the Flammable Gas Watch List (FGWL) or those tanks recommended by the contractor to be included on the FGWL.<br>Each tank shall be evaluated against the checklist in Section 7, and the evaluation results shall be reviewed and approved by the PRC before initiating any FG/RMCS operations. | 1 | SA assumptions in regard to tank specific parameters such as gas and waste composition, gas release probability etc. may become non-conservative by a new analysis or data for a specific tank considered to be sampled by RMCS prior operations.<br>See section 7. | No FG/RMCS operations can proceed without checklist approval.<br>If FG/RMCS operations are initiated without checklist approval, immediately terminate activities and notify plant management. |
| 6.6.1.2. Existing procedures and controls | Use controls identified in this document for specified phases of FG/RMCS operations. | Procedural evaluation | The PRC shall verify that all FG/RMCS controls specified in this SA are implemented in the operating procedures.<br>Non-RMCS-related activities on the flammable gas tank being sampled shall be performed under existing Contractor controls and procedures, unless superseded by FG/RMCS controls. | 3 | SA analyses requires changes in current procedures. New procedures are needed to maximize safety to personnel, equipment and the environment.<br>Provides defense in depth to all aspects of safety. | NA |
| **6.6.2. Ignition Test Results** | | | | | | |
| 6.6.2.1. Ignition and envelope testing | Use of qualified equipment of FG/RMCS operations | Approved test results | Ignition and envelope test requirements and acceptance criteria provided in Appendices F, G and T shall be used to verify drill bit and material performance.<br>The results of initial testing shall be reviewed and approved by the PRC before proceeding with any FG/RMCS activities. | 1 | Significant part of fire hazards are considered to be a beyond extremely unlikely event based on proposed ignition testing. SA determines the functional requirements and acceptance criteria of ignition testing. | NA |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
|---|---|---|---|---|---|---|
| | | | | | See Section 7. | |
| **6.6.3. Flammable Gas Detection System** | | | | | | |
| 6.6.3.1. Flammable gas detection system verification | Use of verified detection system | Approved test results and periodic calibration | Functional requirements and performance acceptance criteria, as provided in Appendix U, shall be used to verify the performance of the flammable gas detection system. | 1 | The use of a redundant and adequate flammable gas detector is a key assumption to provide safe shutdown of FG/RMCS operations during a GRE. This reduces the likelihood of spark in flammable gas atmosphere and also provides protection for toxic gas exposures.<br>This mitigates unacceptable offsite consequences resulting from a dome collapse.<br>See Section 4.2.1. | NA |
| 6.6.3.2. Flammable gas detection system design review | Use of reviewed design | Design approval | The PRC will review the design package to verify that SA Appendix U requirements are met. | 3 | See Section 7.4. | NA |
| **6.6.4. Tank Dome Conditions** | | | | | | |
| 6.6.4.1. Flammable gas detection system operation | Limit setpoint of flammable gas detection system at $\leq$ 25% LFL. | Flammable gas detection system connected between riser and exhauster housing with system readout and alarmed setpoints<br>One out of two redundant logic | A redundant, calibrated flammable gas detection system shall be operational before FG/RMCS waste intrusive operations begin, and operate consistent with exhauster operation defined in Section 4.1.3.<br>The flammable gas detection system shall be trip setpoint limited at:<br>• > 5000 ppm hydrogen | 1 | System detects flammable gas accumulation sufficient for deflagration or detonation in tank.<br>Detects GRE and provides protection for fire and toxic hazards.<br>Reduces the likelihood of spark | Upon detection, the exhauster will continue to operate. If drilling, the drill rig engine will automatically trip and automatically close the nitrogen purge flow solenoid-operated valve (SOV). |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
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| | | | concentration equivalent; and<br>• > 100 ppm/s rate of equivalent hydrogen concentration increase over a 10-s period.<br>Send a shutdown signal to the truck PLC. One out of two redundant logic. | | in flammable gas atmosphere.<br>Provides protection for exposure to toxic gas releases.<br>This mitigates unacceptable offsite consequences resulting from a dome collapse.<br>Section 4 and Appendix B. | All personnel within a 100-m radius from the edge of the tank will evacuate and don protective equipment before returning for further equipment stabilization.<br>FG/RMCS activities can resume in compliance with appropriate controls in Section 4.1.1. |
| 6.6.4.2. Tank gas pressure detection system | Detect rate of tank pressure increase. | Gas pressure detection system in dome or riser<br>One out of two redundant logic | A redundant gas pressure detection system shall detect an increase in tank pressure of > 2 in. w.g. in any 5-6 minute period.<br>Send a shutdown signal to the truck PLC. One out of two redundant logic. | 1 | Prevent burn in and out of dome by detecting gas release rates >1000 $ft^3$/min.<br>Provides protection for fire and toxic hazards.<br>Reduces the likelihood of spark in flammable gas atmosphere.<br>Provides protection for exposure to toxic gas releases.<br>This mitigates unacceptable offsite consequences resulting from a dome collapse.<br>Sec. 4.1.1, 4.1.3, 4.2.1, 4.2.4, and Appendix B | Upon detection, the exhauster will continue to operate. If drilling, the drill rig engine will automatically trip and automatically close the nitrogen purge flow SOV.<br>All personnel within a 100-m radius from the edge of the tank will evacuate and don protective equipment before returning for further equipment stabilization.<br>FG/RMCS activities can proceed in compliance with appropriate controls in Section 6.4. |
| **6.6.5. Spark-free environment** | | | | | | |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
|---|---|---|---|---|---|---|
| 6.6.5.1. Spark-free environment | Use spark-resistant tools, materials, and FG/RMCS components at all times within a radius of 36 in. of open riser or sampled riser | Procedural evaluation | An administrative control shall be developed and implemented that imposes an environment that significantly reduces the likelihood of sparking by:<br>• The use of spark-resistant tools, materials, and FG/RMCS components at all times within a radius of 36 in. of the riser being sampled or any open riser.<br>• Nonsmoking environment on top of the tank. | 3 | Prevent ignition sources in proximity with flammable gas environments.<br>Prevent fire and its propagation above the tank dome.<br>See Sections 4.3.3, 4.2.2, and 4.2.3. | No FG/RMCS activities can be initiated or proceed until a spark-free environment is established. |
| **6.6.6. Material compatibility** | | | | | | |
| 6.6.6.1. Material compatibility | Use waste compatible materials and lubricants | Procedural evaluation | An administrative control shall be developed and implemented that requires, when in contact with the DS or tank waste, the use of:<br>• waste-compatible materials, and<br>• pipe compounds, lubricants and tapes that do not contain spark-inducing or waste-incompatible materials. | 2 | Prevent gas generation caused by material incompatibilities.<br>Protects against local exothermic chemical reactions that could produce large quantities of flammable gas and heat and cause a waste fire if propagates.<br>Prevents equipment damage.<br>Sections 4.3.1, 4.4.2, 4.5.3. | No FG/RMCS activities can be proceed until the use of waste compatible materials is implemented. |
| **6.6.7. Exhauster emissions** | | | Contractor Controls | | See Section 4.1.1 | |
| **6.6.8. Simultaneous activities** | | | | | | |
| 6.6.8.1. FG/RMCS vehicle operations on tank | Limits on vehicle operations during active rotary drilling or with open riser | Procedural evaluation | An administrative control shall be developed and implemented that evaluates flammable gas concentrations in the FG/RMCS tank during open riser conditions or waste-intrusive activities before any vehicle operations. | 3 | Minimize the potential for vehicle operations igniting flammable gas concentrations.<br>See Section 4.1.9. | Upon detection, vehicle operations will be immediately terminated and not resumed until flammable gas limits are met. |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
|---|---|---|---|---|---|---|
| 6.6.8.2. Simultaneous activities on FG/RMCS tank | Limits on simultaneous non-FG/RMCS activities on sampled tank | Procedural evaluation | An administrative control shall be developed and implemented that prevents non-FG/RMCS activities on the tank during waste-intrusive operations.<br>Simultaneous dome-intrusive activities can be performed provided:<br>• the equipment is qualified for operation in a Class I, Division 1, Group B environment, and<br>• operation is based on its own safety assessment.<br>• operation does not physically interact with the drill string, and is not waste-intrusive. | 1 | Tank dome is considered to be Class I, Div. 1, Group B environment because RMCS can induce a GRE. Sparks in the dome or volumes having a connecting path to the tank dome must be controlled. Control prevents ignition of flammable gas by non-FG/RMCS-related ignition sources.<br>This mitigates unacceptable offsite consequences resulting from a dome collapse.<br>See Section 4.2.7 and Appendix B. | No non-FG/RMCS activities can proceed during period defined by control, or until any simultaneous tank activities comply with the control. |
| 6.6.8.3. Interconnected tanks | Limits on simultaneous non-FG/RMCS activities on interconnected tanks | Procedural evaluation | An administrative control shall be developed and implemented that prevents non-FG/RMCS activities on interconnected tanks when waste-intrusive activities are in progress.<br>If necessary, an action plan shall be prepared for PRC review and approval to proceed with noncompliant activities. | 3 | Tank dome is considered to be Class I Div. 1 Group B environment because RMCS can induce a GRE. Sparks in the dome or volumes having a connecting path to the tank dome must be controlled. Control mitigates gas release or fire from interconnected tank resulting in burn in FG/RMCS tank.<br>See Section 4.7.1 | No non-FG/RMCS activities can proceed during period defined by control, or until all simultaneous activities on interconnected tanks comply with the control. |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
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| | | | | | and Appendix B. | |
| **6.6.9. Refueling Activities** | | | | | | |
| 6.6.9.1. Flammable gas concentrations | Limits on refueling with flammable gas concentrations≥25% LFL | Procedural evaluation | No refueling operations shall be performed inside the tank farm when FG/RMCS tank flammable gas concentrations are ≥25% LFL. | 3 | Limit flammable gas concentrations in proximity with ignition sources.<br>Operations when the tank dome have flammable gas concentration above 25% LFL is prohibited to prevent dome fires. Control reduces the likelihood of fire accident in the dome.<br>See Sections 4.1.7 and 4.1.8. | All FG/RMCS activities will be terminated until flammable gas concentrations are within limits specified in Section 6.9. |
| 6.6.9.2. Equipment refueling | Limits on equipment refueling operations | Procedural evaluation and implementation | An administrative control shall be developed and implemented for equipment refueling operations that:<br>• prevents refueling operations around open risers,<br>• controls refueling operations, and<br>• defines management of fuel spills and leaks. | 3 | Limit ignitable material in proximity with flammable gas environment during refueling operations. Prevent fuel fire and fire propagation to the tank.<br>See Sections 4.1.7 and 4.1.8. | No FG/RMCS activities can proceed until refueling activities comply with the control. |
| **6.6.10. External events** | | | | | | |
| 6.6.10.1. Meteorological verification | Monitor external events | Procedural evaluation | Before and periodically during FG/RMCS operations external event status shall be verified with meteorological station or appropriate authorities<br>Contractor shall identify an acceptable meteorological station and acceptable verification authorities. | 3 | Monitoring mitigates the effects of external events on FG/RMCS activities. | When external events exceed given controls, terminate activities, secure auxiliary equipment, and place sampling truck in stabilized mode as required by approved Tank Farm Operating |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
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| | | | | | | Procedures. |
| 6.6.10.2. Range fires | No range fires within 5 mile radius | Procedural evaluation | At the discretion of the PIC, no FG/RMCS activities shall be performed if a range fire is within a 5 mile radius. | 3 | Minimize spark sources.<br>Reduces likelihood of fire propagation into dome.<br>Prevents equipment damage.<br>See Section 4.9.3. | As required by General External Event control. |
| 6.6.10.3. Thunderstorm & lightning, high winds, dust devils and tornadoes | No thunderstorm activity or lightning strikes within 50 mile radius<br>No sustained wind velocities > 25 mph | Procedural evaluation | At the discretion of the PIC, no FG/RMCS activities shall be performed when:<br>• thunderstorm activity or lightning strikes are reported within a 50 mile radius.<br>• Sustained wind velocities are > 25 mph.<br>• Dust devil activity that can disrupt operations<br>• tornado activity has been predicted within the next 8 hours within a 50 mile radius. | 3 | Prevent personnel injury, equipment damage, and reduce potential for electrostatic sparking.<br>See Section 4.9.1 | As required by General External Event control. |
| 6.6.10.4. High rain fall or flooding, seismic activity, and volcanic activity/ashfall | Reduce potential for personnel injury and equipment damage. | Procedural evaluation | An administrative control shall be developed and implemented that assesses the limits of safe FG/RMCS activities with:<br>• excessive rain fall<br>• extreme temperature conditions<br>• seismic activity<br>• volcanic activity or ashfall accumulation | 3 | Prevent personnel injury and equipment damage.<br>See Section 4.9.6. | As required by General External Event control. |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
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| **6.7. Pre-Installation Phase** | | | | | | |
| **6.7.1. Waste Reactivity Evaluation** | | | | | | |
| 6.7.1.1. Waste reactivity | FG/RMCS operations on tanks specified in Appendix G of this SA | Procedural implementation | FG/RMCS operations shall be performed only in tanks listed in Table G-3 of Appendix G in this SA. | 1 | Prevents propagating exothermic chemical reaction that could produce large quantities of flammable and toxic gas and heat. Waste and flammable gas ignition consequently a possible dome collapse is prevented.<br>This mitigates unacceptable offsite consequences resulting from a dome collapse.<br>See Appendix G | No FG/RMCS activities can proceed in tanks not listed. |
| **6.7.2. Tank and riser conditions** | | | | | | |
| 6.7.2.1. Gas leak paths | Identify and repair leaking risers prior to waste-intrusive activities | Visual inspection<br>Procedural evaluation | An administrative control shall be developed and implemented for a formal tank walkdown prior to waste-intrusive activities that:<br>• assesses the general condition of risers,<br>• identifies observable leaks<br>• as a minimum, documents identified leaks $\geq$ 1 in.,<br>• as a minimum, seals or add deflectors to identified leaks with an equivalent leak diameter $\geq$ 1 in. | 1 | Above ground fires that could propagate into the dome are managed by controlling position of the non-qualified equipment. Since sparks from non-qualified equipment can not be eliminated, a safe distance criteria is developed in App. B. This criteria requires that possible leak diameter is to be | No FG/RMCS activities can proceed until procedural controls are implemented. |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
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| | | | | | known and controlled.<br>This mitigates unacceptable offsite consequences resulting from a dome collapse.<br>See Section 4.1.3 and Appendix B. | |
| 6.7.2.2. Open riser exclusion zone | Exclusion zone with radius of 36-riser-diameters around open risers during waste-intrusive activities | Procedural evaluation and verification | An administrative control shall be developed and implemented for an exclusion zone with a radius of 36-riser-diameters around any open riser during waste-intrusive FG/RMCS activities. | 1 | Minimizes ignition sources in proximity with flammable gas.<br>Minimizes gas leakage in proximity with ignition sources or unqualified equipment.<br>This mitigates unacceptable offsite consequences resulting from a dome collapse.<br>See Section 4.1.3 and Appendix B. | No FG/RMCS activities can proceed until procedural controls are implemented. |
| **6.7.3. Grounding and bonding** | | | | | | |
| 6.7.3.1. Equipment attached to tank | Ensure equipment grounding | Resistance measurement<br>Procedural evaluation and verification | An administrative control shall be developed and implemented for grounding and bonding all FG/RMCS equipment attached to the riser or inserted into the tank, including the drill string such that:<br>• Electrical power grounding shall comply with the requirements of NFPA 70, Article 250.<br>• Lightning protection shall be consistent with the principles stated in "Evaluation of | 3 | Prevent static electricity discharge and lightning strike initiated sparks.<br>See Sections 4.1.1.1, 4.2.5, 4.3.10, 4.91. | No FG/RMCS activities can proceed until grounding and bonding activities are completed and verified. |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
|---|---|---|---|---|---|---|
| | | | Hazards From Lightning Strikes to Tank Farm Facilities", W. L. Cowley, WH-SD-WM-SARR-027, Rev 0 (June 29,1994). | | | |
| 6.7.3.2. Equipment not attached to tank | Ensure equipment grounding | Resistance measurement<br>Procedural evaluation and verification | Equipment not attached to the riser or inserted into the tank shall be grounded commensurate with Contractor grounding and bonding controls, using independent verification before FG/RMCS activities. | 3 | Prevent static electricity discharge and lightning strike initiated sparks.<br>See Section 4.1.1. | No FG/RMCS activities can proceed until grounding and bonding activities are completed and verified. |
| **6.7.4. Energized equipment** | | | | | | |
| 6.7.4.1. Energized equipment in the dome | All energized equipment exposed to the tank dome (as defined in approved contractor safety documentation) or dome of connecting tanks shall be rated for operations in Class I, Division 1, Group B environment or Class I, Division 2, Group B environment with automatic shut down for flammable gas concentrations ≥25%LFL. | Procedural evaluation of verification and certification | During waste-intrusive operations, all energized equipment exposed to the tank dome vapor space (as defined in approved contractor safety documentation) or dome vapor space of connecting tanks shall be rated for operations in Class I, Division 1, Group B environment or Class I, Division 2, Group B environment with automatic shut down for flammable gas concentrations ≥25%LFL.<br>All existing energized equipment not meeting the above control shall be de-energized. | 1 | Prevents ignition sources in proximity with flammable gases.<br>This mitigates unacceptable offsite consequences resulting from a dome collapse.<br>See Section 4.0, 4.1.1.3, 4.3.4 and Appendix B. | No FG/RMCS activities can proceed until equipment in the tank dome or dome of connecting tanks complies with control. |
| 6.7.4.2. Energized equipment in open riser exclusion zones | Qualifications of energized equipment in open riser exclusion zones. | Procedural evaluation of verification and certification | During waste-intrusive operations, all energized equipment in open riser exclusion zones as defined in section 6.7.2.2 shall be rated for operations in Class I, Division 1, Group B environment, or rated for Class I, Division 2, Group B environment with automatic shut down for flammable gas concentrations ≥25%LFL.<br>All energized equipment in riser exclusion zones not meeting the above control shall be de-energized. | 1 | Prevents ignition sources in proximity with flammable gases.<br>This mitigates unacceptable offsite consequences resulting from a dome collapse.<br>See Section 4.1.3. | No FG/RMCS activities can proceed until equipment in the riser exclusion zones complies with control. |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
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| **6.7.5. Equipment positioning and Setup** | | | | | | |
| 6.7.5.1. Tank loading | Prevent loading exceeding tank structural capabilities. | Procedural evaluation<br>Engineering review for equipment positioning on tank top | Loading on each tank shall comply with IOSR requirements for simultaneous static and dynamic loading for each specific FG/RMCS tank. | 1 | Limits on tank loading can prevent collapse.<br>This mitigates unacceptable offsite consequences resulting from a dome collapse.<br>See Section 4.6.1 and Appendix N. | No equipment positioning or set up can proceed until tank load capabilities are verified. |
| 6.7.5.2. Vehicle operations on tank | Prevent vehicle impacts. | Procedural evaluation | An administrative control shall be developed and implemented for controlling the safe operation of vehicles on top of the tank during waste-intrusive activities. | 3 | Prevent ignition sources caused by vehicle impacts.<br>See Section 4.1.9. | With procedural noncompliance, corrective actions must be implemented before resuming any FG/RMCS activities. |
| 6.7.5.3. Truck ramp and jacks | Safe use of ramps and hydraulic jacks. | Procedural evaluation | An administrative control shall be developed and implemented for the safe use of the ramp supporting the sampling truck and the truck's hydraulic jacks. | 3 | Prevent tank riser damage<br>See Section 4.6.1. | With procedural noncompliance, corrective actions must be implemented before resuming any FG/RMCS activities. |
| 6.7.5.4. Truck position | No truck-induced ignition sources near potential gas leak source | Procedural evaluation | An administrative control shall be developed and implemented that, prior to waste-intrusive operations:<br>• prevents positioning the sampling truck over an open riser, and<br>• seals any risers under the truck, and<br>• raises the truck a minimum of 36 inches between any potential ignition source on the truck and the top of any riser or pit over which the truck is positioned. | 1 | Truck when parked over an unused riser must be protected from flammable gas releases. This requires to control the distance between the leak source and truck. Reduces above tank fire frequencies by mitigating human error and minimizing ignition sources | No FG/RMCS activities can proceed until procedural controls are implemented. |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
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| | | | | | within area surrounding leak sources.<br>This mitigates unacceptable offsite consequences resulting from a dome collapse.<br>See Section 4.1.3. | |
| 6.7.5.5. Lift operations | Prevent sparks induced from equipment lifting over the tank. | Procedural evaluation | An administrative control shall be developed and implemented that, during waste-intrusive activities:<br>• controls safe lifting operations over the tank, and<br>• restricts lift operations over the exhauster during installation, sampling or restart activities. | 3 | Minimizes potential for above tank fires caused by frictional spark induced by load impacts on tank and exhauster.<br>See Section 4.1.1. | No lifting of FG/RMCS equipment, during waste-intrusive activities, over the tank can proceed without the procedure.<br>With procedural noncompliance, corrective actions must be implemented before proceeding with any FG/RMCS activities. |
| **6.7.6. Exhauster setup** | | | | | | |
| 6.7.6.1. Exhauster installation | Prior to waste-intrusive activities, ensure accurate exhauster positioning, set-up and maintenance per procedures | Procedural evaluation | An administrative control shall be developed and implemented that, prior to waste-intrusive activities, controls the positioning, setup and maintenance of the exhauster system. | 3 | Optimum exhauster performance mitigates unfiltered releases.<br>See Section 5.4.2. | No waste-intrusive FG/RMCS activities can proceed without procedure.<br>With procedural noncompliance, corrective actions must be implemented before proceeding with any FG/RMCS activities. |
| 6.7.6.2. Exhauster duct | Prevent duct-induced static ignition sources | Procedural evaluation and verification | An administrative control shall be developed and implemented that controls the following: | 3 | Grounding verification controls sparking | No FG/RMCS activities can proceed without |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
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| | | | • The exhauster duct shall be mounted in compliance with Contractor procedures.<br>• The exhauster duct shall be inspected for leaks after the exhauster is installed, with independent verification. | | caused by static electricity, lightning, etc.<br>Prevents exposure of flammable gas to non-qualified equipment around flexible hose.<br>See Section 4.1.1, 4.1.2. | procedural compliance. |
| 6.7.6.3. Duct exclusion zone | No unqualified equipment < 18 in. from exhauster duct | Procedural evaluation and verification | An administrative control shall be developed and implemented that locates unqualified equipment greater than 18 in. away from exhauster duct, or provides deflectors for equipment located within 18 in., using independent verification. | 3 | Prevent undetected hose leak in contact with unqualified equipment resulting in fire.<br>See Section 4.1.2. | No FG/RMCS activities can proceed until exhauster duct exclusion zone is established. |
| 6.7.6.4. Exhauster fan | Prevent ignition source from exhauster fan. | Procedural evaluation | The exhauster fan shall meet the requirements of this SA for operation in flammable gas environment commensurate with Std 99-0401-86, Air Movement and Control Association, and NFPA 91. | 3 | Prevent a fan-induced ignition source in a potentially flammable environment.<br>See Section 4.1.1.4. | No FG/RMCS activities can proceed until ignition sources are eliminated from the exhauster's potentially flammable environment. |
| **6.7.7. Tank Breather Inlet HEPA Filter** | | | | | | |
| 6.7.7.1. Portable Inlet Stack | Controlled releases from stack during GRE | Procedural evaluation and verification | An administrative control shall be developed and implemented that, prior to waste-intrusive activities, ensures that inlet breather filter effluent (in the event of tank pressurization) is directed vertically to a height of at least 15 ft above ground level. | 1 | Directing the breather inlet HEPA effluent 15 ft vertically:<br>• allows atmospheric dispersion coefficients to decrease so that toxicological acceptance guidelines at the onsite boundary can be met.<br>• prevents electrically | No waste-intrusive FG/RMCS activities can proceed until inlet HEPA effluent is directed 15 ft vertically. |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
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| | | | | | unqualified equipment in proximity with flammable gas.<br>This mitigates unacceptable offsite consequences resulting from a dome collapse.<br>See Section 4.1.3. | |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
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| **6.8. Installation Phase** | | | | | | |
| **6.8.1. Riser preparation** | | | | | | |
| 6.8.1.1. Gas concentrations while breaching tank containment | Detect flammable gas concentrations | Flammable and toxic gas monitoring procedures | An administrative control shall be developed and implemented for monitoring the riser for flammable and toxic gas concentrations every time before opening a riser. | 3 | Detects flammable gas concentrations sufficient for deflagration before installing riser equipment.<br>See Section 4.1, 4.2, and 4.3 involving accidents during installation phase. | No FG/RMCS activities can proceed without procedural compliance. |
| 6.8.1.2. Riser exposure | Limit personnel exposure | Radiation monitoring procedures | Direct exposure to open riser shall be limited to values specified by approved Tank Farm Operating Procedures. | 3 | Minimize personnel direct exposure from open riser conditions.<br>See Section 4.8.8.4. | No FG/RMCS activities can proceed until personnel protection is appropriately ensured. |
| 6.8.1.3. Riser equipment | Prevent tool drops to waste through open riser. | Procedural evaluation | Activities and use of tools around open risers shall be strictly controlled, especially during installation and removal of the riser adapter, frisbee and washer and foot clamp assemblies, in compliance with approved Tank Farm Operating Procedures. | 3 | Limited open riser time reduces the potential for aerosol, particulate and gas releases.<br>Frequency of gas release accidents considers a 8-hour open riser period.<br>See Section 5.4.1. | No FG/RMCS activities can proceed until procedural corrective actions are implemented. |
| 6.8.1.4. Sleeve insertion | Minimize ignition sources from sleeve insertion | Procedural evaluation | An administrative control shall be developed and implemented for installing the riser conductive sleeve.<br>• The sleeve insertion and removal rate shall be limited to $\leq$ 1 foot/sec. | 3 | Equipment drops are potentially spark inducing.<br>Control further reduces the likelihood of spark caused by drops.<br>See Sections 4.2.2, 4.2.3 , 4.3.3, and 4.4.3. | No FG/RMCS activities can proceed until procedural corrective actions are implemented. |
| 6.8.1.5. Frisbee installation | Minimize flammable gas leakage from | Procedural evaluation | An administrative control shall be developed and implemented for inspecting frisbee to verify | 3 | Control minimizes frictional sparking potential between | No DS insertion or operations can be initiated unless |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
|---|---|---|---|---|---|---|
| | frisbee | Visual inspection | that:<br>• the frisbee inner diameter is smaller than the drill rod outer diameter, and<br>• the frisbee is in good physical condition before DS insertion. | | riser and sleeve.<br>See Section 4.1.3. | functional frisbee is in place. |
| 6.8.1.6. Frisbee/DS interface lubrication | Improved contact between frisbee and DS<br>Mitigate frisbee damage. | Procedural evaluation and verification | The frisbee/DS interface shall be lubricated with a waste-compatible, spark-resistant lubricant before DS insertion. | 3 | Correct frisbee/DS interface reduces gas leak potential during operations.<br>Lubricant eases drill rod insertion and removal, and mitigates seal damage, therefore gas/particulate releases.<br>See Section 4.2.5. | No DS insertion can be initiated unless frisbee is lubricated. |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
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| **6.9. Operations Phase** | | | | | | |
| **6.9.1. Sampler** | | | | | | |
| 6.9.1.1. Leakage | Reduce contamination from sampler leakage | Procedural evaluation<br>Visual inspection | An administrative control shall be developed and implemented for:<br>• visually inspecting the sampler for leakage during retrieval, and<br>• properly handling a leaking sampler. | 3 | Leaking samplers result in equipment contamination, and the potential for gas generation and accumulation in uncontrolled spaces.<br>See Section 4.1.4. | No FG/RMCS activities can proceed until leakage is contained. |
| **6.9.2. Drill string** | | | | | | |
| 6.9.2.1. Drill bit, core barrel and drill rods | Baselined performance of rotary drilling equipment | Procedural evaluation<br>QA/QC over selection and use of materials | The FG/RMCS drill bit, core barrel and drill rods shall be of the configuration and material tested by the Bureau of Mines and performance evaluated in this SA. | 1 | Results from envelope testing and ignition testing are only valid for equipment of the design tested.<br>This mitigates unacceptable offsite consequences resulting from a dome collapse.<br>See Section 4.4.4. | No waste-intrusive FG/RMCS activities can proceed until incorrect drilling equipment is replaced or tested and evaluated for performance. |
| 6.9.2.2. DS open to atmosphere | Detect flammable gas accumulation. | Flammable gas meter<br>Procedural evaluation | An administrative control shall be developed and implemented for:<br>• sniffing the contained DS before the quill rod is disconnected, and<br>• isolating the DS immediately (maximum of 60 minutes) after the drill string is disconnected from the quill rod.<br>• Sniffing the DS before breaking containment if left isolated for > 60 minutes. | 3 | Sniffing detects gas accumulation in the DS and reduces potential for a fire.<br>Immediate change-out assembly installation mitigates flammable gas interactions.<br>See Section 4.3.2 and 4.3.3. | No sample retrieval operations can proceed without DS sniffing commensurate with control. |
| 6.9.2.3. Gas accumulation | Purge drill string | Procedural evaluation | An administrative control shall be developed and implemented | 3 | Purging eliminates gas accumulation | No FG/RMCS waste-intrusive |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
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| | | | for sniffing and purging the DS sufficiently to evacuate flammable gas accumulations before FG/RMCS activities if:<br>• sampler is left in DS without nitrogen flow or hydrostatic pressure for ≥ 60 minutes; or<br>• DS hydrostatic head is lost with no sampler in place. | | in the DS and reduces potential for a fire.<br>See Section 4.3.1. | activities can proceed until requisite purging activities have been completed. |
| 6.9.2.4. Waste flooding | Minimize flooded waste in DS. | SR visual inspection of sampler or loss of hydrostatic head during change-out activities | The DS shall be flushed and purged with indications of waste flooding in the DS, based on approved Tank Farm Plant Operating Procedures, to the extent practicable. | 3 | Waste flooding in the DS can result in gas generation and accumulation.<br>See Section 4.1.6. | No waste-intrusive FG/RMCS activities can proceed until control is implemented, and the source of flooding is verified. |
| **6.9.3. Shielded Receiver** | | | | | | |
| 6.9.3.1. Sampler retrieval | Ensure sampler completely in SR | Visual inspection of sampler | An administrative control shall be developed and implemented for verifying that the sampler is completely within the SR when held by the RLU before disconnecting the SR from the DS, the X-ray or the cask. | 3 | Prevents spills and waste discharges from samplers, which mitigates unanticipated waste releases to the environment.<br>See Sections 4.1.4 and 4.8.4. | If sampler is not completely in SR, no FG/RMCS activities can proceed until procedural corrective actions are implemented. |
| 6.9.3.2. Waste accumulation | Detect waste accumulation >100 mrem/hr. | Radiological monitoring procedures | The external SR contact dose rate shall not exceed 100 mrem/hr, without sampler in SR. | 3 | Monitoring reduces potential personnel exposure and excessive waste accumulation in the SR which can generate gas concentrations sufficient for ignition.<br>See Section 4.1.4, 4.1.6 and Appendix R. | No FG/RMCS activities can proceed until waste accumulation levels are decreased below the specified limit. |
| 6.9.3.3. Waste contamination | Minimize waste-generated gas | Procedural evaluation | An administrative control shall be developed and implemented | 3 | Decontaminating the SR mitigates | No FG/RMCS activities can |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
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| | accumulation | | for decontaminating the SR if it becomes contaminated with waste levels > 100 mrem/hr. | | the effects of waste-generated gas accumulation, and reduces personnel exposure.<br>See Section 4.1.6. | proceed without procedural compliance for SR decontamination. |
| **6.9.4. RLU/Grapple** | | | | | | |
| 6.9.4.1. Travel rate | Travel rate< 1 ft/s | Sampling truck instrumentation<br>Procedural evaluation | The travel rate for the grapple and the RLU shall not exceed 1 foot/sec. | 3 | Controlled travel rate mitigates potential for frictional sparking.<br>See Section 4.3.6. | With excessive travel rates, no FG/RMCS activities can proceed until procedural corrective actions are implemented. |
| 6.9.4.2. Load | RLU load < 250 lbf | Sampling truck instrumentation<br>Procedural evaluation | An administrative control shall be developed and implemented for handling RLU loads > 250 lbf. | 3 | Controlled loads prevent sampler drop consequences and potential for fire.<br>See Sections 4.3.2 and 4.3.6. | No FG/RMCS activities can proceed until procedure is implemented. |
| **6.9.5. X-ray** | | | | | | |
| 6.9.5.1. Sampler insertion | Minimize waste accumulation in X-ray | Visual inspection<br>Procedural evaluation | An administrative control shall be developed and implemented preventing a known leaking sampler, or sampler contaminated in excess of Contractor controls, to be placed into the mobile X-ray system. | 3 | Mitigates waste-generated gas accumulation.<br>See Sections 4.1.4 and 4.1.5. | No FG/RMCS activities can proceed until procedural corrective actions are implemented. |
| 6.9.5.2. X-ray sample liner | Minimize waste or flammable gas entering X-ray | Procedural evaluation | A redundant barrier shall protect the X-ray system from flammable gas penetrating into the system, and from sampler contamination. | 3 | Prevents flammable gas in proximity with X-ray ignition source.<br>See Section 4.1.5. | No FG/RMCS activities can proceed until procedural corrective actions are implemented. |
| **6.9.6. Exhauster** | | | | | | |
| 6.9.6.1. Duct inspections | Prevent duct leaks and static-induced sparking. | Procedural evaluation<br>Visual inspection | The exhauster duct shall be visually inspected for leaks and adequately supported for environmental loads before FG/RMCS operations, and after any situation the operators | 3 | Inspecting verifies hose functional capabilities.<br>Reduces likelihood of above ground fire that could | No FG/RMCS activities can proceed until duct has been inspected. |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
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| | | | believe the duct may have been damaged. | | propagate into the dome.<br>See Section 4.1.4. | |
| 6.9.6.2. Operations | Operate exhauster 1 hr before purge established, during rotary drilling, and 16 hours following purge termination. | Procedural evaluation | An administrative control shall be developed and implemented that mandates that the exhauster be fully operational:<br>• 1 hour before the nitrogen purge flow to the DS is established at 30 scfm, and the flammable gas concentration < 1000 ppm<br>• during all rotary drilling operations<br>• cumulative 16 hours following termination of nitrogen purge flow to the DS.<br>When rotary drilling operations are resumed within any 16 hour waiting period, a new 16 hour period will be initiated following termination of DS nitrogen purge flow of 30 scfm.<br>The PIC shall be authorized to prematurely terminate exhauster operation for external events that threaten personnel or equipment. | 1 | Flammable gas concentrations are mixed, dispersed and reduced with exhauster preparation. Accumulation of aerosols, particulates and flammable gases following waste intrusive activities must be minimized.<br>This mitigates unacceptable offsite consequences resulting from a dome collapse.<br>See Sections 4.1.1 and 5.4.2. | No DS nitrogen purging or waste-intrusive activities can proceed unless the exhauster is operational.<br>With noncompliance to procedures, no FG/RMCS activities can proceed until procedural corrective actions are implemented. |
| 6.9.6.3. Riser aerosols | Mitigate aerosol, particulates and gas releases | Radiation monitoring procedures | An administrative control shall be developed and implemented that:<br>• prevents opening a riser within 1 hour following termination of rotary drilling, and<br>• limits the riser open period to less than 8 hours per activity. | 2 | Limited open riser time reduces the potential for aerosol, particulate and gas releases.<br>See Section 5.4.1. | For periods greater than 8 hours, no FG/RMCS activities can proceed until procedural corrective actions are implemented. |
| 6.9.6.4. Exhauster-induced tank pressure | Tank pressure<br>• <atmospheric pressure, and<br>• $\geq$ -3 in. w.g. | Procedural evaluation | Exhauster operation shall not draw a tank pressure less than value specified in approved IOSR. | 1 | Mitigate excessive tank negative pressure, potential for dome collapse.<br>This mitigates | No FG/RMCS activities can proceed until tank pressures are in the specified limits. |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
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| | | | | | unacceptable offsite consequences resulting from a dome collapse.<br>See Section 4.6.1. | |
| 6.9.6.5. HEPA radiological monitoring | HEPA filter housing loading < 100 mrem/hr contact dose rate on filter housing | Radiological monitoring procedures | An administrative control shall be developed and implemented for manually monitoring the HEPA filter housing loading daily during operations for radioactivity.<br>• HEPA filter housing radiological loading shall be limited to < 100 mrem/hr contact dose rate. | 3 | Control prevents accumulation of radioactive waste particulate on HEPA filters reduces the likelihood of unfiltered releases. See Section 4.8.8.1 and Appendix R. | If the radiological levels are exceeded, then no waste-intrusive FG/RMCS activities can proceed until the HEPA filters are changed. |
| 6.9.6.6. Operational-induced exhauster shut down | Exhauster flow during operation<br>• <250 scfm, and<br>• >150 scfm | Exhauster detection system | The exhauster shall automatically shutdown and send a shutdown signal to the truck PLC:<br>• immediately with > 5.9 psid differential pressure across the HEPA filter bank, or<br>• after 5-6 minutes for ≥250 scfm high flow, or<br>• immediately with ≤150 scfm low flow.<br>An administrative control shall be developed and implemented for timely exhauster restart: following an operational shut down. | 3 | Exhauster operation in out-of-tolerance condition can impair overall exhauster performance and could result in unfiltered radioactive waste releases, toxic gas release, exposure of radioactive waste to workers.<br>To prevent tank overpressurization due to purge gas.<br>To prevent unacceptable vacuum in the dome<br>To provide acceptable emission of radioactive waste particulates. | Upon detection, the exhauster will shut down within 5-6 min. when flow exceeds 250 scfm. If drilling, the drill rig engine will automatically trip and automatically close the nitrogen purge flow SOV.<br>No FG/RMCS activities can proceed until the cause of shut down is identified and corrected. |
| **6.9.7. DS Nitrogen purge system** | | | | | | |
| 6.9.7.1. Bypass leakage verification | Ensure sufficient nitrogen purge flow | Procedural evaluation and | The nitrogen purge system for the DS shall be tested for bypass | 1 | Bypass leakage testing ensures that | No nitrogen purge flow activities can |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
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| | during rotary drilling | verification | leakage every 6 months, with independent verification and indication of failures.<br>System leak rates must be within the uncertainty range of the instrumentation system, or less than 2% of the required flow. | | the purge flow is adequately provided to drill bit for cooling during drilling.<br>This mitigates unacceptable offsite consequences resulting from a dome collapse.<br>See Section 4.4.1. | proceed unless testing has been completed, and flow levels increased as appropriate. |
| **6.9.8. Riser/sleeve Purge Flow** | | | | | | |
| 6.9.8.1. Bypass leakage verification | Ensure adequate purge in sleeve to DS annulus | Procedural evaluation | The nitrogen purge system for the sleeve to DS annulus shall be tested for bypass leakage every 6 months, with independent verification and indication of failures. | 3 | Bypass leakage testing ascertains nitrogen flow in annulus.<br>See Section 4.2.4. | No nitrogen purge flow activities can proceed unless testing has been completed, and flow levels increased as appropriate. |
| **6.9.9. Hydrostatic Head** | | | | | | |
| 6.9.9.1. Bypass leakage verification | Mitigate waste flooding | Procedural evaluation and verification | The hydrostatic head systems for the DS and the SR will be tested for bypass leakage every 6 months, with independent verification and indication of failures.<br>System leak rates must be within the uncertainty range of the instrumentation system, or less than 2% of the required flow. | 3 | Ensure hydrostatic head capabilities before sample retrieval.<br>Prevents inadvertent waste and flammable gas accumulation in the drill string during retrieval of core samplers.<br>See Section 4.3.1. | No hydrostatic head activities can proceed unless testing has been completed. |
| **6.9.10. Instrumentation and controls** | | | | | | |
| 6.9.10.1. I&C | Ensure accurate I&C measurements | Procedural evaluation and verification | All exhauster and truck shut down shutdown indication system elements shall be calibrated every 6 months with independent verification and tested with indication of all failures. | 1 | Periodic calibration ensures accuracy.<br>Control provides assurances for critical measurements, proving protections for waste, dome ,drill string fires, to | With noncompliance, no FG/RMCS activities can proceed until procedural corrective actions are implemented. |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
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| | | | | | be adequate during RMCS operations.<br>This mitigates unacceptable offsite consequences resulting from a dome collapse.<br>See Section 4.0. | |
| **6.9.11. Rotary Drilling Operations** | | | | | | |
| 6.9.11.1. Installation and removal of drill rod, spray washer and change-out assembly | Restrict ignition sources around open risers | Procedural evaluation | Activities and use of tools around open risers shall be strictly controlled during installation and removal of the drill rod, spray washer and change-out assembly. | 3 | Limits potential for inducing spark in flammable environment.<br>See Section 4.3.1. | With noncompliance, no FG/RMCS activities can proceed until procedural corrective actions are implemented. |
| 6.9.11.2. Last sampler | Terminate drill 3 in. From bottom | Procedural evaluation | Based on evaluation of the depth to the tank bottom, drill string length shall be calculated to terminate drilling $\geq$ 3 inches above the tank bottom. | 3 | Reduces the likelihood of the bottom liner penetration.<br>See Section 4.6.2.<br>Appendix N | With noncompliance, no FG/RMCS activities can proceed until procedural corrective actions are implemented. |
| **6.9.12. Rotary Drilling Operational Parameters** | | | | | | |
| 6.9.12.1. Down force | DS down force $\leq$ 750 lbf | Force detector and walkdown function used for all samples except the last<br>The force detector and the hydraulic bottom detector used for the last sample<br>Procedural evaluation and verification | The drill string shall not be operated with a down force > 750 lbf.<br>• The drill rig engine shall automatically shut down with down force > 750 lbf.<br>• Automatic shutdown signal is assumed to occur within 2 seconds for out-of-tolerance conditions.<br>• The force detector shall be used for all samples, automatically armed. The walkdown function used for all samples except the last, shall be enabled using independent verification. | 1 | Drill bit overheating and waste ignition is prevented, while factoring the potential effects of DS failure.<br>Control prevents a local exothermic chemical reactions as well as an ignition of flammable gas in the waste, consequently a possible dome collapse due to | With noncompliance, the DS will shut down. Nitrogen purge and exhauster systems will remain operational within specified limits.<br>No FG/RMCS activities can proceed until procedural corrective actions are implemented. |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
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| | | | The hydraulic bottom detector used for the last sample, shall be enabled using independent verification. | | frictional sparks.<br>This mitigates unacceptable offsite consequences resulting from a dome collapse.<br>See Sections 4.4.1, 4.4.4, and 4.6.3. | |
| 6.9.12.2. Down Force with DS length > 45 ft. | DS down force $\leq$ 650 lbf | Walkdown function used for all samples except the last<br>The hydraulic bottom detector used for the last sample<br>Procedural evaluation and verification | An administrative control shall be developed and implemented that manually maintains the down force < 650 lbf with DS length >45 ft. | 3 | Prevent drill string failure.<br>See Section 4.2.1. | With noncompliance, the DS will be manually shut down. Nitrogen purge and exhauster systems will remain operational within specified limits.<br>No FG/RMCS activities can proceed until procedural corrective actions are implemented. |
| 6.9.12.3. RPM | DS rotational speed $\leq$ 55 rpm | RPM detection system<br>Procedural evaluation<br>One out of two redundant logic | The drill string shall not be operated with rotational speed > 55 rpm.<br>• The drill rig engine shall automatically shut down with DS rotational speed > 55 rpm.<br>• Automatic shutdown signal is assumed to occur within 2 seconds for out-of-tolerance conditions. | 1 | Drill bit overheating and waste ignition is prevented, while factoring the potential effects of DS failure.<br>Control prevents local exothermic chemical reactions as well as an ignition of flammable gas in the waste, consequently a possible dome collapse due to frictional sparks.<br>This mitigates unacceptable | With noncompliance, the DS will shut down. Nitrogen purge and exhauster systems will remain operational within specified limits.<br>No FG/RMCS activities can proceed until procedural corrective actions are implemented. |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
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| | | | | | offsite consequences resulting from a dome collapse.<br>See Sections 4.4.1., 4.4.4, and 4.6.3 | |
| 6.9.12.4. RPM with DS length > 45 ft | DS rotational speed $\leq$ 40 rpm | RPM detection system<br>Procedural evaluation | An administrative control shall be developed and implemented that manually maintains the rotational speed < 40 rpm with DS length >45 ft. | 3 | Prevent drill string failure.<br>See Section 4.2.1. | With noncompliance, the DS will be manually shut down. Nitrogen purge and exhauster systems will remain operational within specified limits.<br>No FG/RMCS activities can proceed until procedural corrective actions are implemented. |
| 6.9.12.5. Nitrogen purge flow | DS nitrogen purge $\geq$ 30 scfm | Purge flow detection system<br>Procedural evaluation | The DS shall be purge with nitrogen at $\geq$ 30 scfm.<br>• The drill rig engine shall automatically shut down with nitrogen flow less than 30 scfm, using two out of three redundant logic.<br>• Automatic shutdown signal is assumed to occur within 2 seconds for out-of-tolerance conditions.<br>• Nitrogen purge gas temperature entering the tank shall be > 10°F and < 140°F. | 1 | Drill bit overheating and waste ignition is prevented.<br>Control prevents a local exothermic chemical reactions as well as an ignition of flammable gas in the waste, consequently a possible dome collapse due to frictional sparks.<br>This mitigates unacceptable offsite consequences resulting from a dome collapse.<br>See Sections 4.4.1, 4.4.4, and 4.6.3. | With noncompliance, the DS will shut down. Nitrogen purge and exhauster systems will remain operational within specified limits.<br>No FG/RMCS activities can proceed until procedural corrective actions are implemented. |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
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| 6.9.12.6. Riser/sleeve purge operations | Sleeve to DS annulus purge $\geq$ 2 scfm | Designated measurement system<br>Procedural evaluation and verification | The sleeve to DS annulus shall be purged with nitrogen at $\geq$ 2 scfm during rotary drilling operations.<br>• Nitrogen flow in the sleeve to DS annulus shall be verified before rotary drilling operations, using independent verification.<br>• Nitrogen purge $\leq$ 40 psid shall be alarmed and will automatically shut down the drill rig with one out of two redundant logic. | 3 | Prevents accumulation of flammable gas in the riser and consequently a dome fire caused by the frictional spark between the rotating drill string and sleeve.<br>See Section 4.2.4. | No FG/RMCS activities can proceed until nitrogen purge flows are adequately established. |
| 6.9.12.7. Slow penetration rate | Prevent extended waste heatup and ignition | Penetration detection system<br>Procedural evaluation<br>One out of two redundant logic to trip DS | The DS shall not be operated with a penetration rate < 0.75 in./min for $\geq$ 60 seconds.<br>• The DS shall automatically trip when the penetration rate is <0.75 in./min. for a cumulative time of 60 seconds in any 3 min. period.<br>The drill bit shall be replaced if drilling is shutdown four times consecutively as a result of low penetration rate, and if the cumulative penetration is <0.3 in. for the last three attempts. | 1 | Waste burn induced by slow penetration is negated.<br>Control prevents a local exothermic chemical reactions as well as an ignition of flammable gas in the waste, consequently a possible dome collapse due to frictional sparks.<br>Control also prevents drilling against materials not covered by envelope testing. Prevents the ignition of flammable gas due to hot spots (exceeding autoignition temperature).<br>Provides protection against severe drill bit tooth wear and protects the Carbon | With noncompliance, no FG/RMCS activities can proceed until procedural corrective actions are implemented. |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
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| | | | | | Steel Blank from exposure to metals.<br>This mitigates unacceptable offsite consequences resulting from a dome collapse.<br>See Sections 4.4.1, 4.4.4 and 4.6.3 | |
| **6.9.13. Shut down and Restart Conditions** | | | | | | |
| 6.9.13.1. Drill Rig shut down | Prevent drill bit overheating | Alarmed setpoints | The drill rig shall automatically shut down with out-of-tolerance values for down force, RPM, nitrogen purge or penetration rate, operational exhauster shutdown, or upon detection of a GRE.<br>A minimum 10-minute wait period shall be imposed following automatic drill rig shut down before any waste-intrusive activities can be resumed. | 1 | Wait period allows cool down of drill bit and localized waste temperatures due to out-of-tolerance down force, RPM or purge flow values.<br>Control ensures that the initial local waste temperature is in thermal equilibrium with the tank waste and provides assurances for drill bit/waste temperature not to be exceed above allowable limits.<br>This mitigates unacceptable offsite consequences resulting from a dome collapse.<br>See Section 4.4.1.1. | No FG/RMCS activities can proceed until wait period is satisfied. |
| 6.9.13.2. GRE shut down | Protect personnel | Alarmed setpoints | A GRE is defined to occur when:<br>• > 5000 ppm hydrogen concentration equivalent, or<br>• > 100 ppm/s rate of equivalent hydrogen concentration | 1 | Automatic shut down during GRE prevents exposure to flammable gas concentrations sufficient for ignition. | All personnel within a 100-m radius from the edge of the tank will evacuate and don protective equipment before |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
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| | | | increase over a 10-s period, or<br>• > 2 in. w.g. increase in a 5-6 minute period above the tank background pressure.<br>Upon detection of a GRE, the exhauster will continue to operate, and drill rig operation will be terminated | | Reduces the possible spark sources in the dome, waste and around drill string.<br>Provides protection for toxic gas exposures.<br>This mitigates unacceptable offsite consequences resulting from a dome collapse.<br>See Appendix B. | returning for further equipment stabilization. |
| 6.9.13.3. GRE restart | Minimize unanticipated ignition sources following GRE. | Procedural evaluation and verification | An administrative control shall be developed and implemented for restart following GRE. | 3 | Flammable gas removal following a GRE is enhanced by exhauster operation and the use of pressure measurement systems qualified to operate in a Class I, Division 1, Group B environment.<br>Appendix B. | FG/RMCS activities cannot resume until restart requirements are implemented and flammable gas concentration limits are met. |
| 6.9.13.4. Power loss restart | Prevent unanticipated ignition sources following power loss. | Procedural evaluation | An administrative control shall be developed and implemented for restart following power loss to include:<br>• The DS shall be sniffed and purged following shut down caused by power loss, sufficiently to evacuate flammable gas accumulations.<br>• Hydrostatic head shall be reestablished.<br>• The exhauster shall be restarted following a power loss event. | 3 | Loss of hydrostatic flow from a power loss can allow waste flooding and gas release into DS and SR.<br>See Section 4.1.6. | FG/RMCS activities cannot proceed until restart requirements are implemented. |
| **6.9.14. Water addition** | | | | | | |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
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| 6.9.14.1. Quantity | Minimize water addition | Procedural evaluation | Per activity, water addition shall be limited to < 250 gallons in compliance with approved Tank Farm Operating Procedures. Increased water addition quantities shall require PRC approval. | 3 | Contractor control<br>See Section 4.5.2 and Appendix O. | No FG/RMCS activities can proceed until procedural corrective actions are implemented. |
| 6.9.14.2. Temperature | Prevent unanticipated temperature-induced, waste-related chemical reactions | Temperature measurement | The temperature of added water shall be limited to < 200°F in compliance with approved Tank Farm Operating Procedures. | 3 | Contractor control<br>See Section 4.5.2 and Appendix O. | No FG/RMCS activities can proceed until water temperature is within specified limits. |

| System or Condition | SCO | Surveillance/ Monitoring | Administrative Controls | Level | Basis for Control | Safe Shut Down Condition |
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| **6.10. Removal Phase** | | | | | | |
| **6.10.1. DS Removal** | | | | | | |
| 6.10.1.1. DS removal | Reduce gas production and ALARA personnel exposures | Procedural evaluation | DS shall be removed to above the waste surface level only with the last sampler, a dummy sampler or water in place, in compliance with approved Tank Farm Plant Operating Procedures | 3 | Minimize gas release potential.<br>See Section 4.1.3. | Removal and decontamination activities cannot proceed until procedural control is implemented. |
| **6.10.2. Decontamination** | | | | | | |
| 6.10.2.1. Decontamination system | Complete DS decontamination | Procedural evaluation | Decontamination systems shall be verified operational before DS removal in compliance with approved Contractor procedures. | 3 | Verification ensure decontamination capabilities.<br>See Section 5.4.2. | No decontamination activities can proceed until system operability is verified. |
| 6.10.2.2. Riser exposure | Minimize radioactive releases | Radiation monitoring procedures | • Personnel direct exposure from open riser shall be limited to values specified by approved Tank Farm Operating Procedures.<br>• Riser open period shall not exceed 8 cumulative hours per activity. | 3 | Minimize personnel direct exposure from open riser conditions.<br>See Section 4.8.8.4, 4.8.8.5 and 5.41. | No FG/RMCS activities can proceed until personnel protection is appropriately ensured. |
| 6.10.2.3. Drill rod removal | Minimize radioactive releases | Radiological monitoring procedures<br>Procedural evaluation and verification | Drill rods shall be monitored and controlled as they are removed commensurate with approved Tank Farm Plant Operating Procedures. | 3 | Limit unfiltered, uncontained releases to environment, as required by Contractor controls.<br>See Section 4.8.5, 4.8.6, 4.8.7 and 5.4.2. | With noncompliance, no decontamination activities can proceed until procedural corrective measures are implemented. |

# 7.0. READINESS REVIEW AND CHECKLIST ITEMS

This safety assessment (SA) assessed safety aspects of the installation, operation, and removal of rotary-mode core sampling (RMCS) equipment in single-shell tanks (SSTs) on the Flammable Gas Watch List (FGWL) or those tanks recommended by the contractor to be included on the FGWL, hence referred to as FG/RMCS operations. The SA was completed before some of the experimental programs supporting the SA and design documentation of the rotary-mode core sampling were complete. Some of the design information includes system schematics and operating procedures provided by Westinghouse Hanford Company (WHC), verbal information from cognizant WHC engineers and technicians, and published sources of data for component reliability.

This SA was prepared with the knowledge that additional areas of concern must be reviewed before this SA becomes a safety basis for FG/RMCS operations. This section provides a readiness review checklist of key safety items that require some additional evaluation. Completion of these tasks is necessary before rotary-mode core sampling in single-shell tanks may be initiated.

In general, the closure of the open issues require the review and approval of the Plant Review Committee (PRC). The PRC may charter a separate technical review group to perform the review and approval responsibilities of the PRC.

## 7.1. Assumptions in Design and Procedures

An operational readiness review will ensure that assumptions in regard to design specifications, definition of operation, and procedures made in this SA are reviewed against the published version of references used in this SA. Any discrepancy or changes in procedures, design and system description, or safety design features require the application of an unresolved safety question (USQ) screening process. When operating procedures based on this SA are complete, they must be reviewed to ensure consistency between the SA and the procedures.

## 7.2. Envelope Testing

Envelope testing was performed to determine safe operating parameters. During the development of this SA, draft data sent by fax or e-mail was used. A formal WHC report documenting the envelope testing and its results and conclusions is being prepared. The analysis was performed using the draft data and presented our results and conclusions in Appendix F. When the formal WHC test reports are published, the analyses and their conclusions must be verified by the PRC to ensure consistency with the conclusions from the analyses provided in this SA.

### 7.3. Bureau of Mines Ignition Test Program

The requirements and the acceptance criteria for the ignition tests (sparking and hot spot formation) are listed in Appendix T of this SA. The tests and the associated analyses must be completed, documented and approved by the PRC before this SA may be used as a safety basis document for FG/RMCS operations in flammable gas single-shell tanks.

### 7.4. Flammable-Gas Meter Implementation Calibration

The exhauster design includes a redundant flammable-gas detection system to trip the drill truck. The SA assumes that this system will provide adequate protection for the flammability hazards of hydrogen and ammonia. The protection against the toxic hazard of ammonia is also assumed to be provided by the detection system.

The requirements for the flammable gas detectors are listed in Appendix U of this SA. PRC must review and approve the 100% design review package to assure that the SA requirements are met. The system must be installed, tested and declared operational prior to RMCS operations in the tanks.

### 7.5. Drill Bit Waste Compatibility

WHC will update the waste compatibility report to include results of the drill bit and drill string components use in actual waste. The report must be made available as part of the readiness review package.

### 7.6. Flexible Duct Material and Resistivity

The flexible hose is at least 1/32 in. thick and made of neoprene over a polyester base. It is conductive from the inner to the outer layer, and the vendor information indicates the conductivity of the flexible duct is $\leq$ 1 Mohms per square inch. Data shall exist to verify that the flexible duct material meets the above requirements

### 7.7. Development of the OSRs and SCE List

Before beginning FG/RMCS activities in flammable gas single-shell tanks, Operational Safety Requirements (OSRs) and Safety Class Equipment (SCE) List must be developed based on the analysis provided in this SA. The OSRs must be implemented into the Interim Safety Basis Document and into the RMCS operation procedures.

If additional Level 1 Controls are found to be necessary as a result of actions needed to close the open items, the SA must be reviewed and approved prior to operations.

## 7.8. Checklist Items

This SA was developed using bounding assumptions. However, these assumptions are not verified against each one of the existing or potential flammable gas tanks (see Section 1 of this SA). The following assumptions must be verified before this SA can be used for RMCS operations in any FGT.

### CHECKLIST ITEMS

| TANK SPECIFIC HAZARDS/OTHER WATCHLISTS |
|---|
| If a given tank has a specific hazard or accident initiator that is not analyzed in Sections 3 and 4 of this SA, the analysis must be supplemented to cover the tank specific conditions. For instance, this SA does not address ferrocyniade issues even though some of the FGTs may also be on the ferrocyianite watchlist. This checklist item is especially important for tanks that are on multiple watchlists (in addition to flammable gas watchlist). |
| **FLAMMABLE GAS COMPOSITION** |
| This SA assumes that 25% of the LFL is greater than 5000 ppm hydrogen based on the analysis provided in Appendix C. The only flammable gas species considered are hydrogen and ammonia with small amounts of methane. If new information (information that is not cited in Appendix C) reveals that, for a given tank, there are other flammable gas species and/or the assumed value of the LFL is not conservative, the analysis in Appendix C must be revised to incorporate the new data. |
| **TOXIC GAS COMPOSITION** |
| For toxic effects, the gas composition in a given GRE is assumed to be 60% ammonia or 75% nitrous oxide. If any evidence before the FG/RMCS operation exists to indicate that these values (especially the ammonia fraction) may be exceeded in one of the SSTs as a result of new analysis or data, or if they are not conservative, the consequence analysis must be re-evaluated. This can be achieved by simply scaling the new data with the 60% fraction used in the consequence analysis.<br><br>Also, the results of vapor space sampling program were reviewed. Major toxic gases that are found in the dome space of the presently defined flammable-gas tanks are ammonia and nitrous oxide. Other gases are found in trace quantities and do not pose a concern. However, it was recognized that the existing data are limited and all tanks of interest are not covered. Thus, if new data reveal that toxic gases in excess of the hazardous limits are detected in a given tank, the consequence analysis must be reevaluated. The reevaluation may be done by simply scaling the toxic gas fraction and the guidelines against the ammonia fraction and the associated RGs. |
| **WASTE TEMPERATURE** |
| The best available tank temperature data must show that the peak waste temperature (considering uncertainties) must be less than 90°C. If the peak waste temperature is ≥ 90° C, the envelope testing results discussed in Appendix F must be re-evaluated. |

CHECKLIST ITEMS (Cont.)

| WASTE ENERGETICS |
| --- |
| This SA covers the RMCS operations only in those tanks listed in Appendix G, Table G-3. A revision to the SA is necessary to extend the list using the discussion provided in Section 4.2.3 of Appendix G. |
| **LIKELIHOOD OF GAS RELEASE EVENTS** |
| The GRE probability includes statistical distributions for gas-release amounts and rates that are based on limited data and expert judgment. If additional data or analyses exist for a specific tank to indicate that the GRE probabilities used in this SA are not conservative, the accident frequencies need to be re-evaluated for that tank.<br><br>In general, before the FG/RMCS operation starts on a given tank, the best available tank specific data for gas inventory and gas release evidence must be evaluated to confirm that the statistical model for gas-release amounts and rates used in the SA are still conservative. In general, if one or more of the following conditions are observed for a given tank, the GRE probability model given in Appendix L must be re-evaluated.<br><br>• Periodic level drops and level swells in excess of ± 3 in.<br>• Level drop ≥ 3 in. during or after an intrusive event<br>• Dome concentration measurements ≥ 25% of the LFL before, during or after a waste intrusive event.<br>• A well defined nonconvective layer (parabolic temperature profile) below a supernate or convective layer (flat temperature profile) that would be indicative of potential rollovers.<br>• Retained gas inventory estimates (via level swell, fill history, etc) is greater than 20% of the available dome space volume.<br><br>If the re-evaluation indicates that the existing GRE model given in Appendix L is not conservative for a given tank, a revision to the SA will be necessary. |

# APPENDIX B

# EQUIPMENT RATING AND AUTOMATIC SHUT-DOWN REQUIREMENTS

## 1.0. OBJECTIVE

The objective of this appendix is to provide the basis for the requirements imposed on equipment capable of generating sparks in a flammable-gas environment. Also included in this appendix are the trip set points necessary to shut down the equipment that is not designed to operate in a flammable-gas environment.

## 2.0. BACKGROUND

The gas-retention and release mechanisms in the waste tanks are not fully understood. The understanding is even poorer for the single-shell tanks (SSTs). Although semi-quantitative estimates are available for SST gas-release mechanisms,[1] in the absence of detailed data, it is difficult to argue that such analyses provide bounding estimates. The gas composition and maximum allowable gas-release estimates provided in Appendix C show that, in some of the SSTs, small releases may result in a flammability hazard. Our current understanding of the gas-release phenomena in the SSTs is limited and does not allow us to develop reliable administrative controls to limit or control the gas releases during the proposed intrusive activities. Consequently, the major emphasis in this safety assessment (SA) is on managing the spark sources when flammable gases are present. Furthermore, a burn even with a small amount of flammable gas in the tank dome space is likely to result in dome failure (Appendix C), which may result in unacceptable radiological and toxicological consequences (see Section 5 of this SA) if the failure is catastrophic.

As with gas releases, gas-storage mechanisms are poorly understood. Waste gases may be stored in the waste in the form of elongated/dentritic bubbles that may be connected through the pores. Demonstrating that an ignition in the waste will not propagate also is difficult without a detailed knowledge of pore sizes, heat dissipation mechanisms, and the moisture content in the pores. The pressure resulting from a burn in the waste, the subsequent damage to the tank, and amount of material release is difficult to bound. Consequently, this SA is aimed at preventing ignition inside the waste as opposed to demonstrating that propagation is impossible.

Under these conditions, as a general rule, design restrictions are imposed so that no single failure should lead to sparking conditions. A minimum of double engineering protection against a sparking condition is required. These requirements are developed assuming that the likelihood of flammable-gas presence during the activity is high.

## 3.0. SAFETY RATING REQUIREMENTS

During the proposed intrusive activities, the following regions must be carefully protected from possible spark sources:

- Tank dome space,
- Regions below the waste surface (waste volume),
- Confined regions with possible flow paths to waste or waste gas in-leakage and accumulation,
- Pump pits (if not sealed from the dome),
- A specified region outside an open riser or a leak path,
- Tanks adjacent and connected to the subject tank, and
- Other equipment connected to the dome space.

### 3.1. Electrical Equipment

Before beginning the discussion of safety requirements for the electric equipment, it is important to note that the intent of this section is not to develop a National Fire Protection Association (NFPA) classification for the tank farms. NFPA classification requirements are used merely as a guidance in achieving the desired very low frequencies for the burn accidents.

During FG/RMCS operations, all electrical equipment located in these regions must be rated to operate in a Class-I, Division-1 (Div.-1) Group-B environment according to National Fire Protection Association (NFPA) classification. Recognizing the fact that the flammable gases will not continuously exist in these regions, Class-I, Div.-2, Group-B-rated equipment may also be operated in these regions provided they are equipped with a reliable automatic shut-down system. It requires an unlikely sequence of multiple failures and malfunctions for Class-I, Div.-1, Group-B-rated equipment to cause a spark.

Class-I, Div.-2, Group-B equipment is capable of sparking upon single failure. Consequently, such equipment must be protected by a reliable shut-down circuit. Furthermore, the background concentrations of flammable gases must be measured and shown to be less than 25% of the lower flammability limit (LFL) before energizing this equipment. In order to cause a spark, a sequence of double independent failures are necessary (the shut-down circuit must fail, and the Class-I, Div.-2, Group-B equipment must also fail simultaneously). If Class-I, Div.-2, Group-B equipment is used in the above regions, the reliability of the shut-down

circuit must be evaluated and must be shown that it will perform with a desired reliability.

All equipment that must continue to operate upon detection of flammable gases must be designed to Class-I, Div.-1, Group-B requirements. Examples of such equipment are the ventilation fan needed to discharge the flammable gases and flammable-gas monitoring equipment.

Regions immediately adjacent to the Class-I, Div.-1, Group-B regions discussed above are automatically classified as Class-I, Div.-2, Group-B spaces, and the equipment must meet the requirements of this classification.

### 3.2. Mechanical Systems

All moving mechanical systems capable of generating frictional forces must be assumed to be sparking, unless bounding analyses or experiments show otherwise. Without specific experiments, it is very difficult to demonstrate that such mechanical systems will not generate sparks capable of igniting the flammable mixtures of interest. Consequently, such mechanical systems also must have double protection against either sparking or being exposed to a flammable atmosphere. The necessary protective measures could be a combination of the following systems:

- Spark-resistant and electrically conductive material(s) (to protect against static electricity buildup) must be used in the regions specified above.
- Mechanical devices must be protected by a seal that prevents waste or flammable-gas in-leakage.
- The region around the mechanical device must be protected by an adequate purge. The adequacy of the purge system must be demonstrated by analysis.
- Upon loss of purge flow, the system must be quickly deenergized.
- Upon detection of flammable gases, the system must be quickly deenergized before the gas mixture reaches the LFL.

As a minimum, two of the above methods must be used to protect the mechanical systems capable of sparking. Depending upon the reliability required by accident analysis, more than two systems may be necessary.

### 3.3. Equipment Over the Tank Dome

Using an algebraic momentum jet model,[2] flammable gas concentration as a fraction of the source concentration may be obtained from the following equation:[2,3]

$$\frac{C_c}{C_o} = \frac{(\lambda^2+1)}{\lambda^2} \frac{0.25}{\left[1.414\alpha\frac{(s-s_o)}{D}+0.5\right]} \quad \text{for } s \geq s_o \quad , \qquad \text{(B-1)}$$

where $C_c$ is the centerline concentration, $C_o$ is the source concentration, $s_o$ is the jet length in the establishment zone ($s_o$ = 6.2 x D), s is the distance to the source, D is the source diameter, $\lambda$ is the spreading parameter ($\lambda$ = 1.16 taken from Ref. 2) and $\alpha$ is the empirical entrainment parameter.

Setting the source concentration to 8% and using an entrainment parameter $\alpha$ = 0.057, the jet centerline concentration drops to 2.4% at a distance of 18 diameters. Using a Gaussian concentration profile,[2] the concentration drops to less than 0.6% at a radial distance of 2.2 x D from the jet centerline.[3] The centerline concentration drops to 1.2% at a distance of 36 x D away from the source.[3]

As discussed in Appendix C, 2.4% hydrogen corresponds to the LFL of gas mixtures that are very rich (70%) in ammonia and less than 30% in hydrogen. For these gas mixtures, prompt gas releases greater than 283 $m^3$ (10,000 $ft^3$) are required to exceed the 8% hydrogen concentration at the source. If one postulates pure hydrogen releases, only 113 $m^3$ (4000 $ft^3$) of prompt release may result in 8% hydrogen in the source. However, the LFL of hydrogen is 4%. A hydrogen concentration of 4% at 18 diameters away from the source corresponds to 13.3% hydrogen at the source, which requires a prompt release greater than 190 $m^3$ (6700 $ft^3$). These calculations are based upon a minimum dome volume of 1400 $m^3$ (50,000 $ft^3$). Therefore, it is believed that an 8% hydrogen concentration at the source combined with 2.4% hydrogen as the LFL provides a conservative bound. Based on the model discussed in Appendix L, the frequency of exceeding 8% hydrogen in the dome would be ~$10^{-3}$ per intrusion.

**Entrainment Parameter.** The use of $\alpha$ = 0.057 is conservative because this value is the lowest magnitude given in Ref. 2. Using the linear mixing law model and the momentum jet solution provided in Schlichting,[4] $\alpha$ is obtained as 0.087. As shown in Eq. (B-1), larger $\alpha$ results in enhanced dilution within a given distance. Furthermore, this analysis does not account for atmospheric turbulence that would further enhance the entrainment.

**Probability of Exceeding 2.4% Hydrogen.** Assuming a random spark source in the hemispherical region around an open riser, the probability of exceeding 2.4% hydrogen at the spark location is computed in Ref. 3 and shown in Fig. B-1. As shown in this figure, the probability of exceeding 2.4% hydrogen drops below $10^{-3}$ at distances ≥ 16 x D.

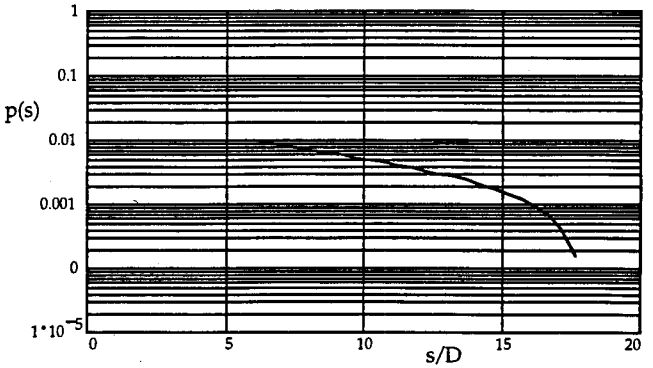



**Fig. B-1. Probability of exceeding 2.4% hydrogen.**

The jet direction is determined by the direction of the open area, initial momentum, buoyancy, and wind direction. In general, the open riser will result in a vertical jet unless the direction is affected by the wind. Thus, the above probabilities may be reduced further by not placing the equipment directly above an open riser and in the prevailing wind direction. The jet coming out of an opening is typically buoyant because

- The dome space is warmer than the ambient, and
- The waste gases are lighter than air if they are predominantly flammable (hydrogen, ammonia, and methane).

Thus, to reduce the probability of the equipment being exposed to a flammable atmosphere, the equipment should be placed near ground level and in the opposite direction to the prevailing wind direction. Furthermore, any opening directly aimed at the equipment location must be sealed, or the equipment must be protected from direct jet impingement.

Based on these conservative calculations, up to a distance of 18 diameters away from the source, the equipment must be rated for operation in a Class-I, Div.-1, Group-B environment. Equipment rated for Class-I, Div.-2, Group-B may also be used, provided it is automatically deenergized upon detection of flammable gases in the riser.

At distances from 18 x D to 36 x D, the equipment must be rated for operations in Class-I, Div.-2, Group-B environments and must be manually deenergized upon detection of flammable gases in the dome space.

If the above classification conditions cannot be met, the open riser must be equipped with a flame arrester to prevent flame propagation into the dome, provided that the consequences of an external fire are shown to be acceptable.

## 4.0. AUTOMATIC SHUT-DOWN REQUIREMENTS.

If an automatic shutdown of equipment upon detection of flammable gases is relied upon, the shut-down system

- must be reliable,
- must respond to rapid transient surges, and
- must be located near the equipment that will be shut down.

The reliability of the protective systems (shut-down systems) is discussed in Appendix D of this SA.

To protect against spatial maldistribution of gases in the dome space, the gas samples must be taken from the region where the target equipment is located. During operations with an active ventilation system, the sampling in the vent lines is adequate, provided the trip points are conservatively set.

The flammable-gas concentrations in the tank dome space are typically very low during the steady-state periods. Only during a gas-release event does the flammable-gas concentration start to increase. If the gas release rates are high, the flammable-gas concentrations may increase very rapidly. Slow detectors may not be able to perform their shut-down function adequately during fast gas-release events. In this SA, two detection mechanisms are considered,

- Trip on high hydrogen concentration or on a high rate of hydrogen increase, and

- Trip on high dome pressure.

### 4.1. Hydrogen Trip

The adequacy of a hydrogen detector time constant is assessed using the Wittaker cell analysis. The standard hydrogen monitoring systems (SHMS) that are used in the tank farms contain Wittaker hydrogen detection cells. These cells measure 90% of a step change in less than 2 min. [5] Assuming a first-order relaxation model that is adequate for diffusion-based devices, the time constant of the cell is obtained as 52 s (Ref. 6). Also using a first-order relaxation model and a constant rate of increase in hydrogen concentration expressed as

$$X_a(t) = \frac{(X_s - X_o)}{T} t + X_o \quad , \qquad \text{(B-2)}$$

where $X_a$ is the actual hydrogen concentration, $X_o$ is the background (initial) concentration, $X_s$ is the target concentration, T is the time necessary for the actual concentration to reach the target concentration, and t is the time. For a linear increase in the actual hydrogen concentration, the measured hydrogen concentration (X) may be obtained as[5]

$$X(t) = \begin{cases} (X_s - X_o)\frac{\tau}{T}\left(e^{-(t-t_d)/\tau} + \frac{(t-t_d)}{\tau} - 1\right) + X_o & t \geq t_d \\ X_o & t < t_d \end{cases} , \qquad \text{(B-3)}$$

where $t_d$ is the delay time (time that it takes to transport the dome gases to the instrument). Figure B-2 shows the necessary trip set points to deenergize the equipment before the dome concentration reaches 2.4% hydrogen. The following assumptions are used in obtaining the results shown in Fig. B-2:

- Initial background concentration ($X_o$) is 1000 ppm,
- After the trip is initiated, it takes 10 s to totally deenergize the circuits of interest,
- The monitor provides one data point per ~5 s, and a minimum of 10 s worth of data are needed for a rate trip,
- $X_s$ is set to 2.4%,
- Dome volume is equal to 1416 $m^3$ (50,000 $ft^3$), and
- 90% of the waste gas is hydrogen.

Based on Fig. B-2, by setting the trip point at 5000 ppm of hydrogen, the equipment can be deenergized on time if the release rate into the dome is $\leq$ 0.47 $m^3/s$ (1000 $ft^3/min$).

If a rate trip set at 100 ppm/s is used, such a trip will provide protection for release rates between 0.14 $m^3/s$ (300 $ft^3/min$) and 1 $m^3/s$ (2200 $ft^3/min$). Thus, in the range between 0.14 $m^3/s$ (300 $ft^3/min$) and 0.71 $m^3/s$ (1500 $ft^3/min$), the concentration trip and the rate trip will both deenergize the equipment before reaching the target concentrations. A rate trip of 100/s corresponds to a concentration increase of 1000 ppm over the 10 s averaging time. Setting the rate trip to lower values may result in premature and unnecessary shutdown when there are small fluctuations in the instrument readings.

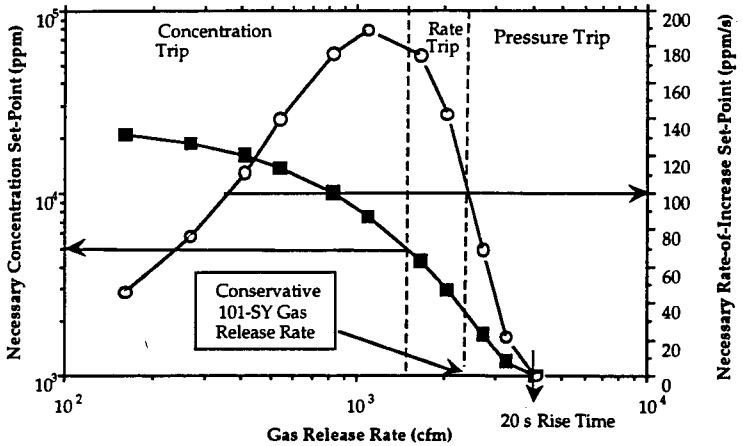



**Fig. B-2. Necessary trip points to shut down the equipment before the concentration reaches 2.4% hydrogen during constant rate of concentration increase.**

A trip based on hydrogen concentration is not adequate in protecting against gas-release rates ≥ 1 $m^3/s$ (2200 $ft^3/min$). Note that 1 $m^3/s$ (2200 $ft^3/min$) is the conservative gas-release rate obtained for 101-SY releases during the first 200 s of a rollover. Based on the analysis provided in Ref. 1, the best-estimate release rates for the most likely fast-release scenario in SSTs is 0.006 $m^3/s$ (12 $ft^3/min$).

### 4.2. Pressure Trip

No specific analysis is performed for the pressure traces during a large gas release. The experience in 101-SY demonstrated that for release rates as low as 0.19 $m^3/s$ (400 $ft^3/min$), the dome space experiences pressure pulse of 50.8 mm (2 in.) w.g. or greater. The pressure pulse is a function of the dome volume, relief area, and the pressure drop through the relief area. The relief area for Tank 101-SY is 0.145 $m^2$ (226 $ft^2$).

A pressure pulse of 50.8 mm (2 in.) w.g. would correspond to a 0.5% increase in the dome pressure. Using a dome volume of 1416 $m^3$ (50,000 $ft^3$), the ideal gas law and adiabatic compression, a 5.1 $m^3$ (180 $ft^3$) sudden release into the dome is sufficient to generate a 2-in. w.g. pressure pulse. Thus, large release rates ≥ 0.47 $m^3/s$ (1000 $ft^3/min$), a pressure switch set at 50.8 mm (2 in. w.g.) above the background pressure will detect the gas release and deenergize the equipment.

### 4.3. Automatic Shut-Down Trips

For deenergizing the equipment that does not meet Class-I, Div.-1, Group-B requirements, the automatic shut-down trip may be set by using the hydrogen detectors and a dome pressure gauge. The hydrogen detector switch must be set to $\leq$ 5000 ppm, and the pressure gauge trip must be set to 50.8 mm (2 in. w.g.) w.g. above the background pressure. The trip for the rate of increase must be set to 100 ppm/s (averaged over 10 s).

If flammable-gas monitors are used instead of a hydrogen detector, upon availability of the calibration curves, the flammable-gas monitor should be set to provide an equivalent trip to 5000 ppm hydrogen and a 100 ppm/s rate of increase in hydrogen. Also, it must be confirmed that the response time of the flammable-gas monitor is bounded by the assumptions listed above.

## 5.0. REFERENCES

1. R. T. Allemann, "A Discussion of Some Mechanisms for Sudden Gas Release from Single-Shell Waste Tanks," Pacific Northwest Laboratory letter report PNL-WTS-101095 (October 1995).

2. B. Gebhart, D. S. Hilder, and M. Kelleher, "The Diffusion of Turbulent Buoyant Jets," *Advances in Heat Transfer*, Vol. 16 (Academic Press, Inc., 1984).

3. K. O. Pasamehmetoglu, "Flammable Gas Concentration Outside an Open Riser," Los Alamos National Laboratory Calc-Note TSA10-CN-WT-SA-GR-044 (December 1995).

4. H. Schlichting, *Boundary Layer Theory*, 7th Edition, (McGraw-Hill, New York, 1979).

5. T. C. Schneider, "Wittaker Electro-Chemical Cell $H_2$ Monitoring System Accuracy," WHC Memorandum to G. F. Vargo (January 8, 1993).

# APPENDIX C

# BOUNDING GAS COMPOSITION, LEAN FLAMMABILITY LIMIT, AND ALLOWABLE GAS RELEASE AND BURN VOLUMES

## 1.0. OBJECTIVE

The objective of this appendix is to provide a bounding estimate for the gas composition of the waste gas that might be released during intrusive operations in single-shell tanks (SSTs) that are on the Flammable Gas Watch List (FGWL). This appendix also evaluates the bounding value for the lower flammability limit (LFL) for the estimated gas compositions. A brief summary of the maximum allowable gas-release volumes into the dome space and the maximum allowable burn volume in the waste are discussed in this appendix. Finally, the current estimates for the gas inventory in the tanks are summarized and compared to the maximum allowable releases.

## 2.0. SST DOME VOLUMES

The SST types are typically characterized by their waste storage capacity. The three types of interest and the associated tanks are summarized in Table C-1.

Figure C-1 shows a schematic of the different types of SSTs in which the characteristic dimensions taken from Reference 1 are given in Table C-1. The dome vapor space volumes are obtained assuming an ellipsoidal dome as shown in Fig. C-1, where H is the dome apex height, W is the height of the cylindrical tank, R is the tank radius, and L is the waste level. Using the approximate waste levels

**TABLE C-1**
**CAPACITY AND CHARACTERISTIC DIMENSIONS OF THE SSTs OF INTEREST**

| TYPE | CAPACITY (gal.) | TANKS | R (ft) | W (ft) | H (ft) |
|---|---|---|---|---|---|
| 1 | 1,000,000 | A-101, AX-101, AX-103, SX-101, SX-102, SX-103, SX-104, SX-105, SX-106 and SX-109 | 37.5 | 32.5 | 12.0 |
| 2 | 758,000 | S-102, S-111 and S-112 | 37.5 | 22.5 | 14.0 |
| 3 | 530,000 | T-110, U-103, U-105, U-107, U-108 and U-109 | 37.5 | 19.2 | 9.5 |

obtained from References 2 and 3, the dome volumes (V) are calculated[4] and reported in Table C-2. Also, the maximum drop height (Z) used during a dome collapse accident and the waste volume ($V_W$) are shown in Table C-2.

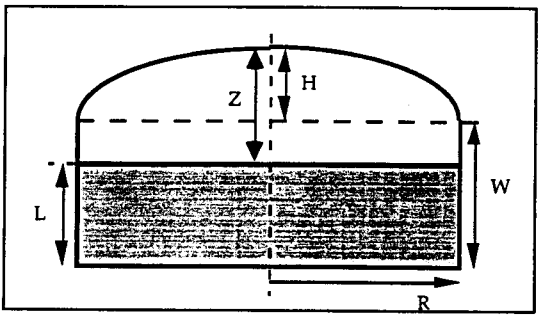



**Fig. C-1. Schematic of an SST.**
**(Dish bottom is not represented in this figure.)**

**TABLE C-2**
**DOME VOLUMES AND IMPORTANT DIMENSIONS**

| TANK | L (in.) | V ($ft^3$) | $V_W$ ($ft^3$) | Z (ft) |
|---|---|---|---|---|
| A-101 | 345 | 51,910 | 127,010 | 15.8 |
| AX-101 | 278 | 76,570 | 102,350 | 21.3 |
| AX-103 | 42 | 163,460 | 15,640 | 41.0 |
| SX-101 | 172 | 115,600 | 63,320 | 30.2 |
| SX-102 | 205 | 103,450 | 75,470 | 27.4 |
| SX-103 | 245 | 88,720 | 90,200 | 24.1 |
| SX-104 | 237 | 91,570 | 87,250 | 24.8 |
| SX-105 | 257 | 84,310 | 94,620 | 23.1 |
| SX-106 | 207 | 102,710 | 76,210 | 27.3 |
| SX-109 | 95 | 143,950 | 34,980 | 36.6 |
| S-102 | 205 | 65,160 | 75,470 | 19.4 |
| S-111 | 205 | 65,160 | 75,470 | 19.4 |
| S-112 | 197 | 68,110 | 72,530 | 20.1 |
| T-110 | 148 | 57,600 | 54,490 | 16.3 |
| U-103 | 167 | 50,600 | 61,480 | 14.8 |
| U-105 | 150 | 56,860 | 55,220 | 16.2 |
| U-107 | 168 | 50,240 | 61,850 | 14.7 |
| U-108 | 165 | 51,340 | 60,750 | 14.9 |
| U-109 | 145 | 58,700 | 53,380 | 16.6 |

## 3.0. GAS COMPOSITION

There is no direct measurement for the waste gas composition for any of the tanks. The waste gas composition must be inferred from dome space concentration data. Unfortunately, there are very limited data regarding concentration in the dome space of the SSTs. The SSTs that are on the FGWL are currently being instrumented with a standard hydrogen monitoring system (SHMS) for continuous hydrogen measurements. As a means of baselining the SHMS, vapor grab samples from the FGWL SSTs were taken during the summer of 1995, and the samples were analyzed using mass spectroscopy. The resulting data are reported in Reference 5. Only the noncondensable gases are identified in the grab samples.

### 3.1. Noncondensable Gas Composition

The sample analysis provided dome concentrations for hydrogen, methane, and nitrous oxide. The available data are converted to waste-gas composition, assuming that these three species make up the noncondensable portion of the waste gas. The following model is used in converting the measured concentrations into a waste-gas composition estimate:[6]

$$X_{nc,hydrogen} + X_{nc,methane} + X_{nc,nitrous} = 1 \quad , \tag{C-1}$$

$$\frac{X_{nc,hydrogen}}{X_{nc,nitrous}} = constant \quad \text{and} \quad \frac{X_{nc,methane}}{X_{nc,hydrogen}} = constant \quad \text{or} \quad \frac{X_{nc,methane}}{X_{nc,nitrous}} = constant . \tag{C-2}$$

This model is based on the assumption that the species ratios obtained from the dome space measurements are the same for the gas bubbles that exist in the waste. Thus, it is assumed that

- The mass transfer (including the molecular diffusion out of the waste) from the waste surface is negligible, and
- The species ratios do not change with time or bubble location in the waste.

The noncondensable species of interest are not very soluble in the waste. Consequently, the mass transfer effects are expected to be negligible. Likewise, provided that all the species are generated at constant proportions independent of the location, the surface diffusion effects also are expected to be small. As discussed later, the amount of methane in all the tanks analyzed is small. Thus, the uncertainties associated with the above assumptions for methane releases are not expected to influence the final conclusions. Continuous monitoring data for nitrous oxide and hydrogen concentrations during and between large gas-release events are available for Tank 101-SY. The data show that during steady-state

releases, nitrous oxide concentration is slightly above the hydrogen concentration (nitrous-oxide-to-hydrogen ratio is > 1). During gas-release events, the hydrogen-to-nitrous-oxide ratio is slightly less than 1 (see Ref. 7). Moderate solubility of nitrous oxide, the response time, the accuracy of different instruments used for monitoring hydrogen and nitrous oxide, and variations in the waste temperature near the surface may be responsible for small differences. As long as the results of the present model are interpreted conservatively, such small differences are not expected to influence the conclusions.

In determining the bounding gas composition in which the fuel is maximized, $X_{nc,hydrogen}/X_{nc,nitrous}$ and $X_{nc,methane}/X_{nc,hydrogen}$ ratios are used. In cases where the nitrous oxide is maximized for toxicological release analysis, $X_{nc,hydrogen}/X_{nc,nitrous}$ and $X_{nc,methane}/X_{nc,nitrous}$ ratios are used.

In summary, for each grab sample obtained from a given tank, the ratios shown in Eq. (C-2) are computed. The mean values and the standard deviations for these ratios are obtained using all the grab samples' data from a given tank. To obtain the bounding gas composition with the maximum fuel content, $X_{nc,hydrogen}/X_{nc,nitrous}$ and $X_{nc,methane}/X_{nc,hydrogen}$ ratios are obtained as the mean plus 2 standard deviations (for tanks where there are greater than two samples). For tanks with only two samples, the maximum computed ratio is used.

The same methodology is followed in obtaining the gas composition with maximum nitrous oxide content. For this case, mean plus 2 standard deviations are used for $X_{nc,nitrous}/X_{nc,hydrogen}$ and $X_{nc,nitrous}/X_{nc,methane}$ ratios for tanks with more than two grab samples. The maximum of the two samples is used for tanks with only two grab samples.

In the grab samples, the minimum detection limit appears to be 1 to 2 ppm. Thus, analyzing samples with very low waste gas concentrations results in a bias towards the minor species. Consequently, only those samples that contain hydrogen concentrations that are $\geq$ 30 ppm are analyzed. The results are shown in Table C-3.

As shown in Table C-3, in general, the tanks in the A-, AX-, S- and SX-Farms appear to be rich in fuel (hydrogen and methane), with the exceptions of AX-103 and S-102 that show ~40% nitrous oxide in the release gas. The maximum hydrogen concentration is estimated as 89.2% for Tank SX-106. The maximum methane concentration is estimated for Tank AX-103 as 7.2%. However, the grab sample data for this tank yielded low concentrations in the dome space and are believed to be biased towards minor species (methane). The maximum methane concentration measured in the dome of AX-103 is 3%. Furthermore, the waste level in this tank is only 1.07 m, and the flammable-gas release in this tank with a large dome volume is not expected to be a major problem.

The tanks in the U-Farm appear to be richer in nitrous oxide. The upper-bound estimate for the nitrous oxide is obtained as 75.4% in Tank U-105. This value will be used to compute the toxicological consequences of nitrous oxide releases.

TABLE C-3
HYDROGEN, NITROUS OXIDE, AND METHANE FRACTION IN THE NONCONDENSABLE RELEASE GAS

| | MAXIMUM FUEL | | | | MAXIMUM $N_2O$ |
|---|---|---|---|---|---|
| TANK | $X_{hydrogen}$ (%) | $X_{methane}$ (%) | $X_{nitrous}$ (%) | EF (%$H_2$) | $X_{nitrous}$ (%) |
| A-101 | 86.7 | 1.3 | 12.0 | 90.9 | 15.4 |
| AX-101 | 88.1 | 4.5 | 7.4 | 103.0 | 11.3 |
| AX-103 | 55.1 | 7.2 | 37.7 | 79.1 | 49.6 |
| SX-101 | | | | | |
| SX-102 | 81.4 | 4.6 | 14.0 | 96.8 | 15.4 |
| SX-103 | 79.7 | 3.8 | 16.4 | 92.4 | 18.1 |
| SX-104 | | | | | |
| SX-105 | 81.8 | 3.0 | 15.2 | 91.9 | 15.2 |
| SX-106 | 89.2 | 3.7 | 7.1 | 101.7 | 33.3 |
| SX-109 | | | | | |
| S-102 | 59.1 | 0.9 | 40.0 | 62.2 | 42.5 |
| S-111 | 82.8 | 2.2 | 15.0 | 90.0 | 17.8 |
| S-112 | | | | | |
| T-110 | | | | | |
| U-103 | 51.9 | 1.5 | 46.6 | 57.0 | 61.2 |
| U-105 | 40.9 | 1.6 | 57.5 | 46.2 | 75.4 |
| U-107 | 53.3 | 2.1 | 44.6 | 60.4 | 62.6 |
| U-108 | 59.2 | 2.1 | 38.7 | 66.2 | 57.2 |
| U-109 | 55.0 | 1.4 | 43.6 | 59.7 | 58.7 |

The data from these samples are not used because the concentrations are either too low or are reported as < values.

Justifying the use of tank-specific gas compositions based on these analyses is difficult. The difficulty is primarily in extrapolating steady-state gas concentration measurements to predict the gas concentration during a prompt release event and stems from the modeling assumption discussed above. Conservatively, the gas ratios used in obtaining the values in Table C-3 are evaluated at 2 standard deviations in which either fuel or nitrous oxide is maximized and the existence of nitrogen (that is known to be generated in the waste) is ignored. However, the concentrations shown in Table C-3 are obtained using a very limited database. Furthermore, the single-shell tanks within a given farm are connected through overflow lines, and most single-shell tanks are passively ventilated. Consequently,

it is possible that the dome gases in connected tanks intermix, and the grab sample data may not necessarily represent the waste gas that is released from a specific waste tank. Thus, one must be cautious in using the computed gas compositions on a tank-by-tank basis.

In order to determine the bounding case, the concept of equivalent fuel[6] is used for the compositions shown in Table C-3. Table C-3 lists the equivalent fuel in terms of hydrogen concentration in the noncondensable waste gas. The equivalent fuel[6] is obtained as

$$EF = R_m \times X_{methane} + X_{hydrogen} \quad , \qquad (C\text{-}3)$$

where $R_m$ is the ratio of combustion energy of methane (798 kJ/mole) to the combustion energy of hydrogen (241 kJ/mole). Thus, $R_m$ is obtained as 3.32.

Based on this analysis, the composition obtained for AX-101 results in the maximum equivalent fuel as 103% hydrogen and appears to be the limiting composition for the flammability analysis.

### 3.2. Condensable Gases

The gas monitoring done in the tank farms in general show that almost all the tanks contain and release ammonia. Unfortunately, there are limited ammonia data available to quantify the amount of ammonia in the tanks of interest. Because the waste in SSTs is typically older than the waste in the double-shell tanks (DSTs) for which ammonia content estimates are available, the amount of dissolved ammonia in the SST waste is expected to be higher than the amount of ammonia in the double-shell tank (DST) waste. There are two DSTs for which there are sufficient data to estimate the ammonia content in the waste gas during a release event. For Tank 101-SY, the maximum ammonia fraction in the release gas, including the mass transfer from a freshly exposed surface during a rollover, is obtained as 15%.[7] For tank 103-SY, the bounding ammonia fraction in the release gas is given as 17%.[8]

For Tank A-101, the amount of dissolved ammonia is estimated by comparing the total organic carbon, radiolytic loads, sodium nitrite inventory, and the age of the waste to 101-SY waste using bounding assumptions.[9] Based on these calculations, the mean plus 2 standard deviations ammonia fraction in the release gas is estimated as ~40%.[9] Currently, similar analyses are not available for other tanks.

There are limited amounts of ammonia data available in Reference 10. Typically, one value for a few of the tanks on the Flammable Gas Watch List is reported along with the corresponding value of nitrous oxide and hydrogen. Nitrous oxide and hydrogen values are within the range reported in Reference 1. The gas concentration measurements reported in Reference 10 are given in Table C-4 for

those tanks that are on the Flammable Gas Watch List. Note that data for each tank on Table C-3 are not available.

TABLE C-4
GAS CONCENTRATION DATA REPORTED IN REFERENCE 10

| TANK | $NH_3$ (ppm) | $H_2$ (ppm) | $N_2O$ (ppm) | $X_{ammonia}$ (%) |
|---|---|---|---|---|
| A-101 | 754 | 758 | 218 | 46.5 |
| S-102 | 412 | 669 | 509 | 26.8 |
| S-111 | 122 | 391 | 48 | 20.5 |
| SX-103 | 77 | <23 | <23 | 72.8 |
| SX-106 | 179 | 98 | 14 | 62.0 |
| U-103 | 730 | 555 | 878 | 40.7 |
| U-105 | 325 | <49 | 154 | 61.4 |
| U-107 | 453 | 500 | 701 | 32.5 |

One can obtain a conservative estimate of ammonia fraction in the release gas through

$$\frac{X_{ammonia}}{1-X_{ammonia}} = X_{nc,i}\frac{X_{ammonia}}{X_i} \quad , \qquad \text{(C-4)}$$

where $X_{nc,i}$ is the hydrogen or nitrous oxide fraction in the noncondensable gas that may be obtained from Table C-3 and $X_{ammonia}/X_i$ is the ratio obtained from data shown in Table C-4. The resulting ammonia fraction ($X_{ammonia}$) is shown in the last column in Table C-4.

In obtaining the results for $X_{ammonia}$, either the hydrogen or the nitrous oxide data from Tables C-3 and C-4 are used. In general, the hydrogen data are used except for Tank U-105 for which the nitrous oxide data are used because the hydrogen data are given as "less-than" value. For Tank S-103, both the hydrogen and nitrous oxide numbers are given as less than value, and the hydrogen data are used for this tank neglecting the < sign. The results for Tank S-103 have the highest uncertainty. First, the analysis reported in Table C-3 is based on two data points only. Secondly, the low concentrations in ammonia and hydrogen result in a large uncertainty in the ratio. Especially, the low ammonia concentration measured suggests that the mass transfer contribution to the total ammonia release is probably very large (see discussion for Tank 101-SY below).

Obviously, there is much uncertainty in the ammonia results reported in Table C-4, primarily because the analysis is based on a single data point. However, the

application of these results in consequence analysis for prompt and large gas releases is conservative because of the following:

- Nitrogen in the gas composition is neglected. Nitrogen is known to exist in the waste gas. Especially, nitrogen fraction is expected to be high in waste gas that is rich in ammonia and nitrous oxide.

- Undoubtedly, some water vapor also will exist in the form of condensable gas. The water vapor content of the waste gas is conservatively set at zero.

- Extensive data from 101-SY indicate that a large fraction of ammonia during the steady-state periods is released by mass transfer of the surface. During steady-state periods, dome space ammonia-to-hydrogen ratio typically ranges between 2 and 3 in Tank 101-SY.[7] During the steady-state period, the background hydrogen concentration would typically be ~20 ppm, but the ammonia concentration would be between 50 and 60 ppm. In this respect, the data for S-103 appear similar to the 101-SY data. However, during episodic large gas-release events, the ammonia-to-hydrogen ratio drops to 0.3 to 0.5 (Ref. 7). This behavior is explained by the high solubility of ammonia in the waste. During steady-state releases the mass transfer of the surface significantly contributes to ammonia releases. Also, slowly released bubbles are expected to come to thermodynamic equilibrium at the waste surface where the pressure is atmospheric. During large episodic releases, mass transfer contribution is small, and the bubbles are rapidly released from the lower layers where the ammonia fraction is small because of high hydrostatic pressure. Thus, applying the ammonia-to-hydrogen ratios obtained from background data is believed to be very conservative in predicting the large prompt releases that may be triggered from the deep layers during an intrusion.

Considering all these conservative assumptions, it is expected that the ammonia fraction during a prompt release to be much less than the 60% computed for Tanks SX-106 and U-105. For instance, Reference 9 uses a simple model based on the energy of formation of nitrogen and other species to obtain the best-estimate ammonia fraction in the release gas as 20% for Tank A-101, but the above methodology yields ~47%. However, given the other uncertainties, the ammonia fraction is conservatively set to 60% for bounding analysis. Once the ammonia concentration is known, the overall waste-gas composition is estimated as

$$X_i = (1 - X_{ammonia}) X_{nc,i} \quad , \qquad \text{(C-5)}$$

where $X_i$ (i is hydrogen, nitrous oxide, or methane) is the species fraction in the release gas, and $X_{i,nc}$ is the species fraction in the noncondensable portion of the release obtained from Table C-3.

The ammonia fraction in the release gas is important in determining the safety envelope for the proposed activities. The presence and amount of ammonia affects the safety analyses in the following major areas:

- Ammonia is a more energetic fuel than hydrogen. Thus, the existence of ammonia increases the fuel energy of the waste gas. The effect of ammonia on the equivalent fuel is discussed in Section 3.2.1. of this appendix.

- Ammonia affects the LFL of the mixture. When expressed in terms of hydrogen concentration, the LFL decreases with increasing ammonia content. The effect of ammonia on the LFL is discussed in Section 3.3 of this appendix.

- Ammonia appears to combust very energetically in a pure nitrous oxide environment.[11,12]

- Ammonia is corrosive, and the consequences of the ammonia releases must be kept below the acceptance guidelines (see Section 5 of this SA).

**3.2.1. Effect of Ammonia on the Equivalent Fuel.** Including ammonia, the equivalent fuel is obtained as

$$EF\left(X_{hydrogen}\right) = R_m \times X_{methane} + R_a \times X_{ammonia} + X_{hydrogen} \quad , \qquad \text{(C-6)}$$

where $R_m$ is 3.32 (discussed above) and $R_a$ is the ratio of combustion energy of ammonia (317 kJ/mole) to the combustion energy of hydrogen (241 kJ/mole). Thus, $R_a$ is obtained as 1.32.

Using 60% ammonia and the noncondensable gas composition given in Table C-3 for Tank AX-101, the equivalent fuel becomes equal to 120% hydrogen compared to 103% hydrogen obtained without any ammonia.

### 3.3. Lower Flammability Limits

The LFL of hydrogen, ammonia, methane, and nitrous oxide mixtures is discussed in References 13 and 14. Based on References 13 and 14, Le Chatelier's linear mixing law[15] appears to be adequate, and the effect of nitrous oxide on the LFL is minimal for the mixtures of interest. The linear mixing law can be expressed in terms of hydrogen concentration as follows:

$$LFL\left(\frac{1}{LFL_{o,hydrogen}} + \frac{X_{ammonia}/X_{hydrogen}}{LFL_{o,ammonia}} + \frac{X_{methane}/X_{hydrogen}}{LFL_{o,methane}}\right) = 1 \qquad \text{(C-7)}$$

where the LFL of the hydrogen, methane, and ammonia ($LFL_{o,i}$) are bounded by 4%, 5%, and 15%, respectively.[13,14] The LFL for each gas composition shown in Table C-3 is computed as a function of the ammonia fraction in Reference 6. Adding 60% ammonia to the AX-101 composition shown in Table C-3, the LFL is obtained as 2.7% hydrogen.

## 4.0. MAXIMUM ALLOWABLE RELEASES INTO THE DOME

In this section, the maximum allowable gas releases into the dome space considering the flammability issues and toxicological consequences are discussed first. Also, the maximum allowable burn volume in the waste is quantified. Finally, current estimates for the retained-gas inventory in the tanks of interest are summarized at the end of this section.

Using the LFL values computed for each tank, the maximum allowable release based on the flammability hazard is defined as the gas-release volume necessary to reach 25% of the LFL when the waste gas is homogeneously mixed in the dome space.

For the bounding tank with a 1415.8 $m^3$ (50,000 $ft^3$) dome volume, the maximum allowable release corresponding to 6000 ppm hydrogen in the dome space would be 8.5 $m^3$ (300 $ft^3$) of hydrogen. Currently, all intrusive activities are stopped when 6000 ppm hydrogen are detected in the dome space (see Appendix B). Using the gas composition obtained for 101-AX (with 60% ammonia), the release volume corresponding to 6000 ppm hydrogen becomes 24 $m^3$ (850 $ft^3$).

Using an adiabatic burn model, one can show that if burned, a gas-release volume of 96 $m^3$ (3400 $ft^3$) corresponding to 2.4% hydrogen in the dome space would result in a peak pressure greater than 240 kPa (35 psia). The maximum peak pressure that could be experienced by SSTs without dome failure is <82 kPa (<12 psig).[16] Thus, even small volumes of gas burned in the dome space may result in catastrophic dome failure.

The above values for the maximum allowable limit are obtained considering flammability issues only. Ammonia and nitrous oxide also must be considered for toxicological consequences. The Emergency Response Planning Guideline-1 (ERPG-1) values for ammonia and nitrous oxide are 25 ppm and 150 ppm, respectively. ERPG-1 values are used to determine the dose limit for an on-site receptor located at 100 m (328 ft) from the tank for likely releases (see Section 5 of this SA for the Risk Acceptance Guidelines). The maximum allowable release is then determined as the maximum waste-gas volume that results in ≤ ERPG-1 when discharged out of the dome and received at 100 m (328 ft) from the source.

The atmospheric dispersion factor using 95% weather conditions at the Hanford site for a 100-m receptor is ~ 3.44 x $10^{-2}$ s/$m^3$ obtained from Reference 17. For a 0.12 $m^3$/s

(250 $ft^3$/min) discharge rate, the maximum source concentration may be obtained as 6000 ppm of ammonia and 36,000 ppm of nitrous oxide. Assuming 60% ammonia in the waste gas and a dome volume of 1415.8 $m^3$ (50,000 $ft^3$), the maximum allowable release may be obtained as 14.2 $m^3$ (500 $ft^3$) to meet the ammonia guidelines. Waste gas releases of up to 68 $m^3$ (2400 $ft^3$) will meet the nitrous oxide guidelines, assuming a maximum of 75% nitrous oxide in the waste gas and a 0.12 $m^3$/s (250 $ft^3$/min) discharge rate. These numbers are directly proportional to the discharge rates.

## 5.0 MAXIMUM ALLOWABLE BURN VOLUME IN THE WASTE

In this safety assessment, it is assumed that, if the gases are ignited in the waste, the combustion will propagate through the gas phase. If a large enough gas volume is burned, the resulting pressure may be high enough to cause structural damage to the tank and/or the dome.

In the previous sections, the concern was the release of flammable and toxic gases into the dome space. For dome burn accidents, the gas composition with the maximum fuel is used as the bounding composition because the dome contains sufficient oxidizer. Likewise, for bounding toxicological analysis, the maximum toxic gas fraction is used. For a burn inside the waste, the worse-case composition would be a stoichiometric mixture of fuel and nitrous oxide. For gases to burn inside the waste, there must be sufficient oxidizer. The only known oxidizer in the waste gas is nitrous oxide. While the results in Table C-3 have uncertainties associated with them, they show that most of the tanks may be oxidizer limited. Among the tanks for which the gas composition data are analyzed, the nitrous oxide concentration is less than 20% except for the tanks in the U-farm, tanks AX-103, SX-106, and S-102. Within the uncertainty of the data, the tanks in the U-farm could certainly have a stoichiometric composition of fuel and oxidizer. In the subsequent analysis, a stoichiometric mixture of hydrogen and nitrous oxide is used. Adding methane and ammonia into the mixture would increase the energy per mole. However, theoretically, complete combustion of one mole of methane requires four moles of nitrous oxide, and one mole of ammonia requires one and a half mole of nitrous oxide. Thus, methane and ammonia, while more energetic, require more oxidizer than the hydrogen. Thus, for a constant gas volume, adding ammonia and methane to the stoichiometric mixture of hydrogen and nitrous oxide has a small impact on the total combustion energy.

Starting at atmospheric pressure, the adiabatic constant-volume combustion of one mole of hydrogen with one mole of nitrous oxide results in a peak pressure of 11.2 atm. If the combustion products are allowed to expand isentropically while compressing the dome gases, the equilibrium pressure may be obtained by solving the following simultaneous equations:

$$V_f + V_{cf} = V + V_c \quad , \qquad \text{(C-8)}$$

$$\frac{P_a}{P_f} = \left(\frac{V_f}{V}\right)^{k_a} , \qquad \text{(C-9)}$$

and

$$\frac{P_c}{P_f} = \left(\frac{V_{cf}}{V_c}\right)^{k_c} , \qquad \text{(C-10)}$$

where $P_a$ is the initial dome pressure (1 atm), $P_c$ is the waste gas burn pressure (11.2 atm), $P_f$ is the final equilibrium pressure, V is the initial dome volume, $V_c$ is the volume of the waste gas (combustion products), $V_f$ is the final dome volume after compression, $V_{cf}$ is the final waste gas (combustion products) volume after expansion, and k is the specific heat ratio. For both the dome gases and the combustion products, $k_a = k_c = 1.4$ is used in these calculations. Setting the structural limit to 1.8 atm (Ref. 16), the maximum allowable gas volume may be obtained as 184 $m^3$ (6500 $ft^3$) for V = 1416 $m^3$ (50,000 $ft^3$).

This approach is conservative because it assumes that there is no pressure relief (no outflow from the dome) during the pressurization phase. Furthermore, it is very unlikely that the burn will easily propagate in the waste. The total energy generated by the combustion of 283 $m^3$ (10,000 $ft^3$) stoichiometric waste gas is $4.1 \times 10^6$ kJ ($4.1 \times 10^6$ Btu). The latent heat of 1.8 $m^3$ (64 $ft^3$) water will be sufficient to absorb all this energy. Thus, if the water volume in the waste is only 0.3% of the gas volume and if the gas and water are homogeneously distributed, the combustion cannot propagate. If a large gas volume exists, 184 $m^3$ (6500 $ft^3$) gas volume would correspond to a spherical bubble 7.1 m (23 ft) in diameter. Alternatively, a dendritic bubble of 2.54 cm (1 in.) in average diameter would have to be $3.6 \times 10^5$ m ($1.2 \times 10^6$ ft) long.

Based on these arguments, a gas burn in the waste that could result in dome failure is very unlikely. However, it should not be dismissed completely because of the various unknowns in the gas-retention mechanisms and the waste properties in the single-shell tanks.

## 6.0 ESTIMATES OF TANK GAS INVENTORY

As part of the screening program for potential flammable-gas retaining tanks, Westinghouse Hanford Company (WHC) has a continuing effort to estimate the tank gas inventory using the barometric pressure and level variation data.[18] The results for all the tanks of interest are not currently available. The gas inventories of some of the tanks that are not currently on the FGWL are given in Reference 18.

## 7.0. CONCLUSIONS

In this appendix, the available gas-composition data obtained from the grab samples are analyzed. However, the grab samples only provide limited data. Conservatively assuming that the waste gas does not contain any nitrogen, the grab sample data are converted to noncondensable waste gas composition. The upper bound values for the composition with maximum fuel and maximum nitrous oxide are obtained. In terms of fuel, the bounding tank is shown to be AX-101. Tank U-105 appears to show the highest nitrous oxide content. Tanks A-101, AX-101, SX-102, SX-105, SX-106, and S-111 indicate higher than 80% hydrogen in the waste gas. The highest hydrogen content is estimated for SX-106 as nearly 90%.

Even though the available data are analyzed conservatively, one must exercise caution in using the current findings. The concentrations are obtained using a very limited database. Furthermore, the single-shell tanks within a given farm are connected through overflow lines, and most single-shell tanks are passively ventilated. Consequently, it is possible that the dome gases in connected tanks intermix, and the grab sample data may not necessarily represent the waste gas that is released from a specific waste tank. Furthermore, data for all the tanks of interest are not available.

Using a conservative interpretation of the limited ammonia data provided in Reference 10, the LFL is set equal to 2.4% hydrogen corresponding to an ammonia-to hydrogen-ratio of 2.5. For toxicological consequence analysis, the bounding ammonia fraction in the release gas is conservatively set equal to 60%.

Based on these findings, it is concluded that

- The potential gas releases during the proposed intrusive activities are poorly understood and cannot be controlled to meet these limits.
- Continuous hydrogen or flammable-gas monitoring is necessary as part of the spark management strategy.
- Continuous or frequent ammonia monitoring also is necessary both for flammability and toxicological consequence considerations.
- A deflagration in the dome space is a more likely dome collapse mechanism than a deflagration of the gas trapped in the waste.
- Ammonia concentrations must be monitored, and operations must be stopped when the ammonia concentration in the dome exceeds 5000 ppm.

## 8.0. REFERENCES


1. Westinghouse Hanford Company, "Hanford Site Tank Farm Facilities Interim Safety Basis, Volume 2: Design Description," Westinghouse Hanford Company report WHC-SD-WM-ISB-001, Rev. 0, Vol. 2 (August 1993).

2. H. R. Brager, "Summary of Information on Flammable Gas Watch List Tanks," Westinghouse Hanford Company report WHC-EP-0711, (January 1994).

3. P. Whitney, "Screening of the Hanford Tanks for Trapped Gas," Pacific Northwest Laboratory report PNL-10821 (October 1995).

4. K. O. Pasamehmetoglu, "Single-Shell Tank Dome Volume Calculations," Los Alamos National Laboratory Calc-Note TSA10-CN-WT-SA-TH-086 (November 1995).

5. R. G. Brown, "Status of Single-Shell Tank SHMS," Westinghouse Hanford Company Internal memorandum 74A10-95-068 to G. D. Johnson (October 2, 1995).

6. K. O. Pasamehmetoglu, "Gas Composition Estimates for Single-Shell Tanks," Los Alamos National Laboratory Calc-Note TSA10-CN-WT-SA-GR-048 (December 1995).

7. L. H. Sullivan et al., "A Safety Assessment for the Proposed Pump Mixing Operations to Mitigate Episodic Gas Releases in Tank 241-SY-101: Hanford Site, Richland, Washington," Los Alamos National Laboratory report LA-UR-92-3196, Rev. 14 (March 31, 1995).

8. R. J. Van Vleet, "Basis for Closure of USQ for Tank 103-SY," presented to Tank Waste Chemical reactions Sub-Panel (October 11, 1995).

9. W. L. Kubic, "Summary, Review, and Analysis of Data for Tank 241-A-101," Los Alamos National Laboratory Calc-Note TSA10-CN-WT-SA-DA-001 (December 1995).

10. J. L. Huckaby, H. Babad, and D. R. Bratzel, "Headspace Gas and Vapor Characterization Summary for the 43 Vapor Program Suspect Tanks," Westinghouse Hanford Company report WHC-SD-WM-ER-514, Rev. 1A (September 1995).

11. M. Hertzberg and I. A. Zlochower, "Explosibility of Nitrous Oxide: the Effect of H-Atom Bearing Impurities," Twenty-Fifth International Symposium on Combustion, University of California, Irvine, July 31–August 5, 1994.

12. E. Jones and J. C. Kerr, "Inflammability Limits of Ammonia, Nitrous Oxide and Air," *J.S.C.I.*, Vol. 68, 31–34 (January 1949).

13. K. O. Pasamehmetoglu, "Composition and Lean Flammability Limit for the Release Gases in Tank 241-SY-101," Los Alamos National Laboratory report LA-UR-94-4229 (December 1994).

14. K. O. Pasamehmetoglu, "LFL for 101-SY Release Gas," Los Alamos National Laboratory Calc-Note N6-CN-WT-SA-GR-010 (March 1994).

15. W. Jost, *Explosion and Combustion Processes in Gases* (McGraw Hill, New York, New York, 1946), p. 134.

16. L. J. Julyk, "Static Internal Pressure Capacity of Hanford Single-Shell Waste Tanks," Westinghouse Hanford Company report WHC-SD-WM-TI-623 (July 1995).

17. Westinghouse Hanford Company, "Tank Waste Compositions and Atmospheric Dispersion Coefficients for Use in Accelerated Safety Analysis Consequence Assessment," Westinghouse Hanford Company report WHC-SD-WM-SARR, Rev. 1 (October 1995).

18. K. M. Hodgson et al., "Evaluation of Hanford Tanks for Trapped Gas," Westinghouse Hanford Company report WHC-SD-WM-ER-526 Rev. 0 (December 1995).

# APPENDIX D

# RELIABILITY OF SYSTEMS

## 1.0. INTRODUCTION

This appendix documents the results of an assessment of the reliability of various systems that support the installation, operation, and removal of rotary-mode core sampling (RMCS) equipment in single-shell tanks (SSTs) on the Flammable Gas Watch List (FGWL) or those tanks recommended by the contractor to be included on the FGWL, hence referred to as FG/RMCS operations. The systems that were evaluated are those considered in the accident sequences discussed in Section 4 and documented in Appendix E of this safety assessment.

The reliability of the systems using fault tree analysis were estimated, and event tree analysis were estimated in a few cases. The system fault trees are not detailed fault trees; however, they do provide a reasonable model for estimating system reliabilities. The level of detail included in the fault trees was limited by the availability of detailed up-to-date system design and operating information.

The system models were developed using the following sources of information:

1. Existing Westinghouse Hanford Company (WHC) safety studies,[1-4]
2. System schematics and operating procedures provided by WHC,
3. Verbal information from WHC cognizant engineers and technicians,
4. Published sources of data for component reliabilities, and
5. Engineering judgment.

It should be noted that automatic trip of drill string is defined as automatic trip of the drill rig engine. The following systems were modeled:

- Nitrogen purge gas cooling for drill bit and associated automatic trip of drill string on low nitrogen flow;
- Nitrogen hydrostatic supply to drill string;
- Nitrogen hydrostatic supply to shielded receiver;
- Automatic trip of drill string on excessive force;
- Automatic trip of walkdown function;

- Automatic trip of hydraulic bottom detector;
- Automatic trip of drill string on high rpm;
- Pneumatic footclamp for holding drill string;
- Automatic trip of drill string on:
  Flammable-gas concentration,
  Flammable-gas concentration rate of rise, and
  Dome pressure;
- Sampler rotary valve operation;
- Sampler chevron seal function; and
- Manual sniff of drill string for flammable gas.

To estimate component failure exposure times, the following time periods were used:

- Two drilling activities on a tank per year;
- 144 hours for an activity from arrival at tank for core sampling until leaving tank after core sampling complete;
- 40 hours to take all samples; 2 samples taken per 8-hour shift;
- 20 minutes drilling time required for each of 11 samples; and
- 6 months between calibration check of instrumentation.

## 2.0. SUMMARY AND RESULTS

The details of the systems reliability analysis are provided in Ref. 5. The results are summarized in Table D-1.

Based on these results, human error is concluded to be an important contributor to system failure.

During the development of the system models it was noted that the following qualitative aspects of hardware failures. The reliability of the PLC is important because it is a single failure element for both

- automatically tripping the drill, and

- providing annunciation to the operators for manual response to stop drilling or to trip the drill.

The reliability of the rpm-detection system is important because it must

- Trip the drill on high RPM,
- Detect drill string rotation above 2 rpm to enable the automatic trip on low nitrogen purge gas flow, high down force, low penetration rate, and high RPM.

Both the PLC and the rpm detection systems are sufficiently reliable so that failures in these systems do not excessively contribute to the quantified system failure values.

## 3.0. REFERENCES

1. W. L. Cowley and D. D. Stepnewski, "Evaluation of Hazards to Tank Farm Facilities from Lightning Strikes," Westinghouse Hanford Company report WHC-SD-WM-SARR-027 Rev 0 (June 29, 1994).

2. D. J. Braun, "Risk Assessment for Nitrogen Purge System for Rotary Mode Sampling Truck," Westinghouse Hanford Company report WHC-SD-WM-RA-066 Rev. 0 (September 1992).

3. Westinghouse Hanford Company, "Fault Tree Systems Analysis," Westinghouse Hanford Company report WHC-IP-0690 6.4, Rev 0 (June 30, 1992).

4. J. E. Kelly, "High Downward Force on Rotary Drill," Westinghouse Hanford Company Internal Memorandum 29220-93-030 (July 7, 1993).

5. J. Darby and M. Butner, "Reliability of Systems for Rotary Mode Core Sampling," Los Alamos National Laboratory Calc-Note TSA10-CN-WT-SA-HAZ-004, Rev. 1 (February 1996).

## TABLE D-1
## RESULTS OF SYSTEM RELIABILITY QUANTIFICATION

| Initiating Event Frequency (1/activity) | Probability of Subsequent Failures | Overall Frequency (1/activity) | Contributing Failures (Failure of Following Events Dominates Probability of Subsequent Failures) |
|---|---|---|---|
| Excessive force used while taking any sample except last sample,<br>0.05 per sample,<br>0.55 total for 11 samples | Failure to detect excessive force and stop drill<br>7.9E-5 (Event: force) | 4.3E-5 | Common mode calibration error, pressure transmitters, operator arm walkdown function, solenoid-operated valve (SOV) 12 |
| Excessive force used while taking last sample<br>0.05 | Failure to detect excessive force and stop drill<br>7.9E-5 | 4.0E-6 | Common mode calibration error,<br>Pressure transmitters, operator arm, bottom detector, SOV 11 |
| | | 4.7E-5 total for excessive force with failure to stop drill (sum of two previous values) | |
| High $H_2$ level in exhauster<br>1.0 | Failure to detect hydrogen<br>7.6E-4 | 7.6E-4 | 2 exhauster programmable logic controllers (PLCs) (common mode), instrumentation and control (I&C) calibration |
| | Failure to detect hydrogen and trip the drill string<br>1.3E-3 | 1.3E-3 | 2 exhauster PLCs (common mode),<br>truck PLC,<br>I&C calibration |
| High $H_2$ rate of rise in exhauster<br>1.0 | Failure to detect hydrogen<br>7.6E-4 | 7.6E-4 | 2 exhauster PLCs (common mode),<br>I&C calibration |
| | Failure to detect hydrogen and trip the drill string<br>1.3E-3 | 1.3E-3 | 2 exhauster PLCs (common mode),<br>truck PLC,<br>I&C calibration |

| | | | |
|---|---|---|---|
| High dome pressure caused by $H_2$ release<br>1.0 | Failure to detect hydrogen.<br>7.7E-4<br><br>Failure to detect hydrogen and trip the drill string.<br>1.4E-3<br>(Event: hydrl) | 7.7E-4<br><br>1.4E-3 | 2 exhauster PLCs (common mode),<br>I&C calibration<br>2 exhauster PLCs (common mode),<br>truck PLC,<br>I&C calibration |

**TABLE D-1 (cont.)**
**RESULTS OF SYSTEM RELIABILITY QUANTIFICATION**

| Initiating Event Frequency (1/activity) | Probability of Subsequent Failures | Overall Frequency (1/activity) | Contributing Failures (Failure of Following Events Dominates Probability of Subsequent Failures) |
|---|---|---|---|
| $H_2$ from waste<br>1.0 | Failure of drill string $N_2$ hydrostatic system. 6.4E-3 | 6.4E-3 | Operator connect drill string hydro, operator arm drill string hydrostatic system |
| $H_2$ from waste<br>1.0 | Failure of shielded receiver $N_2$ hydrostatic system.<br>6.4E-3 | 6.4E-3 | Operator connect shielded receiver hydrostatic system, operator arm shielded receiver hydrostatic system<br><br>*(NOTE: The contributing failure associated with connecting the SR hydrostatic system is overly conservative because the system is hard-piped.)* |
| $H_2$ from waste<br>1.0 | Failure of both drill string $N_2$ hydrostatic system and shielded receiver $N_2$ hydrostatic systems.<br>6.9E-4<br>(Event: hydro) | 6.9E-4 | Operator connect drill string hydrostatic system and connect shielded receiver hydrostatic system (common mode),<br>operator arm drill string hydrostatic system and shielded receiver hydrostatic system(common mode)<br><br>*(NOTE: The contributing failure associated with connecting the SR hydrostatic system is overly conservative because the system is hard-piped.)* |
| Hold drill string above waste with footclamp<br>1.0 | Footclamp drops drill string onto waste surface.<br>6.9E-5<br>(Event: foot) | 6.9E-5 | Pneumatic footclamp remains closed |
| Excessive rpm during drilling<br>0.011 | Failure to trip drill string on excessive rpm.<br>6.2E-4<br>(Event: rpm) | 6.8E-6 | truck PLC,<br>I&C calibration |
| Perform drilling operation<br>1.0 | Total loss of $N_2$ cooling and failure to stop drill.<br>3.3E-6 | 3.3E-6 | $N_2$ cooling holes in drill bit plug,<br>truck PLC |

## TABLE D-1 (cont.)
## RESULTS OF SYSTEM RELIABILITY QUANTIFICATION

| Initiating Event Frequency (1/activity) | Probability of Subsequent Failures | Overall Frequency (1/activity) | Contributing Failures (Failure of Following Events Dominates Probability of Subsequent Failures) |
|---|---|---|---|
| Perform drilling operation 1.0 | Partial blockage of $N_2$ cooling holes in drill bit does not lead to total low $N_2$ flow 5E-4 original calculation; operating envelope will ensure no overheating can occur unless $N_2$ low-flow trip also challenged and fails | Operating envelope controls will prevent this. | No blockage of some, but not all, of the $N_2$ cooling holes in the drill bit, no low $N_2$ flow as a result of partial blockage, no local overheating of portions of drill bit |
| Perform drilling operation 1.0 | Loss of drill bit $N_2$ cooling from $N_2$ bypass leakage 1.6E-5 | 1.6E-5 | No $N_2$ bypass flow, no high $N_2$ flow as result of bypass, operator detects $N_2$ bypass flow |
| Perform drilling operation 1.0 | High $N_2$ temperature results in loss of drill bit cooling, Low likelihood based on WHC information that $N_2$ reaches ambient waste temperature | very small | No high $N_2$ temperature, no overheating of drill bit from high $N_2$ temperature, operator trips drill on annunciation of high $N_2$ temperature, temperature transducer |
| | | 1.9E-5 total for overheating drill bit caused by inadequate $N_2$ cooling (sum of four previous values)<br><br>(Event: cool) | |
| Take a sample 11.0 | Failure of rotary valve in sampler to completely close. 0.1<br><br>(Event: rot) | 1.1 | No waste blockage during valve closure |
| Perform drilling operation 1.0 | Failure of sampler chevron seal.<br><br>(Event: seal) | 3.3E-2 | Installation of chevron seal |

| Initiating Event Frequency (1/activity) | Probability of Subsequent Failures | Overall Frequency (1/activity) | Contributing Failures (Failure of Following Events Dominates Probability of Subsequent Failures) |
|---|---|---|---|
| $H_2$ from Waste 1.0 | Failure of $H_2$ sniff in drill string.<br>4.6E-3<br>(3.0E-3 operator, 1.6E-3 hardware)<br><br>(Event: sniff) | 4.6E-3 | Operator fails to perform sniff, sniff sensor fails low |
| Excessive filter $\Delta P$ 1.0 | Fail to trip exhauster on filter $\Delta P$.<br>2.6E-3<br><br>(Event: gate 32) | 2.6E-3 | Failure to sense high $\Delta P$ across filter, calibration I&C error |
| Contact rock in waste 0.1 | Failure of penetration rate and failure of $N_2$ cooling to drill bit systems.<br>3.3E-6<br>(Event: prrate) | 3.3E-7 | $N_2$ cooling holes to drill bit plug, PLC |

# APPENDIX F

# THERMAL ANALYSIS OF ROTARY DRILLING

## 1.0. INTRODUCTION

Figure F-1 illustrates the phenomena occurring at a drill bit tooth for normal cutting and for the case with a dull drill bit that is not cutting. Also, the figure shows some of the nomenclature used in this appendix.

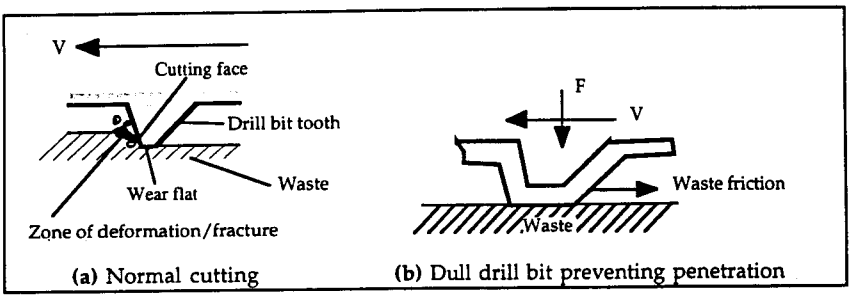



**Fig. F-1. Sketch illustrating the cutting process of the drill bit.**

When the bit is cutting well [Fig. F-1(a)] there is a zone in front of the bit tooth where most of the work is taking place. The material being drilled is compressed and fractured. The zone in front of the teeth where the compression and fracturing takes place is at a high pressure compared to the region where the purge gas flows. This pressure difference causes the chips to be squeezed out along the cutting face of the bit. The purge gas cools the fracture zone and the chips and then carries the chips radially outward. The energy that goes into compressing and fracturing the material is mostly converted to thermal energy. If the drilling is proceeding efficiently, most of the energy goes into the chips. Frictional energy dissipation occurs on the wear-flat as it slides over the substrate and on the cutting face where the chips are squeezed past. Conceptually, the maximum temperature can occur in the chips because of the mechanical-to-thermal energy conversion as the material is compressed and fractured, or along one of the bit surfaces where frictional heating occurs.

In inefficient cutting with dull drill bit teeth [Fig. F-1(b)], penetration may be difficult to achieve. In this scenario, the drill bit and waste in the waste friction zone attain similar temperatures in a short time. In this case, the maximum waste temperature would occur at the interface between the bit and the waste.

A hazard associated with high waste temperatures is the exothermic propagating chemical reaction. Waste ignition could result with unacceptable consequences. In Appendix G safe waste temperature limits are established to prevent propagating exothermic chemical reactions in the tank during rotary core sampling. A limit of 150°C has been set for bulk material in the vicinity of the drill bit. A limit of 180°C has been set for temperatures that may occur over small regions (a few chips in diameter) and for short times. These temperature limits are intended to prevent exothermic chemical reactions from being initiated. Laboratory experiments are conducted with the prototype drill bit by Westinghouse Hanford Company (WHC).[1] These tests were designed to provide the data necessary to set operational limits and to demonstrate that the waste temperature limits will not be exceeded.

The purpose of this appendix is to evaluate the test results and determine an adequate basis for setting limits for the drilling operation to ensure that temperature limits will not be exceeded. Other objectives are to discuss how laboratory test results are applicable to real conditions in tanks.

## 2.0. BACKGROUND

Some drill bit thermal modeling and experimental work has been done for oil and geothermal well drilling. In these cases, the interest in thermal modeling was driven by the need to maximize the life of synthetic diamond cutters. The rate of degradation of these cutters is a function of temperature. Prakash and Appl[2] developed a finite element model of an oil well drilling bit and the rock being cut. Glowka and Stone[3] developed a finite element model for a bit for geothermal applications that examined only the friction component of energy dissipation in which the wear-flat slides over the substrate. In both of these papers, the primary interest was in the temperature of the drill bit. The temperature of the material being cut was only considered as it related to the bit temperature.

In addition to the papers on thermal modeling of drill bits, there are papers that discuss the mechanical energy input per unit volume of material removed. In the rock drilling literature this concept goes by the term "specific energy." Teale[4] discusses this concept and provides numerical values for several materials. Units are expressed as in. lbf/in.$^3$ or MJ/m$^3$. Teale shows that the minimum specific energy for a rock-drilling operation is equal to the compressive strength ($\sigma$) of the material. This is shown by the following equation, where "SE" is the specific energy, "F" is force, "A" is area, "x" is distance, and "length" and "force" are generalized dimensions:

$$SE\left(\frac{\text{length}\cdot\text{force}}{\text{length}^3}\right)=\frac{\int F\,dx}{\int A\,dx}=\frac{\int \sigma A\,dx}{\int A\,dx}=\sigma\left(\frac{\text{force}}{\text{length}^2}\right) \qquad \text{(F-1)}$$

Applying a pressure equal to the compressive strength through some distance gives a specific energy that is numerically equal to the compressive strength if an appropriate system of units is used.

Teale[4] shows examples of specific energy for laboratory tests of rotary drilling in several different sandstones. Specific energies ranged from near the compressive strength of about 6,000 in. lbf/in.$^3$ to about 20,000 in. lbf/in.$^3$. Rabia[5] showed that the specific energy in a field drilling operation was often higher than laboratory drilling operations by a factor of about 2. He shows values of specific energy for field drilling of different rock types that range from 16,000 in. lbf/in.$^3$ to 66,000 in. lbf/in.$^3$. These values represent the total power input to the drill bit and include frictional losses as well as the energy required to fracture the material being cut.

A quantity similar to specific energy has been defined for machining.[6,7] This quantity is known as the "unit horsepower," and is defined as the horsepower needed to remove one cubic inch of material per minute (hp/in.$^3$/min). Operating at less than optimal conditions increases the energy needed to perform the machining operation. Handbook values range from 0.25 hp/in.$^3$/min for soft nonferrous metals and alloys, including free-machining brass, cast aluminum, and zinc alloy to 1.3 hp/in.$^3$/min for hard ferrous alloys. The difference between machining a ductile material and a brittle material is in the nature of the fracturing. To machine a ductile material, shearing takes place along a plane. To drill a brittle material, the material is compressed to the compressive strength, causing a number of fractures to propagate into the material.

The transformation of mechanical to thermal energy takes place along the fracture surfaces of the material being drilled or machined. The temperature that occurs along these fracture surfaces may be significantly higher than the average temperature reached when the thermal energy is distributed over the entire volume of the material removed. The analyses in this appendix consider only these average temperatures. Some of this thermal energy may be transferred to the drill bit, some to the substrate, and some to the coolant, although most of the thermal energy probably heats the chip. If all the mechanical energy needed to remove a chip is converted to thermal energy in the chip, the average temperature rise can be calculated. Table F-1 gives the values for specific energy and unit horsepower discussed above. The original unit is given in bold face. The temperature rise is calculated using values for specific heat and density given by WHC for Tank BY-104 waste simulant.[8]

TABLE F-1
LITERATURE VALUES FOR SPECIFIC ENERGY AND UNIT HORSEPOWER

| Material | Specific Energy (in. lbf/in.$^3$) | Specific Energy (MJ/m$^3$) | Unit horsepower (hp/in.$^3$/min) | Average Temp. Rise (°C) |
|---|---|---|---|---|
| Marble[4] | 1,200,000 | 8,274 | 3.03 | 6,049 |
| Marble[4] | 70,000 | 483 | 0.177 | 353 |
| Pennant sandstone[4] | 13,780 | 95.0 | 0.035 | 69.5 |
| Darley dale sandstone concrete[4] | 7,210 | 49.7 | 0.0182 | 36.3 |
| Monkato stone[5] | 1,581 | 10.90 | 0.00399 | 8.0 |
| Rockville granite[5] | 22,826 | 157.38 | 0.0576 | 115 |
| Dresser basalt[5] | 54,204 | 373.72 | 0.37 | 273 |
| Soft nonferrous metals[6] | 99,000 | 683 | 0.25 | 499 |
| Hard ferrous alloys[6] | 514,800 | 3,549 | 1.3 | 2,595 |

## 3.0. SAFETY ENVELOPE TESTS

The operating safety envelope has been defined by Keller.[8] The safety envelope was obtained by performing experiments with a prototype drill bit and waste simulants. Thermal properties of these simulants were expected to represent typical properties of salt cake. The rotational speed, downward force, and nitrogen purge flow rate were varied. The number of data for a given set of parameters was limited. At maximum operating parameters (55 rpm, 1170 lbf, 20 scfm) the maximum drill bit temperature rise was observed to be 35°C. The maximum waste temperature in single-shell tanks (SSTs) was considered to be 93°C. The critical drill bit temperature was set to 150°C. Thus, the drill bit temperature increase was limited to 57°C. Because the maximum experimentally measured drill bit increase was 35°C, the rotary-mode core sampling (RMCS) operations were considered to be justified (Ref. 8).

Testing by Keller[8] did not measure the waste chip temperature but the drill bit surface temperature. Keller also performed out-of-limit tests. In these tests, the system is operated with maximum operating conditions and a loss of nitrogen; an increase in downward force or speed is simulated. These tests are used to establish the shut-down period after an alarm on operating parameters is received. Our assessment of the envelope testing indicated that the most important parameter for keeping the drill bit below the critical temperature at which an exothermic reaction can occur is the nitrogen purge flow. Loss of nitrogen flow at maximum operating

conditions can heat the drill bit up to 57°C in 5 to 10 seconds. The most important parameter, applied torque, was not measured by Keller.

The data from the tests performed by Keller[8] were found to be insufficient to determine the safety envelope parameters. Recently, Witwer[1] conducted more bounding tests using dry pumice blocks with new procedures and instrumentation. These new envelope tests included torque measurements and numerous temperatures, including purge gas inlet and outlet temperature, bit surface and side temperatures, drill string temperatures, chip and pumice temperatures, exhaust air temperatures, etc.

The new test series included thermocouple temperature measurements on two drill bit teeth. Additional thermocouples were placed within the pumice in the path of the drilling and in the purge gas. Some tests used a stainless-steel sheath over some of the thermocouples within the pumice. The bit depth, rpm, down force, and torque were also measured. Tests were done with different down forces. Also, in some of the tests, the purge gas was turned off to simulate a loss of purge gas flow condition. The pumice blocks used as a test material were very abrasive, and the drill bits wore quickly. The penetration rate was good at the start of the test and then decayed to zero as the drill bit teeth wore down. These tests had a period with reasonably good cutting followed by a transition from good cutting to no cutting, and finally, a period in which the worn drill bit was spinning without cutting. Test conditions are summarized in Table F-2. The details of these test results are discussed by Witwer.[1]

The first five tests were performed without nitrogen flow to assess the rate of increase of the bit temperature. The rest of the tests are aimed to determine the safety limits as well as understand the drilling process. Some tests are performed to address partial plugging in the drill bit. These tests were performed by plugging four of the six purge holes.

## 4.0. ANALYSES METHODOLOGY

The analysis portion of this report is broken down into two major parts. Figure F-2 shows an energy flow diagram. The mechanical-to-thermal energy conversion discussion makes up the first of these major parts. This part is the key for understanding the drilling thermal processes. The second major part deals with the redistribution of heat. Results in this section tend to clarify and validate the results of the previous section. These pieces also are necessary to understand the experimental results.

TABLE F-2
ENVELOPE TEST CONDITIONS

| Test ID | F (lbf) | V (rpm) | Q (scfm) | Drill Bit | Simulant |
|---|---|---|---|---|---|
| RETMP-09 | 1170 | 55 | 0 | Sharp | Pumice |
| RETMP-10 | 1170 | 55 | 0 | Sharp | Pumice |
| RETMP-10A | 1170 | 55 | 0 | Dull | Pumice |
| RETMP-10B | 1170 | 55 | 0 | Dull | Pumice |
| RETMP-11 | 1170 | 55 | 0 | Sharp | Pumice |
| TORQTST-5 | 1170 | 55 | 0,20,30 | Sharp | Pumice |
| TORQTST-6 | 1170 | 55 | 20 | Sharp | Pumice |
| TORQTST-7 | 1170 | 55 | 20 | Sharp | Pumice |
| TORQTST-9 | 650 | 30 | 30 | Sharp | Pumice |
| TORQTST-10 | 1170 | 55 | 21 | Sharp | Pumice |
| TORQTST-11 | 900 | 55 | 30 | Sharp | Pumice |
| TORQTST-12 | 900 | 55 | 30 | Sharp | Pumice |
| TORQTST-14 | 750 | 55 | 30 | Slug therm. | |
| TORQTST-16 | 750 | 55 | 30 | | |
| TORQTST-17 | 750 | 55 | 30 | 4 plugged holes | |
| TORQTST-19 | 750 | 30 | 30 | 4 plugged holes | |
| TORQTST-20 | 900 | 55 | 30 | 4 plugged holes | |
| TORQTST-21 | 750 | 55 | 30 | 4 plugged holes | |
| TORQTST-22 | 650 | 55 | 30 | 4 plugged holes | |
| TORQTST-23 | 750 | 55 | 30 | | Steel |

### 4.1. Derivation of Drilling Energy Conversion Equations

Figure F-3 shows a drawing of the drill bit. This bit is a core drilling bit with 18 teeth in 3 rings with 6 teeth per ring. The bit is sintered bronze material. The faces of the teeth have a negative rake angle of about 30° for the two inner rings. That is, the

cutting face of each tooth is inclined so that the top of the tooth leans toward the material being cut rather than away. A bit of this type is also referred to as a drag bit. This bit is a commercially available, proprietary design. The bit material is soft enough to prevent damage to a steel tank liner should one be encountered. Figure F-4 shows the free body diagram used in the analysis of this bit.

Summing forces in the X and Y directions gives the following equations:

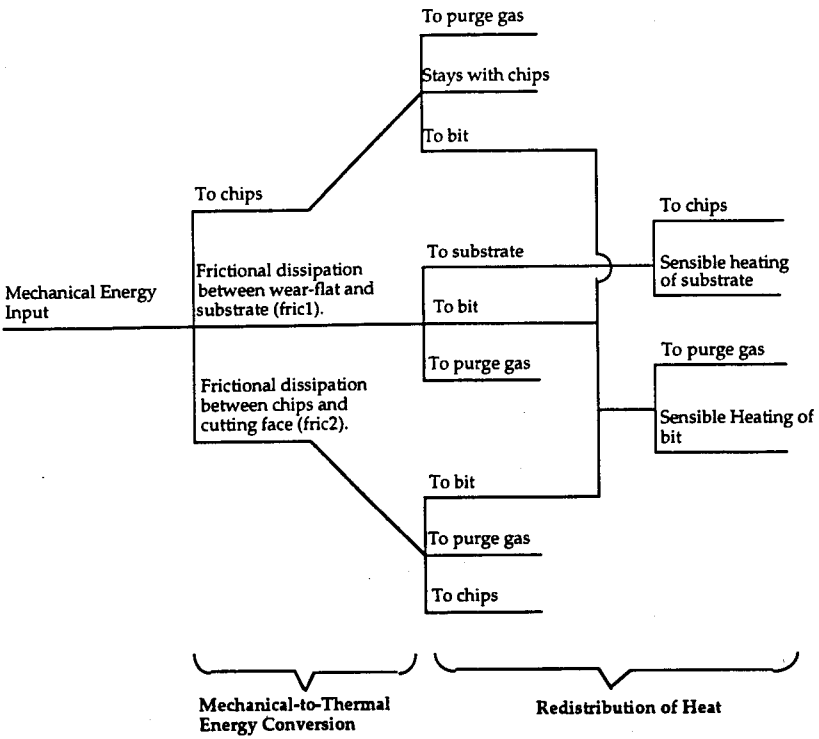



**Fig. F-2. Drilling energy flow diagram.**

$$Uf - Df + Nf \sin(30^\circ) + Ff_A \cos(30^\circ) = 0 \quad \text{(F-2)}$$

$$Ff_B + Nf \cos(30^\circ) - Tq/r_{avg} - Ff_A \sin(30^\circ) = 0 \quad \text{(F-3)}$$

where Tq is the torque and $r_{avg}$ is the average radius.

These equations have four unknowns, so an additional two equations are needed to achieve closure. Four possible equations were identified:

$$Ff_B = Cf_B\, Uf \quad \text{(F-4)}$$

$$Ff_A = Cf_A\, Nf \quad \text{(F-5)}$$

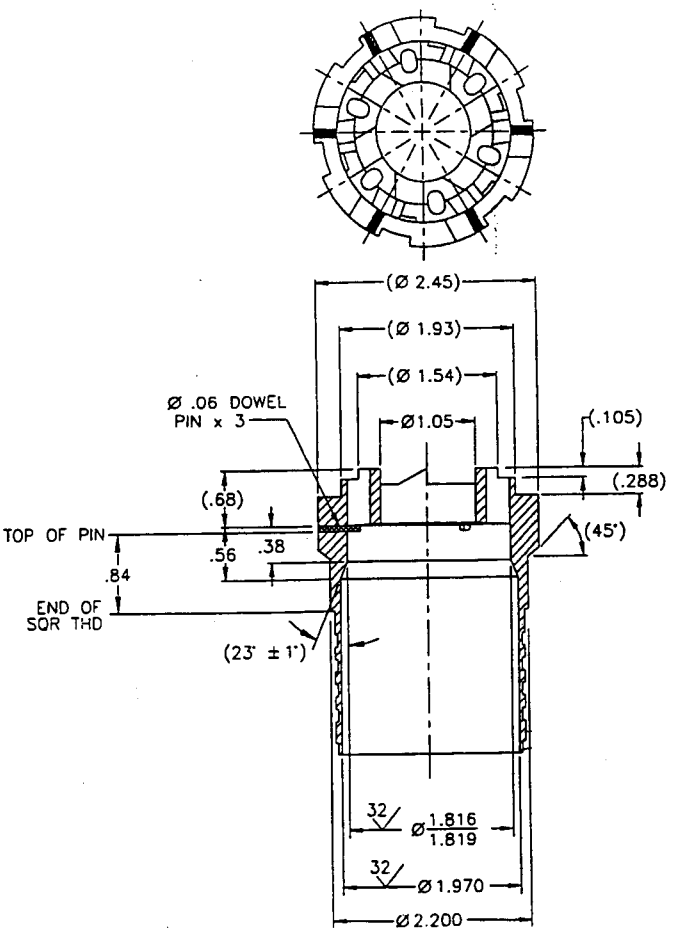
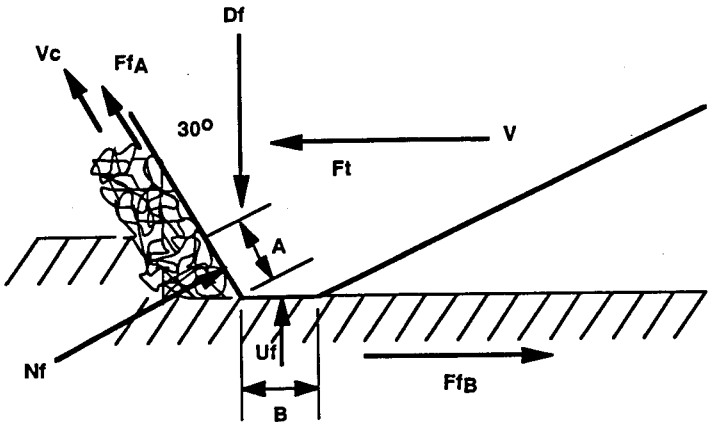



**Fig. F-3. Drawing of Drill Bit.**




Df is the down force.
Nf is the normal force at the cutting surface.
Uf is the upward force of acting on the wear-flat (surface of length B).
$Ff_B$ is the frictional force acting on the wear-flat surface.
$Ff_A$ is the friction force acting on the cutting face.
Vc is the velocity of the chips relative to the face, assumed equal to V.
V is the cutter velocity.
Ft is the force from torque times radius.
A is the area of the face where the cutting takes place.
B is the area of the wear-flat.

**Fig. F-4. Free body diagram of drill bit tooth.**

$$Nf = \sigma A \tag{F-6}$$

$$Uf = \sigma B \tag{F-7}$$

where $Cf_B$ is the coefficient of friction between the wear-flat and the substrate, $Cf_A$ is the coefficient of friction between the cutting face and the chips, and $\sigma$ is the compressive strength.

It proved advantageous to use different combinations of Eqs. (F-4) to (F-7) under different circumstances and to determine different quantities. The coefficient of friction where the wear-flat slides over the substrate can be found from Eqs. (F-2) to (F-4) for cases where the bit becomes worn [Fig. F-1 (b)] and where Nf and $Ff_A$ go to zero. Because the coefficient of friction is independent of the contact area, it should be reasonable to assume that this value is a constant, or nearly so, over the range of conditions.

The coefficient of friction on the cutting face ($Cf_A$) cannot be determined directly as is the case for the coefficient of friction on the wear-flat. However, the coefficient of friction is generally taken as a property of the contacting materials, and the contacting materials are the same at the cutting face and the wear-flat. The material (chips) sliding across the cutting face differs from the substrate in that the chips have been broken up and are no longer a single mass. However, these chips are still under high pressure (about 10,000 psi) and may act like a solid body as they are forced past the cutting face. That is, the chips, which are rough irregular solids, probably cannot move relative to one another when they are under high pressure. Thus, they probably act more like a solid than a fluid in the region between the material being cut and the cutting face. This suggests that $Cf_A$ should at least be approximately equal to $Cf_B$.

Combining Eqs. (F-2) to (F-5) with the assumption that $Cf = Cf_A = Cf_B$ gives the following equations:

$$Nf = \frac{-Df\,Cf + \frac{Tq}{r_{avg}}}{(\cos 30° - 2\ Cf\ \sin 30° - Cf^2 \cos 30°)} \qquad \text{(F-8)}$$

$$Uf = Df - Nf \sin 30° - Nf\ Cf\ \cos 30° \qquad \text{(F-9)}$$

As the area of contact between the material being cut and the cutting face (area A) decreases, Nf, the normal force on the cutting face, decreases. These equations do not have the correct behavior as the cutting face contact area decreases. Thus, they will break down as the bit wears and the penetration rate decreases. The initial attempts to analyze a full data set on a point-by-point basis with a spread sheet used these equations. As the test progressed and the cutting rate decreased, the lack of closure got larger. Alternative sets of equations were derived in response to this problem. Using Eqs. (F-8) and (F-9) with Eqs. (F-6) or (F-7) allows us to back out a value for $\sigma$, the compressive strength. These equations have been used for conditions with good cutting to obtain values for $\sigma$. The equation set that was ultimately used for the full test analysis includes $\sigma$ as a parameter.

Combining Eqs. (F-2), (F-3), (F-4), (F-6), and (F-7), gives an alternative set of equations from which $\sigma$ may also be found.

$$Ff_A = \frac{\frac{Cf\ Df}{Denom} + \frac{A}{B} Df \frac{\cos 30°}{Denom} - \frac{Tq}{r_{avg}}}{\frac{Cf \cos 30°}{Denom} + \frac{A}{B}\frac{(\cos 30°)^2}{Denom} + \sin 30°} \qquad \text{(F-10)}$$

where

$$Denom = 1 + \frac{A}{B} \sin 30°$$

$$Uf = \frac{Df - Ff_A \cos 30°}{Denom} \qquad \text{(F-11)}$$

The value for the wear-flat area (area B) cannot be determined from the data because it is a function of the wear of the bit teeth. Also, as the bit wears, the assumption that the force on the wear-flat area is sufficient to match the compressive strength of the material may break down. Thus, Eqs. (F-10) and (F-11) have been used to validate the results of Eqs. (F-8) and (F-9) under conditions with good cutting. To use these, a wear-flat dimension was assumed. If results from these two sets of equations are consistent, it is assumed that this supports the validity of the conditions for the use of these equations. Equations (F-10) and (F-11) also do not have the correct behavior as cutting face contact area decreases.

A third set of equations was derived using Eqs. (F-2), (F-3), (F-5), and (F-6). Then

$$Nf = \sigma A \qquad \text{(F-12)}$$

$$Ff_A = Nf\, Cf_A \qquad \text{(F-13)}$$

$$Uf = Df - Nf \sin 30° - Ff_A \cos 30° \qquad \text{(F-14)}$$

$$Ff_B = \frac{Tq}{r_{avg}} - Nf \cos 30° + Ff_A \sin 30° \quad . \qquad \text{(F-15)}$$

These equations have the correct behavior as the cutting face contact area becomes small but do require that the value of s, the compressive strength, be known. Values for $\sigma$ were obtained for conditions with good cutting using Eqs. (F-8) to (F-11) in analyses that examined only selected times during the tests considered. The value of $\sigma$ obtained in this manner was used with Eqs. (F-14) and (F-15) to analyze one complete data set. It is assumed that $\sigma$ is a constant. It is possible that as the bit

wears, the size of the chips broken out will decrease, resulting in an increase in s. That is, more energy per unit volume is required to produce small particles than to produce large particles. In tests with simulants, a distribution of particle sizes was measured.[9] These are already skewed toward small particle sizes. Over 80% of the particles by mass were smaller than 40 mm, and 50% were smaller than 20 mm. Less than 3% were greater than 100 mm. A 1-in./min cutting rate at 55 rpm gives a tooth penetration depth of 77 mm. If the maximum chip size is limited by the depth of cut as the bit dulls, there will be fewer large particles and more small particles. Because most of the particles were small in the samples measured, this suggests that eliminating the larger particles from the distribution will not make a large change in the size distribution by mass. Thus, the change in the energy required to remove a given volume of chips is not expected to change significantly as the penetration decreases, and the constant $\sigma$ assumption should be reasonable. To put this argument another way, the measured particle distribution suggests that, for the most part, the material was being crushed to a fine powder rather than broken out as chips. Decreasing the scale of cutting will still result in the material being crushed to a fine powder, though the few larger chips that were being produced may no longer be produced.

The power terms can be derived by multiplying Eq. (F-3) by $r_{avg}$ w. Doing this and rearranging gives

$$Tq\,\omega - Ff_B\, r_{avg}\,\omega - Nf\, r_{avg}\,\omega \cos 30^\circ + Ff_A\, r_{avg}\,\omega \sin 30^\circ = 0 \qquad \text{(F-16)}$$

This equation assumes that the velocity in the downward direction is negligible compared to the velocity from the rotation. This also assumes that the velocity of the chips is equal to the velocity of the drill bit, which means that the thickness of the layer of chips passing across the drill bit face is equal to the thickness of the layer being cut. If a thinner layer passes across the bit face, the velocity would be higher. If a thicker layer passes over the bit face, the velocity would be lower. The first term is the power input, and the second term is the frictional dissipation between the wear-flat and the substrate. The third term is the power required to compress and fracture the material being cut, and the fourth term is the frictional dissipation at the location where the chips are squeezed across the cutting face. The third term may be readily shown to equal the compressive strength times the volumetric cutting rate. The difference in sign between the fourth term and the second and third terms should be noted. This sign difference means that the energy that goes into the frictional work as the chips are squeezed across the cutter face comes from the energy that was used to compress and fracture the chips. Further, the fourth term is a mechanical work term that acts on the bit and helps pull it along. Thus, it is possible for the third term, which is the energy to compress and fracture the chips, to be greater than the first term, which is the energy input to the drill string. Thus, at any moment, previously stored energy is released, and additional energy is stored as elastic compression.

To calculate the temperature rise of the chips, it has been assumed that the energy given by the third term minus the fourth term goes to heating the chips. The temperature rise from this energy should be practically instantaneous. The heat is generated along the fracture surfaces and is then transferred mostly into the chips, although some may be transferred to the purge gas and also to the bit. Including all of this energy is a conservative assumption. There may be additional elastic compressive energy that is recovered in the velocity of the chips as they decompress as well. These components, though expected to be small, contribute to the conservatism of this temperature rise calculation. That is, the calculated temperature increase will be greater than the actual temperature increase.

To calculate the maximum temperature of the chips, the calculated temperature rise has been added to the measured bit temperature. That is, the temperature of a given layer of material immediately before cutting was assumed to be equal to the bit temperature. This assumes that the temperature measured by the thermocouple on the bit teeth is indicative of the interface temperature, which is in turn indicative of the layer average temperature. This is a conservative assumption, at least for conditions with reasonably good cutting. As a layer of material is removed, a fresh, cooler layer is exposed. The frictional heating generated on the surface being cut raises the surface temperature to the interface temperature almost immediately. It takes a longer time for the rest of the layer to approach the surface temperature. Thus, the surface temperature should provide a conservative (high) estimate for the temperature of a layer just before it is cut.

These equations have been applied in two different ways. First, in scoping analyses, portions of tests were analyzed. Average data points for a period of interest were picked off the plots. The mechanical-to-thermal-energy conversion equations derived as shown above were applied. In addition, other calculations that might clarify any of the energy distribution terms were made. These included one-dimensional (1-D) slab calculations for cases with no cutting and temperature decay calculations for the chips produced by the cutting. Secondly, for one test, the energy conversion and distribution terms were calculated on a point-by-point basis. This served to validate our understanding of the phenomena involved. The details of the calculations are provided in Ref. 10.

### 4.2. Two-Dimensional (2-D) Transient Heat Transfer Model of Drilling Process

#### 4.2.1. Model Description

In order to better understand the thermal energy transfer in the drilling process, a 2-D transient heat transfer model was also developed. The primary function of the model is to determine the maximum waste temperature as a function of drilling conditions. The model can then be used to determine the drilling condition limits to avoid reaching the stated temperature limits: 150°C for the substrate and 180°C for the chips. A parametric study can be done using a 2-D model in order to study the effect of extrapolated parameters involved in the drilling process. The model is a

conduction/convection solution, where a conduction solution through the solid materials is coupled with a flow solution of the purge gas.

**4.2.1.1. Conduction Solution.** The general heat transfer equation solved is

$$\rho C_p \frac{\partial T}{\partial t} = -\nabla \cdot q + \frac{Q}{V} \quad . \tag{F-17}$$

The equation is solved numerically. The coordinate system is fixed to the drill bit; therefore, the drilled material is moving (in effect flowing) with respect to the grid. Therefore, as the bit penetrates, an additional term is added to the drilled material heat transfer solution. In effect, this is a steady state, constant property, incompressible flow solution. The material that "flows" through the upper boundary of the drilled material is added to the gas flow.

**4.2.1.2. Flow Solution.** The flow solution is solved separately from the conduction solution. The time frame of the flow solution is much shorter than for the conduction solution. The gas transit time through the system is much less than one second, and the transit time around the bit is on the order of milliseconds. Therefore, a steady-state solution can be used to approximate the flow at each conduction time step.

The flow solution is obtained by setting up a nodal 1-D flow path based on a path-through system. Specified at each node are the node length, flow area, hydraulic diameter, the heat transfer area, and the surface temperature of the conduction nodes that surround the flow node. The heat transfer between the flow and conduction nodes is then given by the standard internal flow relations (h is interpolated between Re of 2000 and 3000 to provide a transition between the laminar and the turbulent flow):

$$Q_w = hA_{ht}(T_w - T_g) \quad \text{where:} \quad \begin{array}{l} h = h1 \ \text{ if } \ Re<2000 \\ h = h2 \ \text{ if } \ Re>3000 \\ h = h1 + (h2-h1)(Re-1000)/2000 \end{array} \tag{F-18}$$

$$h1 = \frac{4.364k}{D_H} \qquad h2 = \frac{.023k}{D_H} Pr^{.3} Re^{.8} \tag{F-19}$$

$Q_w$ is used both in the conduction solution and to calculate the gas temperature as

$$Tg_k = \frac{1}{\dot{m} C_{p_k}} \left( \dot{m}_{k-1} C_{p_{k-1}} Tg_{k-1} + \dot{m}_{chip_k} C_{p_{chip}} T_{sub} + Q_{w_k} + Q_{gas_k} \right) \tag{F-20}$$

where: $\dot{m}_k = \dot{m}_{k-1} + \dot{m}_{chip_k}$ .

$Q_{gas}$ is the energy deposition directly into the gas from the chips and $T_{sub}$ is the temperature of the substrate at the location where the chips are being generated. Also, as chips are added to the flow caused by drilling, the specific heat and other properties of the flow are adjusted. It is assumed that the gas and chips mix uniformly and come instantaneously to equilibrium.

**4.2.1.3. Energy Deposition.** In the above equations, two important parameters have yet to be determined, $Q_{gen}$ and $Q_{gas}$. First, it is conservatively assumed that all of the drill power is deposited in the system as thermal energy. Then it is assumed that this energy results from either breaking up the chips ($Q_{drill}$) or friction ($Q_{fric}$),

$$Q_{tot} = tw = Q_{drill} + Q_{fric} \quad . \tag{F-21}$$

The fractions are then broken up further into components that go to the gas, bit, or substrate. In the code, the chip energy and frictional components are determined by:

$$Q_{drill} = \frac{E_{sp}}{\dot{z}A_{drill}} \qquad \text{and} \qquad Q_{fric} = tw - Q_{drill} \quad . \tag{F-22}$$

Here $E_{sp}$ is the specific energy of the drilled material. The fractional splitting of these powers into their gas, bit, and substrate components are specified in the input. The resulting energy deposition fractions are

$$Q_{gen,bit} = f_{drill,bit}Q_{drill} + f_{fric,bit}Q_{fric} \quad , \tag{F-23}$$

$$Q_{gen,sub} = f_{drill,sub}Q_{drill} + f_{fric,sub}Q_{fric} \quad , \text{ and} \tag{F-24}$$

$$Q_{gas} = f_{drill,gas}Q_{drill} \quad . \tag{F-25}$$

These fractions are determined from benchmarking the experimental drilling.

**4.2.1.4. Maximum Theoretical Chip Temperature.** It is assumed that all of $Q_{drill}$ goes into heating up a chip before energy is transferred elsewhere as

$$T_{chip} = T_{sub} + \frac{Q_{chip}\Delta t}{\rho V C_p} = T_{sub} + \frac{E_{sp}}{\rho C_p} \quad . \tag{F-26}$$

This number places a conservative bound on the maximum chip temperature and is meant only as an absolute upper limit. The chip temperature will be discussed further in the results section.

**4.2.1.5. Model Uncertainties and Limitations.** There are two major model limitations: (1) The model is 2-D, so that the drill bit is smeared in the azimuthal direction. This does not allow for localized heating effects in the "tooth" or the effects of a plugged flow channel, and (2) The flow solution is one-species (chips/gas

mix as one fluid). This does not allow for a separate calculation of chip temperature. Other minor limitations are that the model assumes constant properties, and the flow solution is steady state (which would only matter if very small conduction time steps are required).

There are several uncertainties in the model that may significantly affect the results. These include: drilling energy deposition fractions, friction energy deposition fractions, purge gas heat transfer coefficient, bit/pumice interface conductivity, and material properties. These uncertainties have been limited by benchmarking the model with the experimental drilling results.

## 5.0. RESULTS

The mechanical-to-thermal energy conversion equations show that the energy transfer to the bit can be resolved into three major components, two frictional components and the mechanical energy needed to compress and fracture the material into chips. The analyses show that the frictional components can account for the temperatures measured in the tests. The most significant of the frictional components produces heat between the drill bit and substrate. This heat will be transferred into the bit and into the substrate. The maximum temperature will occur at the interface. The drill bit thermocouples were located on bit teeth where they could measure the interface temperature. Thus, to the extent that the pumice was a limiting material for frictional dissipation, the bit temperature measurements from the test series on pumice blocks should be indicative of the maximum bulk material temperature. A comparison of temperatures between the test series done with pumice blocks as a test material and earlier tests with waste simulants as test materials show that the testing with the pumice blocks produced the highest temperatures. Thus, the coefficient of friction between the bit and the pumice was probably higher than the coefficient of friction between the bit and any of the other materials. Pumice block consists of hard particles in a binder material. This produces a very abrasive material that should have a high coefficient of friction. Thus, it is expected that the testing done on pumice blocks produced bulk temperatures that are limiting, or at least very nearly so.

The mechanical energy needed to fracture the material into chips causes an increase in the temperature of the chips. This temperature increase comes in addition to any temperature increase while the material was part of the substrate and was heated by the frictional dissipation. Thus, a conservative approach to finding the maximum chip temperature is to calculate a temperature increase for the chips and add the interface temperature, as measured on the bit, to this.

Two separate models are used to determine the substrate and chip temperatures. The first model is based on 1-D conduction solutions with adequate boundary conditions and consideration of a force-balance equation. A 1-D model is a first-order approach and is considered in Section 4.1. A 1-D model is used at the earlier phase of study to evaluate expected chip temperatures and to evaluate material

properties important to the cutting process. In Section 4.2, a more detailed 2-D model is developed to simulate drilling. The 2-D model is more realistic and considers solution of a moving boundary of the drill bit. The energy equation is solved for the moving drill bit by considering the energy exchange between both solid-solid and fluid-solid. In the remainder of this section, the results of the 1-D model (Section 5.1) and then the 2-D model (Section 5.2) are discussed.

### 5.1. Results Obtained from 1-D Analysis

Two sets of comparisons are performed. The first set involved an evaluation of three tests, Tests TORQTST 6, 12, and 16. All of these tests used a rotational speed of 55 rpm, and 30 scfm purge gas flow (see Table F-2). The nominal down forces were 1170 lbf, 900 lbf, and 750 lbf. These three tests are analyzed to determine the forces involved in cutting, chip, drill bit, and substrate temperatures by solving the energy and force balance equations given in the previous sections. Details of the analysis are available in Reference 10. Parameters involved in analysis are averaged over a period in which cutting was either effective (constant penetration) or not effective (no penetration). In the second series, only Test 15 is analyzed. For Test 15, time-averaged test parameters are not used but the analysis is performed for each transient recorded data point when the cutting was observed. This test defines the safety limits for RMCS.

#### 5.1.1. Effective Waste Cutting.

Table F-3 shows some key results obtained from three tests for times near the beginning of the tests when there was good penetration. Temperature increase estimates were obtained from the energy balances. Compressive strength was calculated from the force balance for these tests. The value for compressive strength determined from conditions with good cutting was about 10,000 lbf/in.$^2$ with an estimated uncertainty of ±2000 lbf/in.$^2$ (Ref. 10). Using $\sigma$ = 10,000 lbf/in.$^2$ gives a temperature increase of 45°C for compressing and fracturing the chips. These temperature increases are in addition to increases from frictional heating of the substrate before cutting.

**TABLE F-3**
**ANALYSIS RESULTS, TESTS 6, 12, AND 16**

| Test | Downforce (lbf) | Chip Temperature Increase from Energy Balance (°C) | Compressive Strength Estimates (lbf/in.$^2$) |
|---|---|---|---|
| TORQTST6 | 1170 | 39.0-45.5 | 9227-11420 |
| TORQTST12 | 900 | 42.2-50.4 | 9482-9513 |
| TORQTST16 | 750 | 30.8-31.9 | 9230-9730 |

The calculation using Eqs. (F-11) to (F-14) with a compressive strength of 10,000 lbf/in.$^2$ was performed for Test 15. Figure F-5 shows the measured bit temperature with calculated bit and chip temperatures. The figure shows that, with conservative assumptions, the increase in drill bit/substrate interface temperature approach but do not exceed the $\Delta T = 60^{\circ}C$ safety limit. The calculated chip temperature increase, about 83°C, is also lower than the safety limit of $\Delta T = 90^{\circ}C$. This calculation presents the first evidence that when the operating parameters are limited with a downward force of 750 lbf, a rotational speed of 55 rpm, and a minimum purge flow of 30 scfm, a local waste ignition is not expected to occur when there is reasonable penetration. However, this conclusion is valid only if the hard waste layers expected in the tanks have similar properties to pumice in terms of both thermal and cutting processes of drilling.

If there is a reactive layer harder than pumice in the tanks, the truck has enough power available to produce higher torque. In this case, it is possible that chip and substrate temperature may exceed the safety limits. However, when the torque increases as a consequence of encountering a harder material, the penetration rate is expected to decrease. As mentioned in the next section, the penetration rate must be above 0.75 in./min. Therefore, higher torque should correspond to lower penetration rates. As a summary, if the waste layers in SST tanks are not harder than pumice, the proposed safety limits adequately protect against waste ignition hazards based on the results obtained from the 1-D model for effective cutting defined by a penetration rate higher than 0.75 in./min.

**5.1.2. Frictional Heating with No Penetration.**

In all of the tests on the pumice blocks, the penetration rate slowed and then decreased to zero as the bit became worn. The data for the tests that used the limits of 750 lbf for the down force, 55 rpm for the rotational velocity, and 30 scfm for the purge gas flow, showed acceptable temperatures for conditions with a worn bit spinning on the substrate. The analyses showed that there was significant conduction into the bit for these conditions, and this limited the heat transfer to the slab, and thus the slab temperature. Results of Test 15 show that the drill bit and the corresponding substrate interface temperature is lower than the safety limit of $\Delta T = 60^{\circ}C$, even when there is not good penetration and as long as nitrogen flow is available. However, this mode of operation in real drilling is not desired because the cause for no penetration will not be known. No penetration could be the result of encountering a hard reactive or nonreactive layer, metal, or other nonmetal object with different properties. The real waste is not expected to have a layer as hard as pumice. Note that every test done by Witwer[1] resulted in worn drill teeth. WHC engineers indicated to us that one sampling activity requires two rotary-mode core drillings out of a total of 10 samples. WHC engineers also expressed the fact that they have never failed to penetrate hard layers in Hanford tanks. Considering this experience as the available data for conditions of waste, it is not expected that the drill bit will encounter any reactive waste layer harder than pumice. However, if

a waste layer is as hard as pumice, no penetration would be observed as experienced in laboratory testing.

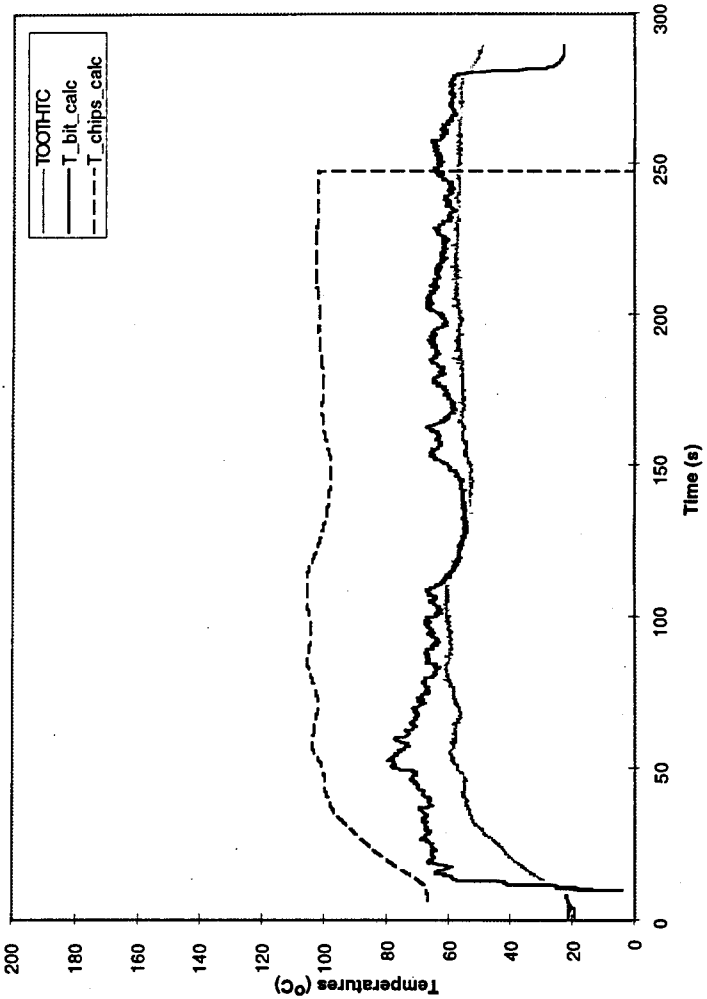



Figure. F-5. Test 15 - Measured bit and calculated bit and chip temperatures.

One of the other reasons why the frictional mode of operation is not desired is that the transition from effective cutting to the frictional mode is not understood clearly. When the downward force was 1170 lbf, in Test 6, a large temperature variation, about 50°C, is observed in the transition region. Although the force is lowered to 750 lbf, the reasons for these higher temperature oscillations are not clearly understood. It is concluded that a penetration rate control is needed. The main reason for this control is to prevent drilling against reactive waste material that is harder than pumice. The lack of penetration rate control also prevents applied torque from being above the values observed in envelope testing.

**5.1.3. Applicability of Envelope Testing to Real Conditions.**
Table F-4 compares properties of the pumice material to the properties of the waste simulant materials developed by WHC.[8] All of the properties except the compressive strength calculated from drilling tests, the specific heats, and thermal diffusivities were measured by WHC.

**TABLE F-4**
**COMPARISON OF WASTE SIMULANT AND PUMICE TEST MATERIAL**

| Property | Evaporator Bottoms | BY-104 Simulant | Pumice Block |
|---|---|---|---|
| Bulk density ($kg/m^3$) | 1560 | 1410 | 1600 |
| Unconfined compressive strength (psi) | 905 | 3,264 | |
| Calculated compressive strength from drilling tests (psi) | | | 10,000 |
| Direct shear strength (psi) | | 459 | |
| Penetrometer resistance (psi) | 23,520 | 34,507 | |
| Thermal conductivity (W/m K) | 2.32 | 1.67 | 1.03 |
| Specific heat (kJ/kg K) | | 0.97* | 0.88** |
| Thermal diffusivity ($m^2/s$) | | $1.221 \times 10^{-6}$ | $7.315 \times 10^{-7}$ |

* Estimate based on handbook value for predominate material.
** Handbook value.

The physical and thermal properties are comparable for pumice and the BY-104 simulant. The density times the specific heat products for the BY-104 simulant and the pumice block are within three percent of each other. Thus, the energy storage terms are very comparable. The lower thermal diffusivity coefficient of the pumice block tends to slow the spread of heat and keep temperatures higher. Thus, the pumice block testing produced temperatures that are conservative compared to the

BY-104 simulant, and WHC has identified the BY-104 simulant as the limiting waste simulant.[8]

The pumice blocks consist of hard pumice grains in a binder material. This makes the pumice material very abrasive. The coefficient of friction between the bit and the pumice was evaluated as 0.4. The temperature at the bit/substrate interface where the bit temperatures were measured is determined primarily by frictional heating. The earlier series of tests[8] with the BY-104 simulant showed lower temperatures. (Torque was not measured for this series of tests, so the effective compressive strength during drilling and the coefficient of friction cannot be calculated from the test data.) The temperatures suggest that the coefficient of friction between the bit and the BY-104 simulant was lower than the value deduced for the bit and pumice. The maximum average chip temperature is a function of two things, (1) the temperature of the waste material layer just before cutting and (2) the energy addition during the cutting process. The effects are additive. The temperature of the material before cutting is primarily a function of the frictional heating, and this was lower for the simulant materials.

The measured compressive strength for the BY-104 simulant is less than one-third the compressive strength deduced from the testing on the pumice blocks. Because the method of determination is very different, these values are not directly comparable. Rabia[5] showed that specific energy values for a series of drilling tests were often about twice the laboratory measured values for the compressive strength of the same materials. Even if the effective compressive strength during drilling conditions were three times the laboratory-measured value, the chip temperature rise from the compressing and fracturing operation would be less than the corresponding value for the tests on pumice blocks. Thus, this temperature should be lower for the BY-104 simulant for comparable drilling conditions.

Three reasons were identified for why the maximum temperature during drilling of the BY-104 simulant or comparable material should be lower than the corresponding maximum temperature during drilling in the pumice block. All three of these factors contribute independently of the others. Thus, the pumice block tests should be bounding for maximum temperature if the BY-104 simulant material can be considered as reasonably representative of the hard waste layers in the tanks. Operating limits based on test data from drilling in the pumice blocks should be conservative for materials that are limited by the BY-104 waste simulant properties. This applies to normal cutting and to off-normal conditions such as the bit becoming dull and no longer drilling and a loss of purge gas flow.

Hitting objects harder than pumice in the waste such as a rock, particularly over a small fraction of the bit face, could cause high temperatures if attempts were made to continue drilling. Drilling materials (nonreactive and reactive) harder than pumice may cause the applied torque to be increased, at least initially. Typical torque values measured in envelope tests varied between 35 and 85 ft lbf. There is

power available to increase the torque. In an ideal situation, if the ratio of torque to the penetration rate defining the specific energy were controlled, safety limits would be implemented with extremely high confidence because the chip and substrate temperatures primarily depend upon the energy density (or unit horse power) which is linearly proportional to the torque and inversely proportional to the penetration rate. As discussed previously, the penetration rate must be monitored and controlled. Torque measurements are not easy and reliable although application of a torque limiter would be easy to implement. However, without torque measurements, operating safety limits involving downward force, rotational speed, nitrogen force, and penetration rate provide conservative protection for any waste ignition hazard.

The lower limit for the penetration rate of 0.75 in./min was set as protection against drilling in a material with a higher compressive strength than the pumice blocks. In the pumice block tests, there was an initial period with good penetration followed by a period with declining penetration, and finally a period with no penetration. The 0.75 in./min penetration rate represents a value at which the transition from the period of good penetration to the period with rapidly declining penetration occurs. In the pumice blocks, the nominal drilling parameters allow drilling with a bit that is at most slightly worn. If a layer of material with a higher compressive strength (which would give higher chip temperatures) is encountered during drilling, the penetration rate will drop below the lower limit. The operators could continue drilling only after a ten-minute cooling period following a trip initiated by out-of-tolerance down force on force, rotational speed, purge flow, or penetration rate. Additional attempts to restart drilling would begin with a cooled substrate. Then, the only energy component contributing to the temperature increase would be the energy to compress and fracture the chips. If the 0.75 in./min penetration rate could not be attained, drilling would be stopped automatically before the substrate could heat substantially and increase the chip temperatures.

Although this limit significantly reduces the possibility of producing chips at a temperature higher than the 180°C limit should a harder material be encountered, this does not guarantee that the temperature limit cannot be exceeded. If the limit is exceeded, only a very small volume of excessively hot chips will be produced for only a very short period of time. The chips are produced in an environment in which they are immediately surrounded by relatively cold nitrogen purge gas with a high convection heat transfer coefficient. Thus, they are expected to cool to below 180°C in much less than 0.1 s and have no detrimental effect.

### 5.1.4. Cases with Inadequate Nitrogen Flow

In several of the tests, the purge gas flow was shut off after the drill had stopped penetrating. With this condition, the energy balance becomes very simple, with only frictional energy dissipation and then conduction, either into the bit or into the substrate. Test 16 was one of the tests with this condition. Figure F-6 shows that the temperatures were measured and that the purge gas was shut off after the drill

stopped penetrating. A 1-D slab analysis was performed for the time 60 s after the purge gas was turned off. To determine the effect of the conduction into the bit, an equivalent convection heat-transfer problem was determined by trial and error. In this case, a convection coefficient of 550 watt/$m^2K$ was needed to match the measured temperature. Thus, there was significant conduction heat transfer to the bit. The operating requirements specify that the drilling be stopped for a loss of purge gas. If all the frictional dissipation went into the substrate for even a short period of time before drilling was stopped, an overheat condition could occur. This result shows that there is sufficient heat transfer to the bit to provide some margin for shut-down time should a loss of cooling occur. If all the energy generated were going into the slab, the time for the surface temperature to rise above the limit would be small. The cooling capacity of the bit gives some margin for spin-down time, should a loss-of-purge-gas-flow condition be encountered. The automatic controls on the drill system are to be set to immediately stop the drilling if a loss-of-purge-gas-flow condition occurs.

### 5.1.5. Chip Temperature Decay in Purge Gas

The maximum chip temperature occurs immediately after energy is added to the material to compress and fracture it. The chips are immediately entrained in the purge gas. This cools the chips quickly. This is important in that the chips have little time to heat any material other than the purge gas.

Two estimates were made for the cooling of these particles. WHC[8] measured a particle size distribution for drilling in simulant materials. The slip velocity was calculated for the top particle size in each range reported by WHC. This was done by equating the weight of the particle and the drag on the particle because of the slip velocity. The drag was calculated from a standard correlation for the drag on a sphere as a function of the Reynolds number. An iterative solution results. Once the velocities had been obtained for each size, a standard correlation for the convective heat transfer was used to estimate the convective heat transfer coefficient (h). References 11 and 12 were checked for appropriate correlations. None were found with a range of applicability that included the small Reynolds numbers being calculated. A correlation with a stated lower limit of applicability of Re = 17 was selected. The extrapolation to lower Reynolds numbers is uncertain. The Reynolds numbers calculated from the slip velocities ranged from $3 \times 10^{-6}$ to 6.4. The convection coefficient for each size and then a reduced temperature for each particle size as a function of time were calculated. A mass-averaged reduced temperature was also calculated as a function of time. This was used to estimate the chip-to-gas heat-transfer rate.

The second approach was similar, but a natural convection correlation was selected. The Grashof numbers calculated were well below the stated limit of applicability.

Using the forced convection correlation, the mass-weighted average particle goes through 63% of the change from the initial hot condition to the gas temperature in

0.1 s. The 150 micron particle size, which is the largest in the given distribution goes through 44% of its cooling in 0.1 s.

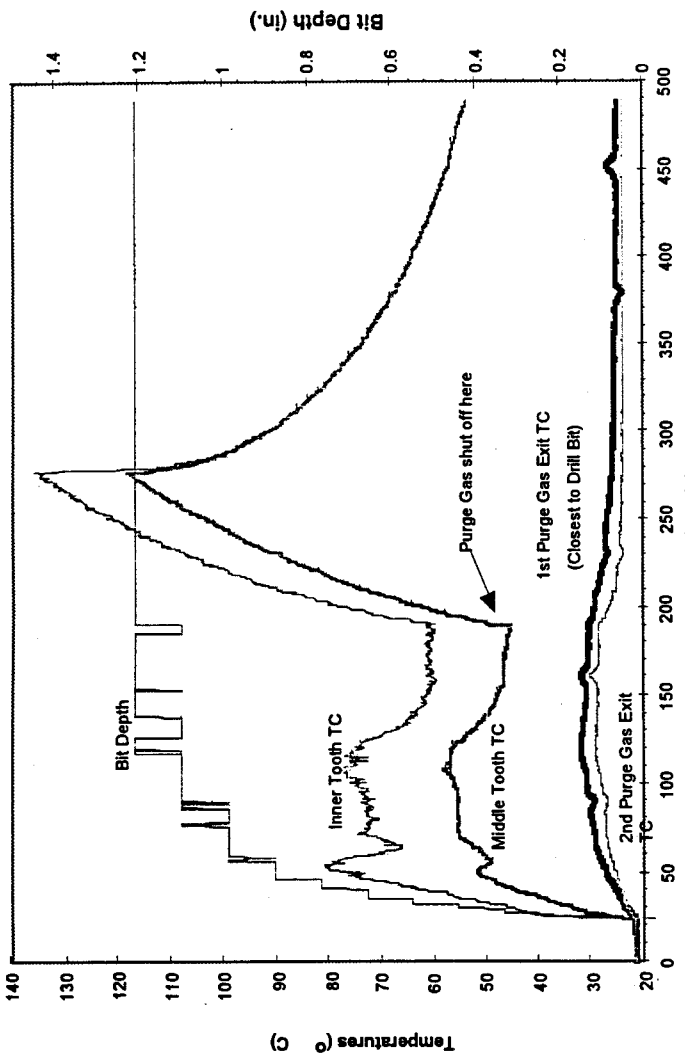



Figure F-6. Test 16 – Measured temperature data.

Using the natural convection correlation, the mass-weighted average particle goes through 98.7% of its cooling in 0.1 s, and the 150-micron particle size goes through 65% of its cooling in 0.1 s. Figure F-7 shows the temperature decrease for the mass-weighted average chips as a function of time for the cases discussed above.

Although both of these estimates use correlations outside the stated range of applicability, resulting in a large uncertainty for the above estimates, the conclusion that the chips cool to much less than the temperature limit in the order of 0.1 s should be valid.

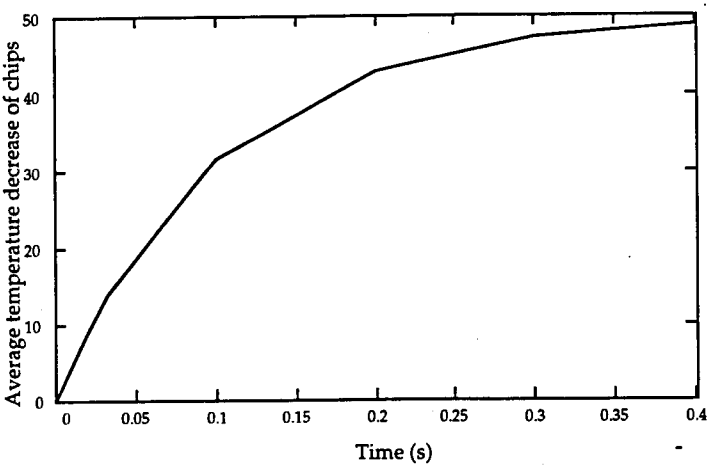
Attempts were made to apply the above calculations to the purge gas conditions at the exit thermocouples to work back to average chip temperatures immediately after cutting. These attempts did not produce any conclusive results. They do support the use of the 180°C limit for the chips because these calculations demonstrate that the chips cool from near this limit to well below this limit in less than 0.1 s.

## 5.2. Results of 2-D Finite Difference Transient Heat Transfer Modeling

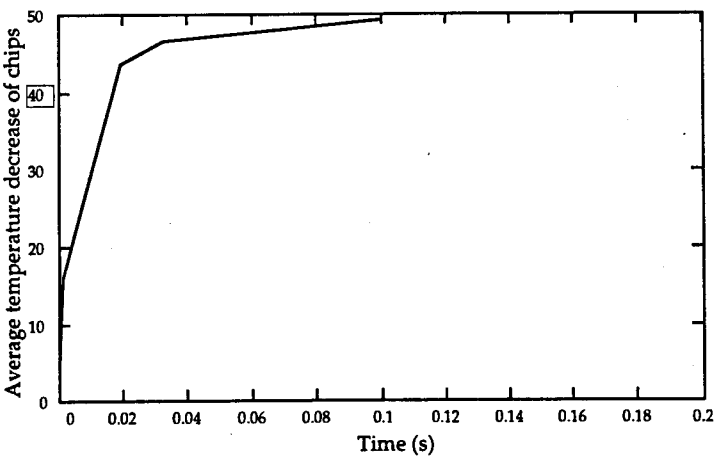
### 5.2.1. Experimental Benchmarking

To begin, the model has been benchmarked versus two separate experimental tests: TORQTST16 and TORQTST23. These tests have printouts that contain most of the information necessary to obtain an energy balance (Ref. 13). In addition, TORQTST23 (which involves drilling into steel), contains reliable temperature measurements below the drilling surface. Initially, the energy deposition fractions (and to a small extent the material properties) were varied so that the experimental and computational results matched for each case separately. A fixed set of parameters was then determined combining the results of the two cases.

Next, the model was used to calculate temperatures for three additional tests: TORQTST15, TORQTST17, and TORQTST18. No model parameters were adjusted in assessing the model against these three tests. The calculated results conform fairly well with the experimental results for each test, especially considering the uncertainty in the experimental measurements. The results for some of these calculations are shown in Figure F-8. The calculated results are plotted alongside the experimental bit temperature. The experimental gas flow temperatures are not plotted, but they conform within 1°C of the calculated temperatures. TORQTST23 involved drilling into a steel slug; the experimental and calculated temperatures in the slug are also plotted for this case. The agreement between experimental measurements and calculated data for tests TORQTST15, 17, and 18 indicates that this model can be used for further parametric analysis.




(a)




(b)

**Fig. F-7. Average chip temperature decrease predicted using (a) forced convection correlation and (b) natural convection correlation.**

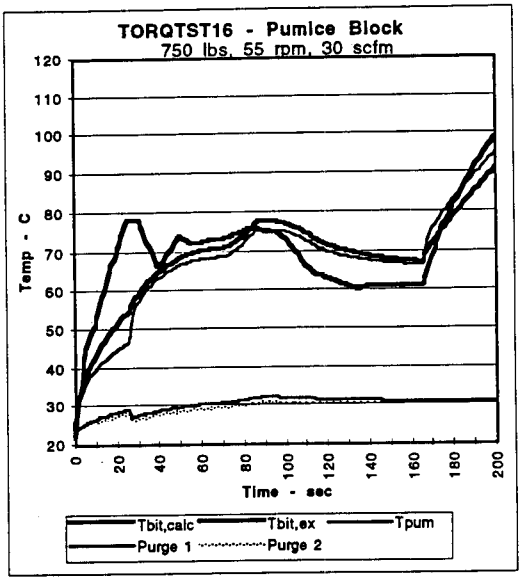



**Fig. F-8(a). Comparison of calculated and measured temperatures of Test 16.**

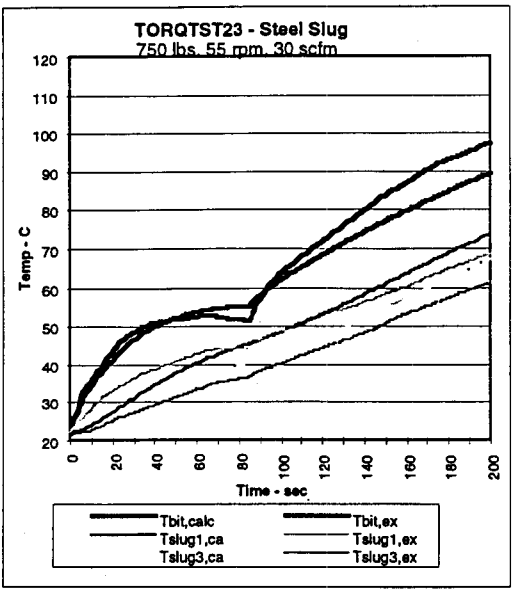



**Fig. F-8(b). Comparison of calculated and measured temperatures of Test 23.**

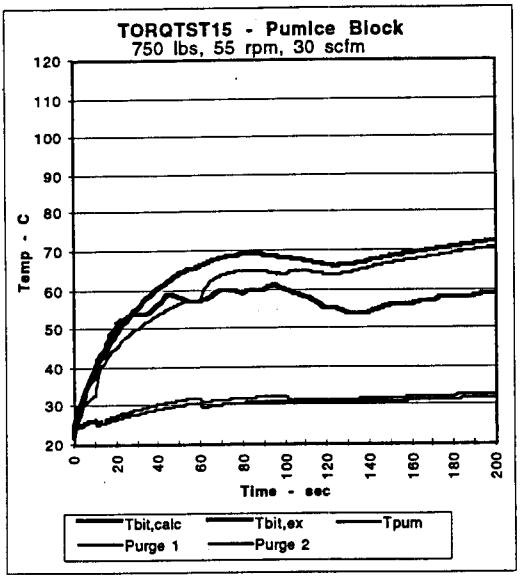



**Fig. F-8(c). Comparison of calculated and measured temperatures of Test 15.**

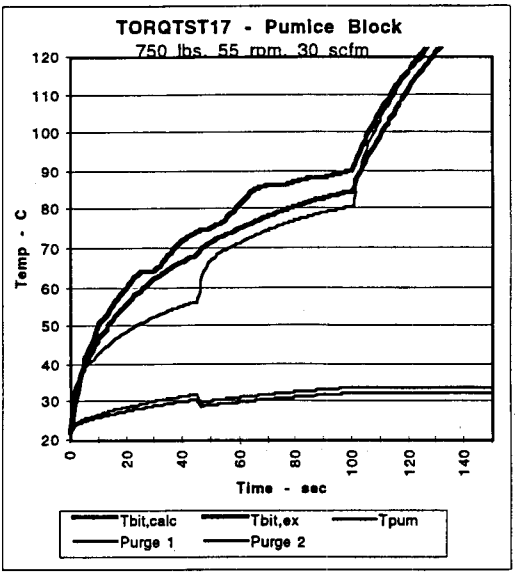



**Fig. F-8(d). Comparison of calculated and measured temperatures of Test 17.**

### 5.2.2. Substrate Temperature.

The primary result of this heat transfer analysis is the maximum substrate temperature as a function of time and drilling conditions. The substrate temperature limit has been set at 150°C; therefore, the model was used to determine how long it would take to reach this temperature under specific drilling conditions. The time to reach 120°C was also calculated to provide a conservative number. The time to reach each temperature was calculated as a function of torque, penetration rate, and initial waste temperature. The material properties were taken to be the same as for the experimental pumice, which is assumed to be a bounding condition (i.e. the waste is expected to have a higher specific heat and a lower specific energy). All of the results are obtained for a down force of 750 lb, a drill speed of 55 rpm, and a purge gas flow rate of 30 scfm. For this calculation, it was conservatively assumed that all of the energy goes into the bit and substrate (i.e., none goes directly to the gas). These results are plotted for the 150°C limit in Figs. F-9 and F-10.

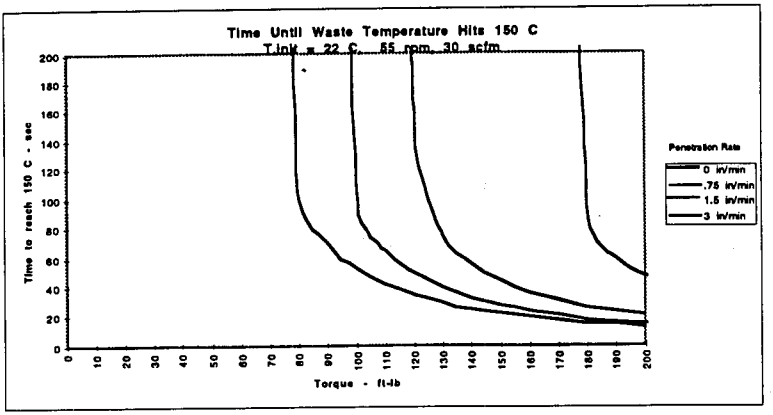



Fig. F-9. Time to reach 150°C as a function of torque for various penetration rates and an initial temperature of 22°C.

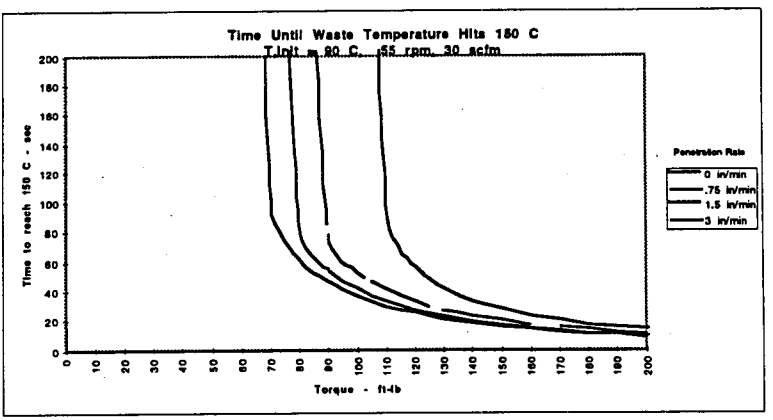



Fig. F-10. Time to reach 150°C as a function of torque for various penetration rates and an initial temperature of 90°C.

On the plots, any condition to the lower left of a given line will produce a maximum temperature below 150°C. Some of the results are also listed in tabular form below in Table F-5.

TABLE F-5
TEMPERATURE INCREASE CALCULATIONS

| Torque (ft-lb) | Penetration Rate (in./min) | Initial Temp = 22°C | | Initial Temp = 90°C | |
|---|---|---|---|---|---|
| | | Time to Reach 120°C | Time to Reach 150°C | Time to Reach 120°C | Time to Reach 150°C |
| 50 | 0.00 | nr | nr | 110 | nr |
| 50 | 0.75 | nr | nr | 152 | nr |
| 50 | 1.50 | nr | nr | nr | nr |
| 50 | 3.00 | nr | nr | nr | nr |
| 100 | 0.00 | 28 | 52 | 19 | 36 |
| 100 | 0.75 | 39 | 97 | 20 | 42 |
| 100 | 1.50 | 74 | nr | 22 | 53 |
| 100 | 3.00 | nr | nr | 26 | nr |
| 200 | 0.00 | 7 | 12 | 4 | 9 |
| 200 | 0.75 | 8.5 | 15 | 5 | 10 |
| 200 | 1.50 | 11 | 20 | 5 | 11 |
| 200 | 3.00 | 20 | 47 | 6 | 15 |

In Table F-5 above "nr" means that the temperature was not reached in 5 minutes. In this case, the system reaches a quasi-steady state, where the energy input equals the energy taken away by the gas plus the energy conducted away to the system "capacitance." Of course, because the system has a finite heat capacity, a steady state is not truly achieved until all of the energy is removed by the gas, but for a system this size, this will take place over the course of hours. So for this analysis, if the temperature has not reached its limit in 5 minutes, it is safe to assume that the temperature will not rise substantially over the course of several more minutes. In effect, "nr" means that the temperature will not be exceeded over any practical drilling time period.

In summary, the data in Table F-4 and in Figures F-9 and F-10 indicate that if the torque is limited to 60 ft lbf, there are no conditions in which the 150°C limit will be violated. At 100 ft lbf, the temperature limit is not violated at a penetration rate of more than 3 in./min, and at low penetration rates, the limit is not exceeded for more than 30 seconds. A 200-ft-lbf torque leaves about a 10-second window to halt operations or for the drill to break before temperature limits are violated. Figure F-11 plots that maximum allowable torque as a function of penetration rate that will not result in exceeding the 150°C limit. This data can be used to determine the optimum limits in terms of torque, penetration rate, and time for the drilling process. Also, the torque and penetration rate limits should consider the maximum chip temperature, which is discussed below.

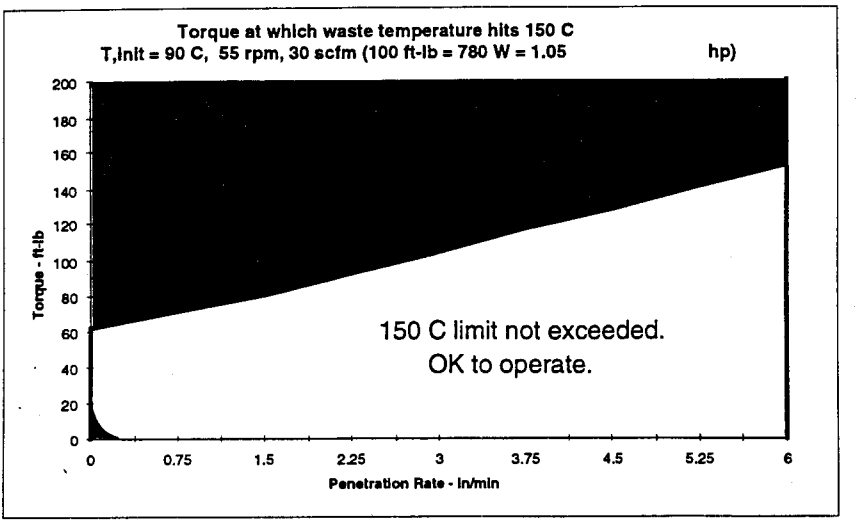



**Fig. F-11. Torque at which waste temperature reaches 150°C as a function of penetration rate.**

Several off-normal conditions were also considered. One case studied an increased purge gas flow of 55 scfm, with an initial temperature of 90°C and a penetration rate of .75 in./min. For a torque of 100 ft lbf the temperature did not even reach 150°C, as opposed to the 30 scfm case that reached 150°C in 42 seconds. For 200 ft lbf the temperature reached 150°C in 12 s as opposed to 10 s. From this result, it can be seen that more safety margin would be provided if the penetration is alarmed at 1 in./min value and the operator can take an action to increase the purge flow to 55 scfm before tripping the drill rig engine. However, the implementation of this suggestion as a control would be not easy because the time to reach the trip value may be so short.

Another case studied was a situation in which the system had reached a quasi-steady state at 3 in./min, 50 ft lbf, 750 lb, 30 scfm, and 55 rpm, and then the down force was suddenly increased to 4500 lb. Similarly, a case was studied in which the drill speed was increased to 110 rpm (as opposed to the down force). Temperature plots are shown for these two cases on Figures F-12 and F-13. Because the 4500-lb case increases the torque by a factor of 6, the temperature passes through 150°C in only a few seconds. The 110 rpm case doubles the torque, and the temperature reaches 150°C about 80 s after the drill speed is increased. The cases studied above indicate

that the period in which the operator can take corrective actions after a trip is initiated can be very short. Therefore, the drilling operation must be shut down immediately (in the time required by the data acquisition system to ensure the signal is real), when the downward force exceeds 750 lbf, rotational speed exceeds 55 rpm, or the purge flow becomes less than 30 scfm. Alarm values are not determined in this appendix. However, alarm values may be selected as long as they are lower than trip values by considering a proper waiting period.

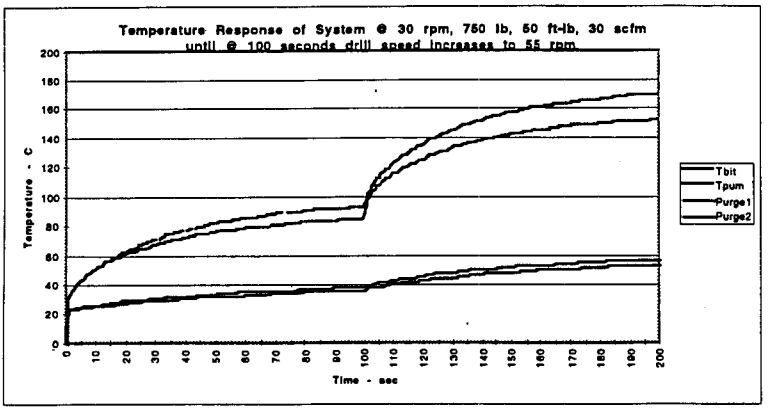



**Fig. F-12. Temperature histories during an abnormal operation; speed is increased.**

5.2.1.1. **Chip Temperature.** As mentioned earlier, this model does not attempt to calculate the chip temperature. The only number calculated is the maximum theoretical chip temperature. This is equal to the substrate temperature at the location of drilling, plus a finite $\Delta T$ associated with the energy deposited in the chips caused by drilling of the material. If the very conservative assumption is made that all of the drilling energy goes to the chip, then this $\Delta T$ is equal to the specific energy of the material divided by the heat capacity. For the pumice used in the experiments, this $\Delta T$ is on the order of 30°C (based on a specific energy of 40 $MJ/m^3$, which can be inferred from TORQTST18). Because the drilling conditions discussed above limit the substrate temperature to 150°C, then this also limits the chip temperature to 180°C (if it is assumed that the pumice is a limiting material on the basis of specific-energy-to-heat-capacity ratio).

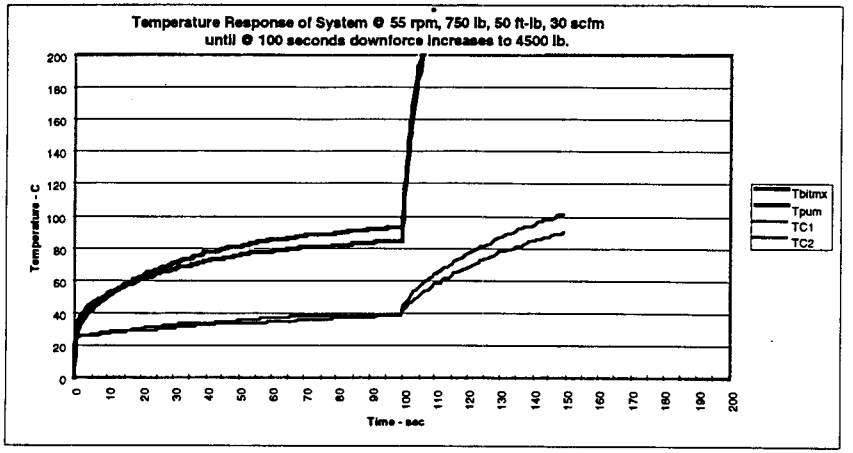



**Fig. F-13. Temperature histories during an abnormal operation force is increased.**

However, it is still possible, although unlikely, that a waste material could be encountered that has a high enough specific energy to heat capacity ratio to cause more than a 30°C chip temperature rise. There is no way to absolutely avoid this possibility. The likelihood of exceeding 180°C could be decreased by setting the substrate temperature limit below 150°C, which would provide more margin for chip $\Delta T$. Also, torque and/or penetration rate limits could be imposed so that the drill is tripped as soon as such a material is encountered (although experiments have shown that the bit wears rapidly as harder materials are encountered, so these limits may not add much safety margin, especially if the detection/trip time is relatively slow). In either case, because the trip or bit wear is not instantaneous, a few chips may be produced that exceed the quoted maximum temperature. Fortunately, it has been determined that the chips cool very rapidly ($<<$ 1 s), so that even if the chip temperature does exceed 180°C for a short time, the risk appears to be negligible.

There are two conclusions that can be drawn from the experimental results that support the contention that the chips are not hot for a substantial period of time; both involve the purge gas temperature. First, there is no abrupt rise in purge gas temperature as drilling begins. If a large fraction of the energy were going to the chips, and then to the gas, there would be an abrupt step increase in the purge temperature in the first few seconds. Because this increase is not seen, then the chips are either not getting very hot, or they are transferring energy quickly to the bit and substrate. Second, the downstream thermocouples do not show any evidence of

chip energy deposition as the flow moves downstream. This implies that the chips have lost most of their energy before the flow reaches the thermocouples. The only other possibility is that the chips remain hot as they travel through the entire system. However, the measured gas temperatures are consistent with a total energy balance, and it is unlikely that the thermocouple would read the correct mean (1-species) temperature if the chips were hotter than the gas. Also, simple calculations confirm that the chip cool-down time is << 1 sec.

As mentioned before, ideally the control of the ratio of torque-to-penetration rate would provide reliable protection against waste ignition hazards. These two parameters, however, are not independent. Suppose a hard object/layer is encountered during drilling that is progressing with a good penetration rate. The penetration rate will decrease and the engine would increase the torque to continue drilling. At this point, torque may exceed values that were observed in envelope testing. If material is cut, some penetration can be achieved. Note that drill bit teeth are also starting to be worn out. Based on envelope testing results, teeth became worn down in about 1 minute. If material is much harder than pumice, this period is expected to be on the order of seconds because drill bit teeth material is designed to be worn down if metal objects are drilled. Once teeth get worn down, the penetration rate becomes zero, and the torque will decrease. Current design features only include the monitoring of the penetration rate. There is an automatic shut-down feature when penetration rate decreases below 0.75 in./min. Controlling only the penetration rate will provide protection against exceeding the temperature limits, although until teeth are worn out, there is a short period in which chips and substrate may get hotter than current limits. However, because of nitrogen-cooling capability, chips and substrate will to be cooled and not cause a propagating reaction. In order to further increase safety, a possible design improvement would be the inclusion of a torque limiter or meter. The established controls provide adequate protection for waste ignition hazards.

## 7.0. CONCLUSIONS

The analyses in this appendix show that the temperature of the chips generated during the drilling tests may have exceeded the measured temperatures from the testing. The chip temperatures during the pumice block testing did not exceed the 180°C ($\Delta T = 90°C$) limit [(and exceed the 150°C ($\Delta T = 60°C$)] limit for only a very brief time immediately after cutting. The 180°C limit seems appropriate for the chips because they are small, the total volume of chips is small, and they are entrained in the relatively cool nitrogen purge gas immediately after being cut. This cools the chips quickly and limits their contact with the bulk material. These analyses also show that the pumice blocks used for a test material are a limiting material in comparison to the waste simulants tested. Thus, the analyses in this appendix support the conclusion that core drilling can be undertaken without exceeding temperature limits if the specified drilling parameter limits are maintained.

The tests analyzed were done on pumice blocks. The temperatures measured on the bits for the drilling tests on pumice blocks were higher than temperatures measured for tests with any of the simulant materials. The analyses suggest that the measured temperatures are dominated by frictional heating of the bulk material. Thus, the drilling tests on these pumice blocks were the most limiting tests for frictional heating. Because of the poor contact between the chips and the areas where the thermocouples were located, it is doubtful that the testing could measure chip temperatures. These are a function of the starting temperature of the material being cut and the compressive strength. The compressive strength calculated from these tests is also about three times higher than the highest value for compressive strength reported by WHC[8] for waste simulant materials. The conversion of compressive strength to specific energy and to thermal energy is condition dependent, and the margin between compressive strength calculated from these tests and the compressive strength measured for the simulants is notable. One can conclude that the average temperatures resulting from the mechanical-to-thermal conversion process are probably lower with simulant materials than with pumice blocks.

In addition to examining normal drilling conditions, experiments were analyzed to determine the temperature response during off-normal conditions. These include a loss of purge gas flow and the spinning of a worn drill bit with no penetration. In these cases, there is sufficient sensible capacity of the system to prevent overheating if attempts to continue drilling are stopped within a reasonable time period. Operational limits set using the test data should be satisfactory if the material conditions encountered during the drilling are no more severe than seen in the drilling tests with the pumice blocks. Comparisons between the pumice properties and waste simulant materials suggest that the pumice blocks provided more severe drilling conditions than are likely to be encountered in the tanks. Should harder materials be encountered, higher temperatures could be reached.

To summarize, the properties of the pumice block used for drill testing produced more severe temperature conditions than the simulant materials produced for an earlier set of tests. If the simulants are reasonably representative of the materials in the tanks, the drilling tests on the pumice blocks were bounding for temperatures. If harder materials are encountered in the tanks, higher temperatures could be produced. A control is established to limit the penetration rate to 0.75 in./min. This control requires an automatic shutdown when the penetration rate is less than 0.75 in./min. This control provides the necessary protection to prevent a propagating waste reaction, although temperature limits may be exceeded for a very short period. Waste temperature limits established in this SA are already conservative, and no credit is considered for water in the waste. The analyses as well as simulants used in the laboratory experiments are on the conservative side. Therefore, it is concluded that controls established in this SA provide adequate protection against propagating an exothermic waste reaction as a result of rotary drilling if the established limits are not exceeded.

## REFERENCES


1. K. S. Witwer, WHC REPORT (IN PROGRESS).

2. V. Prakash and F. C. Appl, "Temperature Distribution in Synthetic Diamond Cutters During Orthogonal Rock Drilling," *SPE Drilling Engineering*, 137-143 (June 1989).

3. D. A. Glowka and C. M. Stone, "Thermal Response of Polycrystalline Diamond Compact Cutters Under Simulated Downhole Conditions," *Soc. Petroleum Engineers Journal*, 143-156 (April 1985).

4. R. Teale, "The Concept of Specific Energy in Rock Drilling," *Int. J. Rock Mech. Mining Sci.* ,Vol. 2, 57-73 (1965).

5. H. Rabia, "Specific Energy as a Criterion for Drill Performance Prediction," *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, Vol. 19, 39 to 42 (1982).

6. C. Donaldson, G. H. LeCain, and V. C. Goold, *Tool Design*, Third Ed., (McGraw Hill, New York, New York, 1973).

7. T. Baumeister, E. A. Avallone, and T. Baumeister III, editors, *Marks' Standard Handbook for Mechanical Engineers*. 8th ed. (McGraw Hill, New York, New York, 1978).

8. C. M. Keller, "Core Drill Operating Envelope Test Report," Westinghouse Hanford Company report WHC-SD-WM-TRP-123 (1993).

9. P. M. Francis, "Aerosol Study for the Rotary Mode Exhauster," Westinghouse Hanford Company report WHC-SD-WM-ES-225, Rev. 1. (March 1993).

10. D. A. Siebe, "Thermal Analysis of Rotary-Mode Core Drilling," Los Alamos National Laboratory Calc-Note TSA10-CN-WT-SA-TH-111 (February 1996).

11. J. P. Holman, *Heat Transfer*, 3rd ed. (McGraw Hill, New York, New York, 1972).

12. S. Kakac, R. K. Shah, and W. Aung, Eds. *Handbook of Single-Phase Convective Heat Transfer* (John Wiley & Sons, New York, New York, 1987).

13. D. I. Poston, "Two-dimensional Transient Heat Transfer Analysis of Rotary Drilling Process," Los Alamos National Laboratory Calc-Note TSA10-CN-WT-SA-TH-109 (February 1996).

# APPENDIX G

# WASTE AND CRUST IGNITION

## 1.0. INTRODUCTION

In this appendix, the waste and crust ignition issues are discussed. Waste ignition is a hazard considered to be the result of drilling. The drill bit cutting includes several modes in terms of heat generation and heat transport. These modes are discussed in Appendix F. In an efficient cutting mode, waste chips created by the drill bit teeth can be hotter than the drill bit or teeth temperature. When there is no efficient penetration, a zone where frictional heating between the drill bit and waste exists. In the first part of the appendix, we discuss the operating safety requirements for drilling. In the second part, we examine another accident in which the drill string is postulated to be dropped on a dry crust. We discuss the possibility of a crust ignition and propagation.

## 2.0. REACTIVE CHEMICAL HAZARDS

Mixtures of sodium nitrate and sodium nitrite with organic compounds can produce violent exothermic reactions.[1,2] Reaction rates generally increase with increasing temperature. For exothermic reactions, increasing the reaction rate increases the heat generation rate. Increasing the temperature of the mixture that reacts exothermically can create an imbalance between heat generation and heat transfer out of the system. This imbalance can create a thermal runaway.

Rotary-mode core sampling (RMCS) causes local heating of the waste. These "hot spots" near the drill string may cause a localized thermal runaway. The consequences of such a local thermal runaway are the following:

- A local thermal runaway may result in temperatures in excess of the autoignition temperature of a flammable-gas mixture trapped in the waste.

- A local thermal runaway will increase the gas-generation rate. There are three potential hazards associated with increased gas generation: increased production of aerosols, production of flammable gases and production of toxic gases.

- The high temperatures produced by a local thermal runaway may vaporize some of the nuclides, which would result in an increased release rate.

- A local thermal runaway may propagate through the entire tank. Propagation of a thermal runaway could produce very high temperatures, which would result in severe structural damage of the tank.

The consequences of these hazards have been evaluated to determine if these hazards are a significant concern.

- The auto-ignition temperature of hydrogen-air mixtures is reported to be 400°C (Ref. 3), and the autoignition temperature of hydrogen nitrous oxide mixtures may be lower.[4] The maximum temperature produced by waste containing 1.0 wt.% total organic carbon (TOC) is estimated to be ~400°C. Therefore, a runaway reaction may produce temperatures exceeding the autoignition temperature even if it contains only a small amount of organic carbon sustaining an exothermic reaction. Exceeding the autoignition temperature is a real hazard.

- The maximum gas-generation rate is estimated to be 3.6 scfm. The maximum volume that could be generated is 250 sfc. The nominal nitrogen flow in the drill string is 30 scfm. The maximum gas-generation rate is small compared to the nitrogen flow, so that gas generation will not have a significant impact on aerosol formation. Tests on dry waste surrogates indicate that nitrous oxide is formed during a runaway reaction.[5] Hydrogen is generated in the waste at normal waste temperatures. There is no reason to expect that these reactions will stop at elevated temperatures; therefore, hydrogen generation is possible. The ignition of ~1000 scf of a stoichiometric mixture of hydrogen and nitrous oxide under the waste surface will cause structural damage; therefore, generating 250 scf of hydrogen or nitrous oxide could be a significant contributor to a flammability hazard. If all of the gas generated is nitric oxide (NO) or nitrogen dioxide ($NO_2$), the maximum concentration at 100 m from the tank is <1 ppm; so there is no toxic gas hazard.

- Volatile nuclides can be a problem in a waste vitrification plant. If an uncontrolled reaction produces very high temperatures, cesium and strontium may vaporize. A bounding calculation predicts a maximum dose of <1 mrem Committed Effective Dose Equivalent (CEDE) at 100 m from the tank. Therefore, vaporization of nuclides is not a hazard.

- If an exothermic reaction propagates throughout the tank, the consequences could be severe. The volume of waste involved in a propagating reaction could be a factor 100,000 times greater than a local reaction. Consequences that are negligible for local exothermic reactions could be significant for a propagating reaction. The high temperatures generated would cause a structural failure of the tank. A propagating exothermic reaction is a significant hazard.

A local runaway reaction is a real hazard. The primary concerns are that a runaway exothermic reaction could be an ignition source in a flammable gas tank, and a local reaction may propagate. The generation of flammable gases or oxidants is a lesser concern because a flammable-gas hazard already exists in the tanks of interest, and there are no consequences of a flammable-gas release unless there is an ignition source.

## 3.0. LOCAL RUNAWAY REACTIONS

### 3.1. Review of Existing Data

Data on exothermic chemical reaction have been obtained using waste samples and using waste surrogates and simulants.

A review of the chemical analyses performed on waste samples was conducted. Between 1974 and 1995, differential thermal analysis (DTA) and differential scanning calorimetry (DSC) were performed on 169 samples obtained from 70 different tanks. In many cases, the reports do not give the onset temperature for exothermic reactions. They only state that no exothermic reactions were observed below 200°C. Such data are useful in establishing a lower bound on the onset temperature. Of the 169 samples, onset temperatures of less than 200°C were reported for 17. The lowest onset temperature reported was 180°C for several samples obtained from Tank 241-SY-101 and Tank 241-SY-103.

Several studies have been performed on waste surrogates and waste simulants. Schelle et al.[5] studied several waste surrogates and a waste simulant using DSC and accelerated rate calorimetry (ARC). The onset temperatures measured by DSC range from 220°C to 364°C. The lowest values correspond to tests with a waste simulant that includes many of the minor waste components, such as nickel, chromium, and iron. Onset temperatures as measured by the ARC are between 113°C and 290°C. The onset temperatures measured below 180°C were obtained using the waste simulant. Although low-onset temperatures were measured between 110°C and 120°C, a self-sustaining reaction did not occur until the temperature reached 150°C. A reactive system screening tool (RSST) also was used to measure onset temperatures.[6,7] The measured onset temperatures were 150°C and 180°C. The lower temperature was obtained using the waste simulant discussed above.

### 3.2. Criteria to Avoid Local Runaway

Local runaway reactions can be avoided by maintaining the waste temperature below the onset temperature for exothermic reactions. The standard practice is to subtract 100°C from the onset temperature as determined by DSC and to subtract 50°C from the measured onset temperature as determined by ARC.[8] The reasons for

these large safety margins is uncertainty. The scanning rate affects the onset temperature of DSC and RSST. The sensitivity of the instrument is also a consideration. Differences between waste simulants and actual waste is also a source of uncertainty as are variations in waste composition. Other factors such as good heat transfer and short time periods can reduce the need for the safety margin applied to the measured onset temperature.

Two length scales must be considered when evaluating the potential for local runaway reactions. The first scale to consider is the microscopic scale. Strain energy added as the drill bit cuts into the waste will heat fragments to temperatures that are greater than the drill bit temperature. The size of these fragments and chips are estimated to be between 1 μm and 150 μm. Note that in Reference 9, page 6, the particle size distribution was determined to be 1 to 100 μm. The samples were collected from drilling tests in simulants. This range was measured by using an optical microscopy technique used by Pacific Northwest National Laboratory (PNNL). Using the same single-shell waste simulant samples from the same collection, Westinghouse Hanford Company's (WHC's) Plutonium Finishing Plant Laboratory covered a particle size range of 0.1 to 10 μm with a laser diffraction analysis. They are small-sized chips, and they are cooled relatively quickly (Ref. 10). The second scale to consider is macroscopic. The drill bit and the surrounding waste will be heated above the bulk temperature of the waste, but it will be cooler than the fragments formed at the drill tip. The thermal inertia of the drill bit and the surrounding waste is much greater than the microsized fragments. Differences in the time scale and the heat transfer rates justify different temperature limits for these two cases.

First, consider the temperature limit for small fragments. The limit will be based on the available data for actual waste samples. The large amount of data available on actual waste samples addresses the problems of errors in surrogate and simulant tests and variability in waste composition. The large number of waste samples obtained from a large number of different tanks addresses the problem of variability in waste composition. Because of the large number and variety of waste samples analyzed, the large margins often applied to onset temperatures measured by DSC and ARC are not appropriate.

The DTA and DSC results for actual waste samples are used to establish the maximum temperature limit. A comparison of data for waste surrogates and simulants is done with results for actual waste samples so that the surrogates and simulants are not unreasonable models of the waste. Therefore, data for waste surrogates and simulants are used as additional evidence that the proposed limit is reasonable. Because this safety assessment addresses rotary-mode sampling in all single-shell, flammable-gas tanks, the limit must be bounding for all tanks. Therefore, the limit is based on the lowest measured onset temperature of 180°C. The proposed limit for heating of small waste fragments is 180°C. Because the limit is based on a large number of waste samples and because the fragments cool

relatively quickly, no additional safety margin is applied to the lowest measured onset temperature.

This temperature limit is supported by the onset temperature measured for waste surrogates, but it is not supported by the onset temperatures measured for the waste simulant data. Exceeding the measured onset temperature for exothermic reactions does not imply that a runaway reaction will occur. Heat transfer also must be considered. The first-order stability criterion for a runaway reaction in a single fragment is

$$\left(\frac{dT}{dt}\right)_o < \frac{6 \cdot U \cdot (T_o - T_s)}{\rho \cdot c_p \cdot D} \quad , \tag{G-1}$$

where

$\left(\frac{dT}{dt}\right)_o$ = self-heating rate at the initial temperature of the fragment,
$U$ = heat transfer coefficient for the fragment,
$T_o$ = initial temperature of the fragment,
$T_s$ = temperature surrounding the fragment,
$\rho$ = density of the fragment,
$c_p$ = heat capacity of the fragment, and
$D$ = diameter of the fragment.

Conservative parameters are used to estimate the critical self-heating rate. The heat transfer coefficient is assumed to be 5 watts/$m^2$ K, the density of a fragment is ~2.7 g/$cm^3$, and the heat capacity of is ~1.8 J/g K. The maximum particle diameter of 150 μm is used in the calculation, and the temperature of the surrounding waste is assumed to be 160°C. The critical self-heating rate for a fragment is estimated to be ~50°C/min. The heating rate used in the DSC and RSST is 1°C/min to 10°C/min depending on the experiment, so these devices should be able to detect self-heating rates of <50°C/min. Therefore, the onset temperature measured by these devices should be a conservative estimate of the stability limit for a fragment. To relate this self-heating rate to the self-heating rate observed in the ARC, it must be divided by the Φ factor[11]

$$\left(\frac{dT}{dt}\right)_{ARC} = \frac{1}{\Phi} \cdot \left(\frac{dT}{dt}\right) \quad . \tag{G-2}$$

The Φ factor accounts for the thermal inertia of the calorimeter, and the value is ~4 for the experiments discussed in Reference 5. The reaction should be stable if the self-heating rates measured for the ARC tests in Reference 5 are <12°C/min. Below the onset temperature, the self-heating rate is <0.025°C/min, so the experiments with waste surrogates support the proposition that a thermal runaway does not

occur in a fragment with a temperature of 180°C. The self-heating rate for the waste simulant is ~0.04°C/min. Although this value is greater than the criteria for determining the onset temperature, it is much less than the stability limit for fragments. The self-heating rate data obtained from the ARC supports the 180°C temperature limit for fragments.

Time is a consideration when evaluating the stability of exothermic reactions if the material is heated for a short period of time; therefore, runaway reactions may not be a problem. In an adiabatic system, there is a period of time before a thermal runaway occurs during which the self-heating rate is relatively small. This period is called the induction time. The adiabatic induction time is a useful gauge for making a qualitative evaluation of whether the duration of the drilling operation is long enough to be a concern. If the drilling duration is less than the adiabatic induction time, runaway reactions should not be a problem. The first order estimate of the adiabatic induction time is

$$t_I = \frac{R \cdot T_o^2}{E_a \cdot \Phi \cdot \left(\frac{dT}{dt}\right)_o}, \qquad \text{(G-3)}$$

where

$t_I$ = induction time,
$R$ = gas constant,
$E_a$ = activation energy, and
$\Phi$ = $\Phi$ factor for the calorimeter.

Based on the data in Reference 5, a reasonable, but conservative, estimate of the activation energy is 240 kJ/mole. An upper bound for the self-heating rate at 180°C is the heating rate of 1°C/min used for the DSC and RSST. The lower bound for the adiabatic induction time of a fragment at 180°C is 7 min. The temperature of the fragment as a function of time can be approximated by the following equation:

$$T = T_s + (T_o - T_s) \cdot \exp\left(-\frac{6 \cdot U}{\rho \cdot c_p \cdot D} \cdot t\right). \qquad \text{(G-4)}$$

Note that the typical Biot number (UD/k) for 150 µm waste chips is less than 0.1, so that Equation 4 is adequate. The time constant for cooling is ~24 s, which is much less than the adiabatic induction time. The life of a hot fragment is much less than the induction time, which supports the 180°C temperature limit for fragments.

The estimates of the critical self-heating rate and the adiabatic induction time indicate that there is considerable margin in the 180°C temperature limit for

fragments. This margin justifies using the minimum measured onset temperature of waste samples as the limit.

Next, a limit must be set for the drill-bit temperature and the average temperature of the waste surrounding the drill bit. As discussed above, the large margins often applied to the measured onset temperatures are not applicable. However, some margin is warranted because thermal inertia may be an important factor at the macroscopic scale. Therefore, a 20°C margin is applied to the minimum measured onset temperature for actual waste samples. The maximum allowable temperature for the drill bit and the surrounding waste is 160°C.

This temperature limit is supported by the onset temperature measured for waste surrogates, but it is not supported by the waste simulant onset temperature data. As discussed above, the onset temperatures measured for the waste simulants may not be applicable because heat transfer also must be considered. The first-order stability criterion for a runaway reaction for the waste immediately surrounding the drill bit is

$$\left(\frac{dT}{dt}\right)_t < \sqrt{\frac{\alpha}{t}} \cdot \frac{(T_t - T_s)}{\Delta x} , \qquad \text{(G-5)}$$

where

$\left(\frac{dT}{dt}\right)_t$ = self-heating rate at time t,
$\alpha$ = thermal diffusivity of the waste,
$t$ = duration of the heating caused by drilling,
$T_t$ = temperature of the waste near the drill string at time t,
$T_s$ = temperature of the bulk waste, and
$\Delta x$ = thickness of the area affected by the drill.

This criterion accounts for the heating of the waste surrounding the drill string. The equation predicts that the stability decreases with time because frictional heating of the waste reduces heat transfer. Significant heating only occurs near the drill bit. The length of the drill bit is approximately 3 in., and the minimum penetration rate is approximately 0.5 in./min. Therefore, heating caused by drilling affects the waste at a given location for less than 10 minutes. The lower bound on waste thermal diffusivity is 0.0008 $cm^2/s$, a bounding temperature for all flammable-gas tanks is 95°C, and the thickness of material affected by the drill is assumed to be 0.5 cm. The limiting self-heating rate, given the temperature control of 160°C, is 9.0°C/min. The heating rate used in the DSC and RSST is 1°C/min to 10°C/min, so these devices should be able to detect self-heating rates of <9.0°C. Therefore, the onset temperature measured by these devices should be a conservative estimate of the stability limit. Equation (G-2) is used to relate this self-heating rate to the self-heating rate observed in the ARC. As stated above, the $\Phi$ factor is ~4 for the

experiments discussed in Reference 5. Therefore, the reaction should be stable if the self-heating rate measured for the ARC tests in Reference 5 is <2.3°C/min. Below the onset temperature, the self-heating rate is <0.025°C/min, so the experiments with waste surrogates support the proposition that a thermal runaway does not occur at 160°C. The self-heating rate for the waste simulant at 160°C is ~0.03°C/min. Although this value is greater than the criteria for determining the onset temperature, it is much less than the stability limit. The self-heating rate data obtained from the ARC supports the 160°C temperature limit.

Time is also considered. The adiabatic induction time can be estimated from Eq. (G-3). A lower bound for the adiabatic induction time at 160°C is 54 min. This estimate is greater than the maximum time allowed for drilling a segment. Because the system is not adiabatic, the actual induction time will be greater than the adiabatic induction time. Thus, the duration of the operation at 160°C is too short for a thermal runaway to be a problem.

It should be noted that the margins for the critical self-heating rate and the adiabatic induction time are smaller on the macroscopic scale than they are for waste fragments. The lesser margin justifies setting the temperature limit below the minimum measured onset temperature. Also, it should be noted that the temperature limit for the macroscopic scale is based on an assumed heating time of 10 minutes. No experiments have been performed in which actual waste samples, waste simulants, or waste surrogates, were maintained at 120°C for longer than 10 minutes. Additional tests are required to confirm that local heating of the waste for longer than 10 minutes is safe before the conservatism in the temperature limit may be reduced.

## 4.0. PROPAGATING EXOTHERMIC REACTIONS

The consequences of propagating an exothermic reaction are serious. The criterion of no local runaway reaction provides protection against propagating exothermic reactions. Because the consequences are very severe and because exceeding the temperature limits is credible, additional measures are required to prevent a propagating exothermic reaction. Rotary-mode sampling should not be performed in tanks in which a propagating exothermic reaction can occur.

### 4.1. Review of Criteria

Criteria have been proposed for evaluating the possibility of a propagating exothermic reactions in the waste.[11] According to these criteria, no propagation is possible if one of following conditions is satisfied:

$$\begin{cases} \text{TOC (wt.\%)} < 4.5 + 0.15 \cdot (\text{wt.\% } H_2O) \text{ or} \\ 20\,\% \geq \text{wt.\% } H_2O \end{cases} \qquad \text{(G-6)}$$

These criteria are based on experimental data for waste surrogates,[12] and they are plotted in Figure G-1.

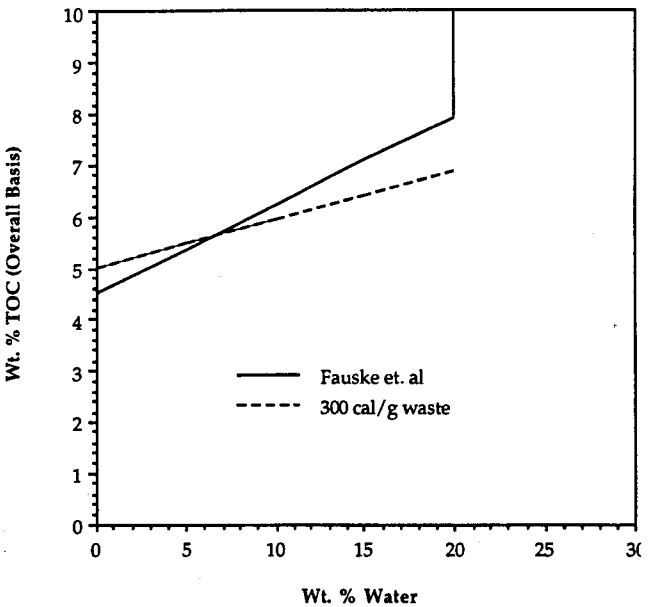



**Fig. G-1. Proposed criteria for no propagation of exothermic reactions in the waste.**

Chemical energy density is used in the chemical process industries to screen for potential reactive chemical hazards.[8] This method may also be useful in evaluating reactive chemical hazards in the Hanford waste tanks. In this method, the degree of hazard as a function of enthalpy of reaction is given in Table G-1. A low degree of hazard means that a deflagration is possible but not likely.

**TABLE G-1**
**DEGREE OF HAZARD AS A FUNCTION OF ENTHALPY OF DECOMPOSITION OR REACTION**

| Degree of Hazard | Maximum Enthalpy of Decomposition/Reaction (kcal/g) | Possible Qualitative Interpretations of the Classifications |
|---|---|---|
| High | < -0.7 | Violently exothermic; detonation likely |
| Medium | -0.3 to -0.7 | Exothermic; detonation possible; deflagration likely |
| Low | -0.1 to -0.3 | Deflagration possible |
| Very Low | > -0.1 | Propagation unlikely |

If the chemical energy density criteria are used to evaluate the potential for a propagating exothermic reaction, a low degree of hazard should be sufficient protection considering that controls have been established to prevent local runaway reactions. Therefore, the heat of reaction must exceed -300 cal/g waste in dry waste for a propagating exothermic reaction to occur. Evaporation of water will provide additional protection against propagation. Therefore, basic energy density limit will be modified to account for the heat of vaporization of water. In wet waste, propagating reactions are assumed to be impossible if the heat of reaction does not exceed -300 cal/g waste minus the latent heat of vaporization of water.

In order to compare the chemical energy density approach used as a screening in the Chemical Process Industries to the criteria given by Eq. (G-6), the heat of reaction is required. The largest heat of reaction was determined using linear programming, which is the method used by the American Society for Testing and Materials (ASTM) in the CHETAH program for evaluating reactive chemical hazards. A maximum value of -9.7 kcal/g total organic carbon (TOC) was obtained for the oxidation of sodium hydroxy-ethanol-diamine-triacetic acid (NaHEDTA). NaHEDTA was one of the complexants used at Hanford. Decomposition of NaHEDTA and other complexants into less energetic compounds is expected as a result of radiolysis. Therefore, the heat of reaction of -9.7 cal/g TOC is a bounding value rather than a realistic estimate of the heat of reaction. Based on data for waste surrogates, a heat of reaction of -6.0 kcal/g TOC should be typical of actual waste samples.[5,7]

By assuming a heat of reaction of -6.0 kcal/g, the maximum TOC content can be estimated as a function of the moisture content. The limit based on a chemical energy density of 300 cal/g waste is plotted in Figure G-1. This limit approximates the criteria proposed by Webb et al.[11] for water content less than 20 wt.%, which indicates that the 300 cal/g waste is a reasonable limit. This comparison

demonstrates that the criterion given by Eq. (G-6) is equivalent to the chemical energy density method for the waste surrogates.

### 4.2. Probability of a Propagating Exothermic Reaction

Because the consequences of a large scale propagating reaction are not acceptable, the real criterion for evaluating safety is whether this accident is credible (i.e. has a frequency $>10^{-6}$ per year). Two methods are used to evaluate this frequency: (1) an event tree is used to model variability in the waste, and (2) PNNL's Analysis of Variance (ANOVA) model[12] is used to evaluate the probability of exceeding the criteria given by Eq. (G-6). This section considers the probability of a propagating reaction in the flammable-gas tanks and the possible flammable gas tanks. There are currently 19 single-shell flammable gas tanks: A-101, AX-101, AX-103, S-102, S-111, S-112, SX-101, SX-102, SX-103, SX-104, SX-105, SX-106, SX-109, T-110, U-103, U-105, U-107, U-108, and U-109.[11] Twenty-three additional tanks have been listed as possible flammable gas tanks: A-103, BX-107, BY-101, BY-102, BY-105, BY-106, BY-109, C-104, C-107, S-101, S-103, S-105, S-106, S-107, S-109, TX-102, TX-111, TX-112, TX-113, TX-115, U-102, and U-106. The following tanks have a potential to be added to the list: B-111, B-201,B-202, S-104, T-201, T-202, T-203, T-204, TX-116, TX-117, U-110 and U-111.

#### 4.2.1. Event-Tree Analysis

The sequence of events leading to a propagating reaction must be determined in an event-tree analysis in order to evaluate the frequency of a propagating reaction accident. Three things must happen in order for a propagating exothermic reaction to occur: (1) the drilling controls must be exceeded, which will cause heating of the waste, (2) the drill temperature must increase to the ignition temperature of the waste, and (3) the failure must occur in waste sufficiently rich in organics to support propagation.

The waste surrogate data indicate that both TOC concentration and the distribution of organic species affect the ability of the waste to support a propagating reaction.[13] The variability of heat of reaction observed in samples taken from Tank 241-SY-101 indicates variability in the distribution of organic species within a tank.[14] At least two variables are required to characterize the organic compounds. Heat of reaction and wt. % TOC are used in the study. Because heat of reaction is used to characterize the organic compounds, the chemical energy density is used to evaluate the probability of a propagating exothermic reaction. It is easier to incorporate variability into the organic compounds by using the energy density method than by using the criteria given by Eq. (G-6).

An event tree for evaluating the probability of a propagating reaction is shown in Figure G-2. The initiating event in the event tree corresponds to exceeding one of the drilling controls. Based on a reliability analysis of the operation, the frequency of violating a drilling control is $2.4 \times 10^{-4}$/yr.

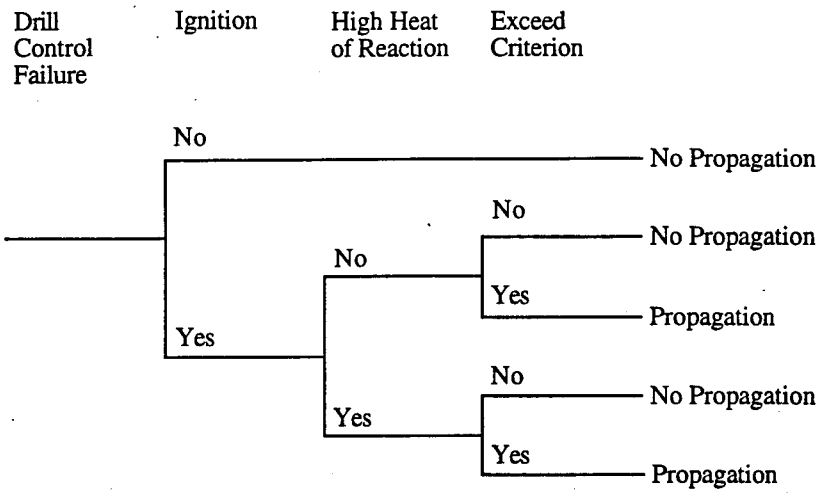



**Fig. G-2. Event tree for propagating exothermic reactions.**

Violating one of the drilling controls will cause the waste to heat. Bounding tests performed using a dry pumice block indicate that failure of a control could result in temperatures in excess of waste ignition temperature. In real waste, the maximum temperature will depend on the hardness of the waste and the moisture content. The ignition temperature also is expected to vary. Because of the factors, the probability of ignition given failure of the controls is <1.0, but there is insufficient data and understanding to quantify the probability. Therefore, the probability of ignition given a control failure is assumed to be 1.0.

To simplify the analysis, the variability heat of reaction is incorporated into the event-tree model by using two bins: a low heat of reaction bin and a high heat of reaction bin. The first bin is waste with a heat of reaction smaller than -6.5 kcal/g TOC. The second bin is waste with a heat of reaction between -6.5 kcal/g TOC and the bound value of -9.7 kcal/g TOC. The high heat of reaction compounds are the original organic complexants, so high heat of reaction bin represents waste rich in these organic compounds. Because of degradation of the organic complexants with time, a zone or layer rich in the original complexants is very unlikely. The probability of drilling control failure in a zone containing high heat of reaction organic compounds is assumed to be 0.1. Core sample data from Tank 241-SY-101 are consistent with this assumption.

The final branch in the event tree determines whether the waste exceeds the chemical energy density criterion. The chemical energy density limit is a function of the heat of reaction bin, the TOC concentration, and the moisture content. Because the drill is assumed to fail at a random location in the waste, the probability of exceeding the limit is equal to the fraction of the waste that exceeds the limit. There are two possible methods of evaluating this probability: (1) evaluation of the fill history and (2) statistical analysis of data. These two methods are complementary. Statistical methods quantify the observed variability, which cannot be determined from the current analysis of waste history. Analysis of waste history can be used to identify the possibility of reminant organic layers that cannot be detected by statistical analysis. The statistical estimates of probability are based on PNNL's ANOVA model.[12] Preliminary analysis indicates that the results obtained from PNNL's ANOVA model are extremely conservative.

As shown in Figure G-2, only two branches of the event tree corresponding to propagating exothermic reaction. The frequency of a propagating reaction is the sum of the frequencies for these two branches.

$$f_{prop} = f_i \cdot \begin{bmatrix} \Pr(\text{Low } \Delta H_{rx}) \cdot \Pr(\text{Exceeding Limit} | \text{Low } \Delta H_{rx}) + \\ \Pr(\text{High } \Delta H_{rx}) \cdot \Pr(\text{Exceeding Limit} | \text{High } \Delta H_{rx}) \end{bmatrix}, \qquad \text{(G-7)}$$

where

$f_{prop}$ = frequency of a propagating reaction, and
$f_i$ = frequency of the initiating event.

Analysis of waste tank history provides a means of identifying tanks that may contain an organic reminant layer. The probability is the fraction of the waste inventory that is in this organic reminant layer. Based on Eq. (G-7), the tank may be unsafe if organic reminant layer is greater than 0.4% of the total inventory. A review of an analysis of waste history[15] indicates that there are six tanks of concern A-102, A-106, C-104, C-107, C-203, and C-204. None of the six tanks are currently flammable-gas tanks. Two are possible flammable-gas tanks: C-104 and C-107. Rotary mode core sampling should not be permitted in these tanks without additional controls or analysis.

PNNL provided probability estimates obtained from their ANOVA model for 65 single-shell tanks.[16] PNNL's analysis included all current flammable gas tanks except SX-109 and T-100 and all possible flammable gas tanks except A-103, BX-107, C-104, and C-107. Best estimate values were used in the calculation because event tree models a range of possible waste reactivities. The frequency of a propagating reaction was determined for these tanks. The frequency was determined to be $<10^{-6}$/yr for 7 of the 18 flammable-gas tanks and 12 of the 23 possible flammable-gas

## TABLE G-2
## ESTIMATES OF PROBABILITY OF A PROPAGATING EXOTHERMIC REACTION IN FLAMMABLE GAS TANKS BASED ON EVENT-TREE ANALYSIS

| Tank | Probability of Exceeding Limit for Low Heat of Reaction Bin | Probability of Exceeding Limit for High Heat of Reaction Bin | Frequency of a Propagating Reaction ($yr^{-1}$) | Flammable Gas Watch List Status[12] |
|---|---|---|---|---|
| BX-110 | 0.00 | $3.02X10^{-5}$ | $6.95X10^{-10}$ | No |
| BX-105 | $4.33X10^{-11}$ | $1.80X10^{-4}$ | $4.14X10^{-9}$ | No |
| TY-102 | 0.00 | $2.11X10^{-4}$ | $4.85X10^{-9}$ | No |
| B-104 | $7.20X10^{-11}$ | $6.35X10^{-4}$ | $1.46X10^{-8}$ | No |
| B-102 | $1.67X10^{-10}$ | $9.97X10^{-4}$ | $2.29X10^{-8}$ | No |
| AX-102 | $3.63X10^{-10}$ | $2.01X10^{-3}$ | $4.62X10^{-8}$ | No |
| BX-111 | $1.59X10^{-10}$ | $2.07X10^{-3}$ | $4.76X10^{-8}$ | No |
| B-105 | $2.82X10^{-10}$ | $2.11X10^{-3}$ | $4.85X10^{-8}$ | No |
| BY-109 | $6.44X10^{-10}$ | $2.29X10^{-3}$ | $5.27X10^{-8}$ | Possible |
| BY-102 | $6.49X10^{-10}$ | $3.49X10^{-3}$ | $8.03X10^{-8}$ | Possible |
| AX-101 | $5.61X10^{-10}$ | $3.51X10^{-3}$ | $8.07X10^{-8}$ | Yes |
| AX-103 | $8.05X10^{-10}$ | $3.72X10^{-3}$ | $8.56X10^{-8}$ | Yes |
| BY-105 | $2.46X10^{-9}$ | $3.89X10^{-3}$ | $8.95X10^{-8}$ | Possible |
| U-103 | $4.54X10^{-10}$ | $3.98X10^{-3}$ | $9.15X10^{-8}$ | Yes |
| U-106 | $2.33X10^{-9}$ | $4.21X10^{-3}$ | $9.68X10^{-8}$ | Possible |
| BY-106 | $6.68X10^{-10}$ | $4.35X10^{-3}$ | $1.00X10^{-7}$ | Possible |
| U-102 | $1.03X10^{-9}$ | $4.38X10^{-3}$ | $1.01X10^{-7}$ | Possible |
| BY-103 | $5.62X10^{-10}$ | $5.18X10^{-3}$ | $1.19X10^{-7}$ | Possible |
| S-107 | $9.49X10^{-5}$ | $4.41X10^{-3}$ | $1.21X10^{-7}$ | Possible |
| A-101 | $3.73X10^{-9}$ | $9.04X10^{-3}$ | $2.08X10^{-7}$ | Yes |
| S-101 | $1.57X10^{-4}$ | $9.76X10^{-3}$ | $2.57X10^{-7}$ | Possible |
| U-111 | $2.61X10^{-8}$ | $1.53X10^{-2}$ | $3.52X10^{-7}$ | Possible |
| S-110 | $3.57X10^{-4}$ | $1.40X10^{-2}$ | $3.96X10^{-7}$ | No |
| S-103 | $5.23X10^{-4}$ | $1.91X10^{-2}$ | $5.48X10^{-7}$ | Possible |
| TX-107 | $6.89X10^{-4}$ | $2.00X10^{-2}$ | $6.03X10^{-7}$ | No |
| S-106 | $5.28X10^{-4}$ | $2.17X10^{-2}$ | $6.08X10^{-7}$ | Possible |
| TX-104 | $4.19X10^{-4}$ | $2.27X10^{-2}$ | $6.09X10^{-7}$ | No |
| S-108 | $4.32X10^{-4}$ | $2.33X10^{-2}$ | $6.25X10^{-7}$ | No |
| S-112 | $4.45X10^{-4}$ | $2.43X10^{-2}$ | $6.51X10^{-7}$ | Yes |
| S-102 | $4.70X10^{-4}$ | $2.42X10^{-2}$ | $6.54X10^{-7}$ | Yes |
| S-109 | $6.03X10^{-4}$ | $2.33X10^{-2}$ | $6.61X10^{-7}$ | Possible |
| U-109 | $7.22X10^{-6}$ | $3.27X10^{-2}$ | $7.54X10^{-7}$ | Yes |

tanks. Of the 65 tanks that PNNL analyzed, the frequency was $<10^{-6}$/yr for 33 tanks. The results for these 33 tanks are summarized in Table G-2.

There are currently 18 single-shell tanks on the Flammable Gas Watch List.[14] Based on the results in Table G-2, RMCS is permitted in seven of these tanks. Twenty-five additional tanks have been listed as candidates for the Flammable Gas Watch List. RMCS is permitted in 12 of these additional tanks. Results are not provided in Ref. 16 for Tanks A-103, BX-107, C-104, C-107, SX-109, and T-110.

#### 4.2.2. Direct Application of Equation (G-6)

PNNL's ANOVA model gives a joint probability distribution for TOC and moisture content of the waste.[16] This distribution can be integrated to estimate the probability of exceeding the criteria given by Eq. (G-6). Reference 16 gives the best estimate as well as the 95% upper bound of the exceedence probability. Because this analysis does not include uncertainty in the criteria for extrapolating waste surrogate data to actual waste, the 95% upper bound is used as the appropriate limit. The probability was determined to be $<10^{-6}$/yr for 4 of the 18 flammable-gas tanks and 7 of the 23 possible flammable-gas tanks. Of the 65 tanks that PNNL analyzed, the frequency was $<10^{-6}$/yr for 21 tanks. The results for these 21 tanks are summarized in Table G-3.

#### 4.2.3. Summary

The second method of analysis is more restrictive than the event-tree analysis given in Section 4.2.1. The more restrictive analysis will be used in this safety assessment. Therefore, RMCS is permitted only in those tanks listed in Table G-3. For completeness, all the tanks that satisfy the probability criterion are listed in Table G-3. However, only those tanks in that are designated as FGTs and that are listed in Table G-3 are within the scope of this SA. More tanks may be added to the list if

- The propagation criterion given in Ref. 11 is verified to be bounding for the actual waste using further test data and a model to extrapolate the criterion to actual waste conditions; and/or
- The RMCS system reliability is enhanced by adding an independent shut-down circuit based on direct drill bit temperature measurements.

## 5.0. CRUST IGNITION CAUSED BY IMPACT

The purpose of this section is to assess the possibility of causing a propagating crust ignition as a result of drill-string drop. The drill-string is held by a hydraulic foot clamp during rotary-mode sampling operations. If the clamp fails (although this is unlikely), the drill string could be dropped on the crust. The impact kinetic energy of the drill string is identified as a crust-ignition hazard because some of the crust or

TABLE G-3
ESTIMATES OF PROBABILITY OF A PROPAGATING EXOTHERMIC REACTION IN FLAMMABLE GAS TANKS BASED ON EQUATION (G-6)

| Tank | Probability of Exceeding Eq. (G-6) Criteria at 95% Confidence Level | Frequency of a Propagating Reaction ($yr^{-1}$) | Flammable Gas Watch List Status[11] |
|---|---|---|---|
| BX-110 | $6.10 \times 10^{-8}$ | $1.46 \times 10^{-11}$ | No |
| TY-102 | $4.41 \times 10^{-7}$ | $1.06 \times 10^{-10}$ | No |
| BX-103 | $5.60 \times 10^{-6}$ | $1.34 \times 10^{-9}$ | No |
| B-104 | $1.74 \times 10^{-5}$ | $5.18 \times 10^{-9}$ | No |
| A-101 | $2.68 \times 10^{-5}$ | $6.43 \times 10^{-9}$ | Yes |
| B-102 | $2.82 \times 10^{-5}$ | $6.77 \times 10^{-9}$ | No |
| BY-109 | $3.75 \times 10^{-5}$ | $9.00 \times 10^{-9}$ | Possible |
| BX-111 | $3.82 \times 10^{-5}$ | $9.17 \times 10^{-9}$ | No |
| U-111 | $4.90 \times 10^{-5}$ | $1.18 \times 10^{-8}$ | Possible |
| B-105 | $5.01 \times 10^{-5}$ | $1.20 \times 10^{-8}$ | No |
| AX-102 | $5.29 \times 10^{-5}$ | $1.27 \times 10^{-8}$ | No |
| AX-101 | $6.54 \times 10^{-5}$ | $1.57 \times 10^{-8}$ | Yes |
| U-103 | $7.20 \times 10^{-5}$ | $1.73 \times 10^{-8}$ | Yes |
| BY-102 | $9.88 \times 10^{-5}$ | $2.37 \times 10^{-8}$ | Possible |
| BY-106 | $1.15 \times 10^{-4}$ | $2.76 \times 10^{-8}$ | Possible |
| BY-103 | $1.16 \times 10^{-4}$ | $2.78 \times 10^{-8}$ | Possible |
| U-102 | $1.19 \times 10^{-4}$ | $2.86 \times 10^{-8}$ | Possible |
| BY-105 | $1.74 \times 10^{-4}$ | $4.18 \times 10^{-8}$ | Possible |
| AX-103 | $1.84 \times 10^{-4}$ | $4.42 \times 10^{-8}$ | Yes |
| U-106 | $2.46 \times 10^{-4}$ | $5.90 \times 10^{-8}$ | Possible |
| U-109 | $1.67 \times 10^{-3}$ | $4.01 \times 10^{-7}$ | Yes |

waste is being heated past its ignition temperature. In this section we examine the crust ignition issue.

### 5.1. Kinetic Energy Determination

A key variable controlling the heat input is the kinetic energy of the drill string. Kinetic energy is maximized at a certain drop height because the weight of the drill string increases and the impact velocity decreases as the drop height decreases. The formulation of Miller (Ref. 17) is used to maximize the kinetic energy for a drop. The kinetic energy is given by

$$KE = \frac{1}{2}(m+M)V^2 \quad , \tag{G-8}$$

where

m = the mass of the sampler in the drill string, 2.86 kg (6.3 m),

M = the mass of the drill-string column, and

V = the velocity on impact.

The maximum length of the drill string is based chosen conservatively as a 16.5-m (648-in.) distance from the riser flange to the tank bottom. The waste depth is minimized in Tank AX-103 at 1.07 m (42 in.). Consequently, the length of the falling drill string is a function of the fall distance, in other words, the distance from the bottom of the drill string to the surface of the waste.

The impact velocity depends on the fall distance. Substitution of all terms into kinetic energy equation gives KE as a function of fall-distance squared. From this expression, there is a unique drop distance that maximizes the kinetic energy. This distance is found to be 7.7 m (25.3 ft). The associated maximum kinetic energy is estimated as 3640 J.

### 5.2. Frictional Ignition

One of the effects of drill string impact is friction between the waste particles. Friction can ignite gun powder and other pyrotechnic mixtures.[18,19] However, sensitivity to friction is attributed to elemental sulfur and not the organic compounds.[18,19] The waste stored at the Hanford Site is basic. Elemental sulfur is not expected to exist under the basic conditions typical of Hanford waste; frictional ignition is not expected.[18]

### 5.3. Absorption of Impact Energy

Another possible effect of drill-string impact is conversion of the kinetic energy into heat. Based on the discussion in Section 2 of this appendix, local exothermic reactions will not occur during drilling operations if the waste temperature is below 160°C. This criterion also applies to the impact of the drill string on a hard crust. No local exothermic reaction will occur if the crust is not heated to 160°C.

The strain energy absorbed by the crust as a result of impact will affect a volume that expands at a 45° angle away from the falling object. Therefore, assuming that all of the energy is absorbed by a hemisphere with a radius equal to the radius of the drill string is conservative. The conservative energy balance for the impact is:

$$KE = \frac{2\pi}{3} \cdot r^3 \cdot \rho \cdot c_p \cdot (T - T_o) \quad , \tag{G-9}$$

where

KE = kinetic energy of the falling drill string,
r = radius of the drill bit,
$\rho$ = density of the crust,
T = temperature after impact, and
$T_o$ = initial temperature of the crust.

The radius of the drill bit is 2.86 cm, the bulk density of dry crust material is assumed to be ~1.35 g/cm$^3$, and the heat capacity of the waste solids is ~1.8 J/g K. The bound initial temperature is 95°C. The maximum waste temperature as a result of impact is 126°C, so significant local exothermic reactions are not expected to occur.

### 5.4. Propagation of Exothermic Reactions in a Crust

The criteria for nonpropagating exothermic reactions in the waste developed in Section 4.1 of this appendix also apply to a crust layer. If the crust material satisfies these criteria, exothermic reactions are not expected to propagate.

If heat transfer to the dome is neglected, the stability criterion given by Fauske[7] applies. The critical radius required for propagation is

$$r_{crit} = \sqrt{\frac{3.32 \cdot \alpha \cdot R \cdot T^2}{\frac{dT}{dt} \cdot E_a}} , \qquad \text{(G-10)}$$

where

$r_{crit}$ = critical radius,
$\alpha$ = thermal diffusivity,
R = gas constant,
T = temperature of the sphere,
$\frac{dT}{dt}$ = self-heat rate, and
$E_a$ = activation energy.

The temperature in this equation is absolute temperature. Because the crust is assumed to be porous, the thermal diffusivity is assumed to be 0.0004 cm$^2$/s, which is half the value used in Section 3.2. The temperature is determined from Eq. (G-9). Section 3.2 states that a conservative estimate of the activation energy is 240 kJ/mole and that a conservative estimate of the self-heating rate at 180°C is 1°C/min. However, to extrapolate to lower temperatures, a lower activation energy is the conservative value. The lower bound on activation energy based on Reference 5 is 20 kJ/mol. Therefore, a conservative estimate of the self-heating rate at 126°C is 0.008 K/s, which is a very conservative estimate based on the waste surrogate and

waste simulant data. The conservative value of the critical radius is 3.3 cm, which is larger than the radius of the drill bit. Therefore, dropping the drill string on a crust will not initiate a propagating exothermic reaction. This result is consistent with the results for local exothermic reactions. If a drop accident does not cause significant local exothermic reactions, there will be no propagating exothermic reactions.

## 6.0. SUMMARY AND CONCLUSIONS

Local runaway reactions are a hazard in the Hanford Site waste tanks. The high temperature produced by runaway reactions is an ignition source for flammable gas and a local runaway may initiate self-propagating exothermic reactions in the waste. Local runaway reactions can be prevented by establishing waste temperature limits. The following limits are placed on temperatures:

- The temperature of small waste fragments produced at the drill tip must not exceed 180°C.
- The temperature of the drill bit and the average temperature of the waste affected by drilling must not exceed 160°C for more than 10 minutes.

Because failure of the controls implemented to satisfy these temperature limits can fail, the possibility of a propagating exothermic reaction must be considered. Because the consequences of a large-scale propagating reaction are potentially very severe, FG/RMCS is not permitted unless it can be demonstrated that the frequency of a propagating exothermic reaction is less than $10^{-6}$ per year. Of the current flammable gas tanks and those currently considered as possible flammable-gas tanks, this SA limits FG/RMCS operations to the tanks listed in Table G-3.

The possibility of a propagating ignition in tank waste following the drop of a sampler drill string is examined. The maximum kinetic energy was found as 3640 J when the drill string drops 26.0 feet. This energy will not heat the waste above the onset temperature of exothermic reactions, so there will be no local exothermic reaction or self-propagating reaction.

## 7.0. REFERENCES

1. L. Bretherick, *Bretherick's Handbook of Reactive Chemical Hazards*, 4th Ed., (Butterworths, London, England, 1990).

2. O. Kubaschewski, C. Alcock, and P. Spencer, *Materials Thermochemistry*, (Pergamon Press, Oxford, England, 1993).

3. F. Lees, *Loss Prevention in the Process Industries*, (Butterworths, London, England, 1980).

4. K. Jones, "Nitrogen" in *Comprehensive Inorganic Chemistry* , J. Bailar, Ed., (Pergamon Press, New York, 1973).

5. D. Scheele, R. Shell, J. Sobolik, and L. Burger, "Organic Tank Safety Project: Preliminary Results of Energetics and Thermal Behavior Studies of Model Organic Nitrate and/or Nitrite Mixtures and a Simulated Organic Waste," Pacific Northwest Laboratory report PNL-10213 (August 1995).

6. N. Kirch, "Adiabatic Calorimetry (RSST and VSP) Test with Sodium Acetate," Westinghouse Hanford Company report WHC-EP-0683 (September 1993).

7. H. Fauske, "Waste Simulant PAS94A and Exothermicity," Fauske & Associates, Inc., letter to Bob Cash, Joe Meacham, and Dave Turner (December 14, 1995).

8. Center for Chemical Process Safety, *Guidelines for Chemical Reactivity Evaluation and Application to Process Design*, American Institute of Chemical Engineers, New York, New York (1995).

9. P. M. Francis, "Aerosol Study for the Rotary Mode Exhauster," Westinghouse Hanford Company report WHC-SD-WM-ES-225, Rev. 1 (March 29, 1993).

10. D. A. Siebe, "Thermal Analysis of Rotary-Mode Core Drilling," Los Alamos National Laboratory Calc-Note TSA10-CN-WT-SA-TH-111 (February 1996).

11. B. M. Hanlon, "Waste Tank Summary Report for Month Ending October 31, 1995," Westinghouse Hanford Company report WHC-EP-0182-91 (January 1996).

12. J. Stewart, D. Turner, M. Plys, B. Malinovic, J. Grigsby, D. Camainoni, P. Healser, W. Samuels, and J. Toth, "Preliminary Safety Criteria for Organic Watch List Tanks at the Hanford Site," Westinghouse Hanford Company report WHC-SD-WM-SARR-033 (November 1995).

13. H. Fauske, M. Epstein, D. Dickinson, R. Cash, D. Turner, and J. Meacham, "The Contact-Temperature Ignition (CTI) Criteria for Propagating Chemical Reactions Including the Effect of Moisture and Application to Hanford Waste," Westinghouse Hanford Company report WHC-SD-WM-ER-496, Rev. 0 (September 1995).

14. D. Herting, D. Bechtold, B. Crawford, T. Welsh, and L. Jensen, "Laboratory Characterization of Samples taken in May 1991 from Hanford Waste Tank 241-SY-101," Westinghouse Hanford Company report WHC-SD-WM-DTR-024 (1991).

15. S. F. Agnew, "History of Organics in Hanford Tanks: HDW Model Rev. 3," Los Alamos National Laboratory draft report (February 1996).

16. P. G. Heasler, "The Probability that a Rotary Drill Failure will Occur in Reactive Waste," Pacific Northwest National Laboratory letter report prepared for D. Turner (WHC) (March 11, 1996).

17. W. O. Miller, "Retained Gas Sampler Drill String Drop Analysis," Los Alamos National Laboratory Calc-Note TSA-6-CN-WT-SA-ST-075-0, (January 1995).

18. G. Beitel, "Chemical Stability of Salt Cake in the Presence of Organic Materials," Atlantic Richfield Hanford Company report ARH-LD-11 (April 1976).

19. R. Lancaster, T. Shimizu, R. Butler, and R. Hall, *Fireworks - Principles and Practice* , (Chemical Publishing Co., Inc., New York, 1972).

# APPENDIX H

# DUST EXPLOSION IN THE DOME

## 1.0. INTRODUCTION

The rotary-core drilling generates a dust aerosol. Some of the aerosol produced during the core drilling will disperse into the vapor space of the dome, some of it will settle on the top of the waste, and some of it will flow into the ventilation line of the exhauster. The concentration in the dome of any given tank is discussed in Appendix Q. The objective of this appendix is to evaluate the possibility of dust explosions in the dome space of a flammable-gas single-shell tank (SST).

## 2.0. EVALUATION OF BUREAU OF MINES EXPERIMENT

The Bureau of Mines (BOM)[1] performed experiments on the dust explosions. The dust particles used in the experiments have the same particle characteristics as those generated in the SSTs during the core-drilling operation. However, the real composition of the salt cake in the SSTs is unknown. An appropriate salt-cake simulant must be used. According to Reference 2, the selection of a simulant was based largely on the following criteria: (1) the average particle density dictates the size distribution of aerosol, (2) the majority of tanks that plan to do rotary drilling are salt-cake tanks and have a high sodium nitrate content, and (3) sodium nitrate would be the most crystalline of all rotary-mode tank solids and therefore would be the waste type that would form the most dust. The simulant used in the BOM experiment covered the sodium nitrate concentration ranging from 0% to 90%. This should cover the sodium nitrate concentration of salt cake in the SSTs.

The dust-particle distribution of simulant is another important factor in studying dust explosion. In Reference 2, a particle distribution analysis was performed on a dust sample generated by the rotary-mode core drilling test operations. The sample was a single-shell tank waste simulant RBM#2, prepared by the Westinghouse Hanford Company (WHC) Chemical Engineering Laboratory (CEL). Two methods were used to analyze the particle distribution, (1) scanning by an optical microscope with automatic image analysis performed by a dapple system and (2) laser diffraction analysis performed on a Brinkman particle-size analyzer. Both sets show a size range between 0 to 150 microns. The actual dust-particle size distribution was not measured in the BOM experiment. However, the fuel and oxidant dusts for these tests were pulverized and sieved through a 200-mesh screen. The test aerosols were apparently very close to those given above.

Another important parameter in studying dust explosions is the minimum explosion concentration. The minimum explosion concentration for various dusts ranges from 0.025 to 2.0 oz/ft$^3$ (0.1 oz/ft$^3$ = 100 g/m$^3$) as given in Reference 3. The dust concentration used in the test ranged from 300 to 2000 g/m$^3$. It covered the

minimum explosion concentration specified in Reference 4. Therefore, the dust concentration was adequately selected.

The minimum cloud ignition energy for various dust concentrations is also given in Reference 3. It ranges from 0.01 to 1.92 joules. The ignition source used in the experiment was a very strong 5,000 J pyrotechnic igniter, which is much higher than the minimum cloud ignition energy given in Reference 3. Therefore, the ignition source should be able to ignite the dust simulant.

The measurement system consists of two optical dust probes measuring the uniformity of dust probe and strain-gauge pressure transducer to measure the pressure generated by the igniter and the pressure from any flame propagation if the dust ignites. The pressure history and degree of mixing in the test vessel were measured as desired.

## 3.0. EXPERIMENTAL RESULTS FROM BOM TESTS

The results from the BOM test are given in Reference 1. The results are summarized below.

The mixture of 15% $Na_4EDTA$, 56.7% $NaNO_3$, and 28.3% $NaNO_2$ in air produced a pressure ratio of less than one. The mixture not only did not deflagrate but actually reduced the pressure from the igniter.

The 10% NPH, 60% $NaNO_3$, and 30% $NaNO_2$ mixture dispersed in air produced pressure ratios greater than one. In these tests there was some burning of the NPH fuel that was within the igniter flame, but they are still not considered to be propagating deflagrations according to the standard propagation criteria. The pressure rises were low. This implies that there was essentially no propagation continuing after the igniter flame ended.

The mixture of 10% polyethylene, which ignites easily, and 90% $NaNO_3$ dispersed in nitrogen produced less of a pressure rise than would be expected from the igniter alone.

The pure fuels (EDTA and NPH) would be explosion hazards if dispersed in air, but the mixture of 15% EDTA and 85% oxidant or 10% NPH and 90% oxidant would not be considered explosion hazards when dispersed in air or nitrogen.

## 4.0. BOUNDING ANALYSIS

The ratio of the radionuclide concentration in the dome to the concentration in the liquid during operation of the airlift circulators is given by R. Kimura and S. Johnson.[4] Airlift circulators were used to simulate the effect of the nitrogen cooling during rotary-core sampling. The ratio of radionuclide concentration in the dome to the concentration in the liquid varies from $1.8 \times 10^{-9}$ to $3.5 \times 10^{-7}$. Assuming the

concentration of the aerosol is the same as the liquid concentration and the waste density is 1.6 g/cm$^3$, the concentration of waste in the dome is calculated as 0.56 g/m$^3$. Adding 350 g to this value, which is caused by rotary-mode core sampling (RMCS) operations, makes a dome concentration of 0.81 g/cm$^3$.

Examination of the available waste composition data indicates that the total organic carbon (TOC) concentration in the waste is bounded by 50 g TOC/L. In terms of weight percentage, it is estimated as 3.1 wt%. The organic carbon concentration in the dome is found as 0.025 g TOC/m$^3$.

The organic compounds in the waste are a complex mixture of degradation products of the chelating agents. It is very difficult to estimate the heat of combustion of this mixture. However, by examining the similar organic constituents, we can roughly estimate the maximum heat of combustion per gram of carbon. We examined 32 compounds including cyanide compounds. The maximum heat combustion of $(CH_3)_2NH$ is -898 kJ/g C. Sodium acetate, which is a likely degeneration product, has a heat of combustion of -310 kJ/g C. We used the upper bound value of -898 kJ/g C to estimate the combustion energy generated by the dust during RMCS activity.

The combustion energy associated with the dust is calculated as -22.5 kJ/m$^3$. This energy can be converted into an equivalent hydrogen concentration. The heat of combustion for hydrogen is -241.8 kJ/mol $H_2$. The equivalent hydrogen concentration is 0.0931 mol $H_2$/m$^3$. Using the ideal gas law, the concentration in terms of ppm was estimated as 2292 ppm. The flammability limit for hydrogen in air is 40,000 ppm (4%). This very conservative calculation indicates that combustible dust contains less than 6% of the energy contained in a flammable hydrogen-air mixture. Therefore, we can neglect the contribution of combustible dust. The presence of dust in a flammable hydrogen-air mixture would not result in an explosion.

## 5.0. CONCLUSIONS

The range of $NaNO_3$ concentrations in the dust and dust distribution in BOM tests were believed to be very close to those in SSTs. The ignition source was strong enough to generate deflagration in the igniter . The test results showed that the mixture of pure fuel and oxidant ($NaNO_3$) would not propagate deflagrations and would not result in an explosion when dispersed in air or nitrogen.

The bounding analysis showed that the energy contribution of combustible dust is negligible and that the presence of dust in a hydrogen-air mixture would not result in explosion. In summary, the probability of dust explosion appears to be extremely unlikely.

## 6.0. REFERENCES

1. K. L. Cashdollar, "Interim Report — Core Drilling into Waste Tanks," Pittsburgh Research Center, Bureau of Mines Interim report WHC-SD-WM-ES-219 (June, 1993).

2. P. M. Francis, "Aerosol Study for the Rotary Mode Exhauster," Westinghouse Hanford Company report WHC-SD-WM-ES-225 (March, 1993).

3. A. E. Cote and J. L. Linville, *Fire Protection Hand Book,* Sixteenth Edition, (National Fire Protection Association, Quincy, Massachusetts, 1990).

4. R. Kimura and S. Johnson, "Tank 101-AZ Vapor Space Radionuclide Concentrations and Partition Function," Rockwell International internal letter 65950-86-607 to D. J. Squires (October 14, 1986).

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**Section** 2 **of** 3

**Title:** A Safety Assessment of Rotary Mode Core Sampling in Flammable Gas Single Shell Tanks: Hanford Site, Richland, Washington

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**Co:**

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# APPENDIX I

# DOME COLLAPSE ACCIDENTS

## 1.0. OBJECTIVE

The objective of this appendix is to compute the bounding respirable waste released during a dome collapse accident in a single-shell tank (SST). The amount of waste material released is used in this safety assessment (SA) to estimate the radiological and toxicological consequences of a dome collapse accident.

## 2.0. DOME COLLAPSE AND RELEASE SCENARIOS

In Section 2.1, we discuss the various accident scenarios that may lead to a dome collapse. Section 2.2 discusses the different mechanisms for material release during a dome collapse.

### 2.1. Dome Collapse Scenarios

As discussed in Sections 3 and 4 of this SA, there may be multiple initiators that result in a dome collapse. In general, the following accident sequences have a potential of collapsing the dome:

- **A deflagration in the dome (either initiated in the dome or initiated elsewhere and propagated into the dome).** The consequences of this scenario are discussed in this appendix. A deflagration is believed to lead to the bounding accident sequence because

1. Convection associated with the deflagration can entrain additional aerosol.
2. The tank blowdown following the deflagration potentially can release aerosol before the actual dome collapse occurs.
3. The initial tank blowdown will temporarily lift some soil above the dome, potentially increasing the effective collapse distance.
4. Following the deflagration, extensive concrete cracking could result in dome collapse occurring quasi-coherently (where increased coherency would increase the aerosol produced upon impact with the waste).
5. The air heated by the deflagration can start a natural convection flow that will assist in the release of aerosol.
6. With a deflagration, there is perceived to be an increased possibility (relative to most other dome collapse sequences) of an associated waste burn that could provide additional aerosol and energy for dispersal.

- **A deflagration in the waste.** As discussed in Appendix C of this SA, this is a less likely scenario for dome collapse. For the short-term release, the approach used for fragmentation of waste following a dome deflagration is conservatively bounding regardless of whether a waste burn has occurred. For the long-term release, the deflagration accident sequence includes the possibility of a burn for waste remaining in the tank.

- **Dome overloading.** This accident is prevented through administratively controlling the allowable loads over the tank dome. The consequences of a dome collapse resulting from overloading are bounded by the consequences of a collapse resulting from deflagration.

- **Dome space vacuum.** Dome buckling is possible if a large vacuum is created in the dome space. Increased ventilation rates with blocked inlets may result in such an accident. The initiators are administratively controlled, and the consequences are bounded by a dome collapse as a result of deflagration in the dome space.

- **Seismic event.** The consequences of a dome collapse as a result of a seismic event are bounded by the dome collapse as a result of deflagration in the dome space.

## 2.2. Material Release Mechanisms

In computing the total material release as a result of dome collapse, we analyzed the following mechanisms that contribute to the total release:

- Initial material that is suspended in the dome space before the accident;

- Material entrained from the waste surface during deflagration;

- Material entrained from the failed high-efficiency particulate air (HEPA) filters;

- Solid material fragmented by impact during dome collapse;

- Liquefied material splashed by impact during dome collapse,

- Solid material released during dome collapse, deposited outside the dome, and resuspended.

- Liquefied material entrained by the wind from a open pool of waste after the dome collapse.

These mechanisms are analyzed in Sections 3 through 6 of this appendix. A more detailed development may be found in (Ref. 1).

## 3.0. INITIAL DOME LOADING AND HEPA FILTER LOADING

In the Mixer Pump SA developed for Tank SY-101, a bounding dome volume loading of 0.64 kg (1.41 $lb_m$) was used (Ref. 2). A high value was used for SY-101 because that tank used to experience periodic gas-release events (rollovers) that were very energetic and that resulted in considerable surface motion. Thus, there was a plausible mechanism of entraining considerable waste material into the dome space during these rollovers.

SSTs do not exhibit similar energetic rollover behavior. For SSTs, the maximum dome loading may result from some intrusive activities such as rotary-mode core sampling (RMCS). At the end of a drilling step, a maximum value of 0.35 kg (0.77 $lb_m$) is estimated for the SST dome loading.[3]

The energetic respirable material release from the failed HEPA filters during a dome burn in Tank SY-101 is estimated to be less than 0.5 kg (1 $lb_m$).[2] This number is expected to be less for the SSTs because the number of filters is less and the ventilation flow rates are lower.

In this analysis, it is conservatively assumed that the total respirable release resulting from the initial dome loading and HEPA failures is ≤ 0.6 L or 1 kg (2.2 $lb_m$). As shown later in this appendix, this release is negligible compared to uncertainty in potential releases during the impact phase of dome collapse.

## 4.0. MATERIAL ENTRAINED DURING A DEFLAGRATION

The only credible deflagration mechanism believed capable of failing the dome is one where the gas has been released to the dome air space so that the dome failure pressures can be exceeded. The temporary pressures of a postulated gas deflagration in the waste may produce some aerosol, but the available energy is small compared to the waste heat capacity. Even if we assume that 10% of the waste volume is a homogeneous, interconnected stoichiometric hydrogen-nitrous oxide mixture at 1.5 atm., the resulting heat of combustion is 10.85 $MJ/m^3$ of waste. The waste heat capacity in 0.9 $m^3$ is 2.6 MJ/°C. Consequently, combustion of this gas will only raise the average waste temperature by about 4°C. More details are given in Ref. 4.

Based on numerical simulation of the SY-101 dome space deflagration (Ref. 2) and using the entrainment correlation given in Ref. 5, the entrainment from the waste surface is estimated as 5.45 kg (12 $lb_m$) for a deflagration front moving at ~45 m/s (150 ft/s). This value is believed to be conservative and will be used for SSTs also. Note that the entrainment correlation given in Ref. 5 is derived using dry powders and is possibly more applicable to SST conditions in which the waste surface may be drier than the SY-101 waste. The correlation in Ref. 5 is independent of particle size, and it was taken from experiments ranging from 4.5 μm to 48 μm aerodynamic

equivalent diameter (AED). Therefore, a respirable fraction (RF) of 0.52 from Ref. 6 was applied to obtain a respirable release of 1.8 L or 2.8 kg. As shown later in this appendix, this release is within the uncertainties of other potential releases during the impact phase of the dome collapse.

## 5.0. MATERIAL RELEASE DURING DOME COLLAPSE

The phenomenology associated with calculating the amount of respirable material released during dome collapse is complex, especially given that the waste material properties are not fully understood. With present algorithms for calculating dome collapse and for the short-term release, the key parameters are the drop height and the associated tank air volume. The larger the drop height, the greater the impact on the waste and the more aerosol that can be produced. Ignoring the watch list tanks that are interim-stabilized, the drop height is bounded by the 30.2 ft (9.2 m) distance in Tank SX-101 and a tank air volume of 115,600 $ft^3$ (3,273 $m^3$). The short-term release is based on these tank dimensions, and it assumes the waste composition can correspond to any watch list SST.

Two difference collapse geometries are perceived to exist, depending on the waste composition. First, if the primary contents of the tank are salt cake or salt cake with some sludge but minimal liquid, the collapsing concrete and soil have limited waste penetration. Second, if the tank contents can be assumed to behave more like a slurry or as salt cake and sludge with extensive interstitial liquid, the fall of material into the tank is assumed to produce a splash and penetrate the waste.

### 5.1. Impact on Salt Cake.

In this situation, the concrete and soil are assumed to collect upon the waste. The aerosol produced is that from the initial impact on each unit area of waste. Additional fragmented waste produced later in the collapse sequence is trapped by the initial soil and concrete debris layer. The analysis objective is to evaluate releases from the initial impacts conservatively. Two numbers are desirable, the airborne release from the tank and the respirable release from the tank. Because of uncertainties in the phenomenology, two methods were used to determine the respirable release.

**5.1.1. The Airborne Release.** In this analysis, an upper limit to the airborne release was determined from an aerosol concentration limit. The appropriate limit is necessarily a transient one. One such limit is ~1 $kg/m^3$, which is possible to achieve in a dust explosion (Ref. 7). This number is not a hard limit; for example, the Fire Protection Handbook (Ref. 8) does reference some dust explosion experiments performed with 2 $kg/m^3$. Nevertheless, it is four orders of magnitude above a tentative Sutter (Ref. 9, p. 2.66) recommendation of 100 $mg/m^3$ "...as a maximum upper-limit quasi-stable air concentration after an explosive event."

The 100 mg/m$^3$ limit appears difficult to justify for a transient situation. Hinds (Ref. 7) states that as a rule of thumb, coagulation is neglected in laboratory experiments and industrial hygiene work if the aerosol number density is less than $10^6$/cm$^3$. Fig. I-1 shows a plot of aerosol concentrations with a number density of $10^6$

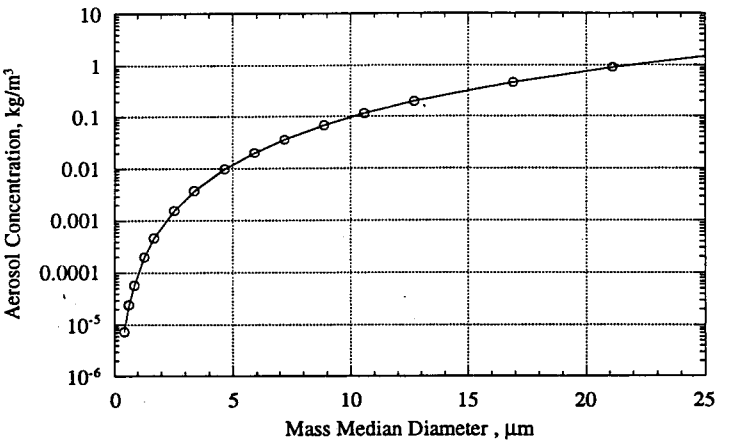


**Fig. I-1. Concentration for 1E+6 particles/cm$^3$ using a lognormal distribution.**

particles per cm$^3$. Lognormal distributions were assumed with a geometric standard deviation, $\sigma_g$, of 2 and a particle density of 1.6 g/cm$^3$. For the 1 kg/m$^3$ lognormal distribution in Fig. I-1, in other words, the point with a mass median diameter (MMD) of 21.8 µm, the RF is 0.072. These are particles with a AED of less than 10 µm. For a 3273 m$^3$ tank volume, this RF is not negligible.

To examine the transient situation more closely, scoping calculations of aerosol agglomeration and aerosol scrubbing by terminal velocity soil particles are evaluated in Ref. 1. They suggest that with an overall concentration of 1 kg/m$^3$, respirable particles will only exist for a few seconds. A lower concentration limit is believed appropriate. However, at this time, selection and justification of a lower number would require numerical calculations that were beyond the scope of this analysis. The airborne concentration adopted here is used in Sections 5.1.3 and 6.0.

### 5.1.2. Respirable release using the MacDougall equation.[10]

The first approach to determine the respirable release involves a formula for a respirable release developed by MacDougall, Scully, and Tillerson (Ref. 10). This formula is independent of the airborne concentration, and is given by

$$V_R = 2 \times 10^{-10} \times (E_{imp}/Vol) \times Vol \ , \qquad \text{(I-1)}$$

where

$V_R$ = respirable release volume,
$E_{imp}$ = impact energy, (J),
Vol = volume of material that absorbs the impact energy, $m^3$, which is also the volume to which the respirable fraction applies.

Equation (I-1) was derived from a series of Argonne National Laboratory (ANL) experiments (Refs. 11, 12, and 13) involving the brittle fracture of small samples of glass, ceramics, uranium dioxide pellets, and concrete. Most tests were in the energy range, $E_{imp}/Vol$, of $10^6$ to $10^7$ $J/m^3$. These energy densities were compared to dome collapse energy densities by formulas from two separate approaches: a projectile penetration equation (Ref. 14) and a relationship describing the crater produced by assuming the collapse energy is equivalent to TNT (Ref. 15). Dome collapse energy densities of from $7.1 \times 10^6$ to $3.6 \times 10^7$ $J/m^3$ were obtained, suggesting that the ANL energy density range is reasonable to apply to the dome collapse accident.

Available calculations of dome loading (Refs. 16, 17, and 18) illustrate that cracking and failure of the dome proceeds from the center outward. An idealized diagram of this collapse mode is given in Fig. I-2. Because of the difficulty in determining aerosol escape with a coherent collapse, and because of the spreading of soil from previously collapsed segments preventing further direct impact on such covered waste, an evaluation was performed varying the fraction of the dome credited with

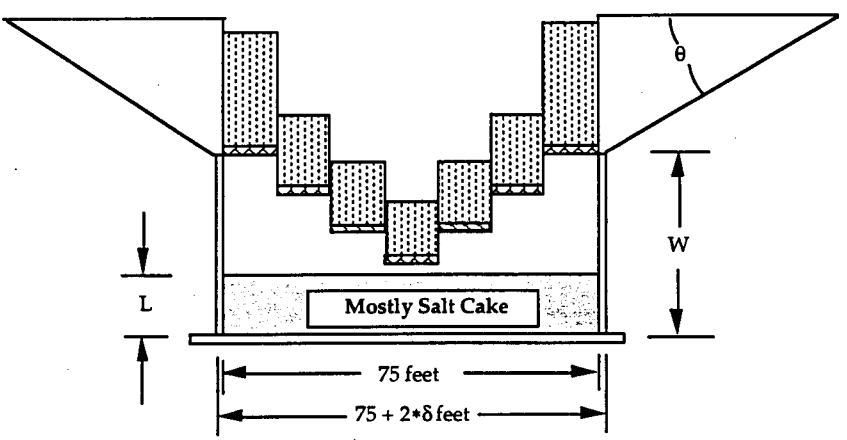


**Fig. I-2. Schematic of dome collapse on salt cake.**

collapsing coherently on salt cake that is not covered by previous debris. Because the variable Vol does not influence Eq. (I-1) results, the release depends only on the $E_{imp}$ associated with the collapsing mass. The results of this analysis are given in Fig. I-3,

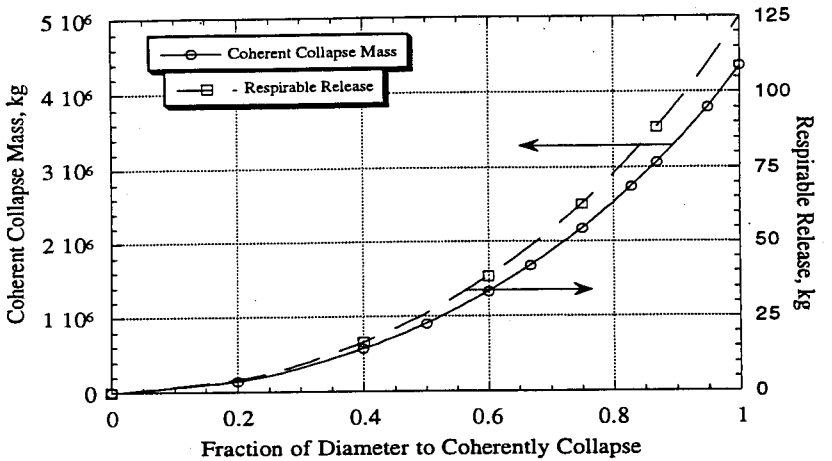


**Fig. I-3. Coherent collapsing mass and associated respirable release.**

which assumes that the minimum depth of soil above the dome is 10 ft. Because of coherency limitations caused by the strongly reinforced haunch region of the dome, a conservative estimate was judged to involve coherent collapse of the concrete and soil up a limiting diameter of ~90%. This release is 60 L or 96 kg (with a waste density of 1600 kg/m$^3$) of respirable aerosol.

### 5.1.3. Respirable Release Using an Energetics Analogy

Collapse does not have to be so coherent. It could start during tank depressurization after the initial deflagration. Expansion calculations show that the residual gas can remain hot, at 600 K or more, and Siebe (Ref. 19) notes that a 150-μm particle has a heat-transfer time constant of about 0.1 s. In short, some of the organic carbon could undergo combustion in airborne particulate. To evaluate a bounding case, a respirable fraction for the 1 kg/m$^3$ of particulate in the tank air was calculated using the prescription of Halverson and Mishima (Ref. 20), which relates the heat of combustion to aerosol formation by an explosive source. To be conservative, $\sigma_g$ was set to 2.5. Results as a function of the heat of combustion are given in Fig. I-4. The heat of combustion, $\Delta H$, upper bound was assumed to be 300 cal/g (1.26 MJ/kg).

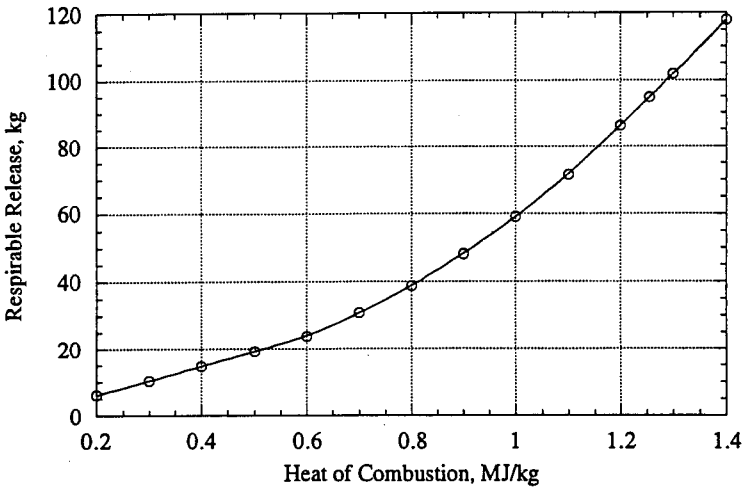


**Fig. I-4. Respirable release treating a burn using an explosion prescription.**

This ΔH gives an RF of 0.0289; application to the assumed 3273 kg of airborne waste in the tank gives a respirable release of 95 kg. This release is highly conservative. As shown in Appendix H of this SA, combustion propagation is very difficult to achieve in dusts produced from simulants of waste in the Hanford SSTs.

### 5.2. Impact on Liquefied Waste

#### 5.2.1. A Scoping Assessment Simulating Impact As An Equivalent Spill.

For liquefied waste, the MacDougall formula for brittle impact does not apply. A splash should be represented. The approach adopted was to model the splash as an equivalent spill, during which the spill energy is assumed to be equivalent to the dome collapse energy. Eq. (26) of a study by Ballinger et al. (Ref. 21) was used to get the airborne release fraction. The Ballinger correlation is based primarily on the Archimedes number, which represents the ratio of gravitational forces to viscous forces. For the gravitational forces, an effective height was used multiplying the real height by the ratio of the mass of the dome over the mass of the waste layer that absorbed the impact. The collapse mass was assumed to contain all the soil out to the angle of repose (30°) because the initially impacting mass may sink, exposing further waste to impact. At the top of the dome, the minimum soil thickness was 10 ft at a conservative density of 120 $lb_m/ft^3$ (1920 $kg/m^3$). With the addition of a 100 $lb_m/ft^2$ external load on the dome, the total collapsing mass was $1.34 \times 10^7$ kg. For the viscous forces, the viscosity of the waste was conservatively estimated to be 20 cP, the minimum supernatant liquor viscosity for Tank SY-101.

Results as a function of the waste thickness that is assumed to absorb the energy are given in Fig. I-5. A conservative bound for the waste thickness was judged to be 1 ft.

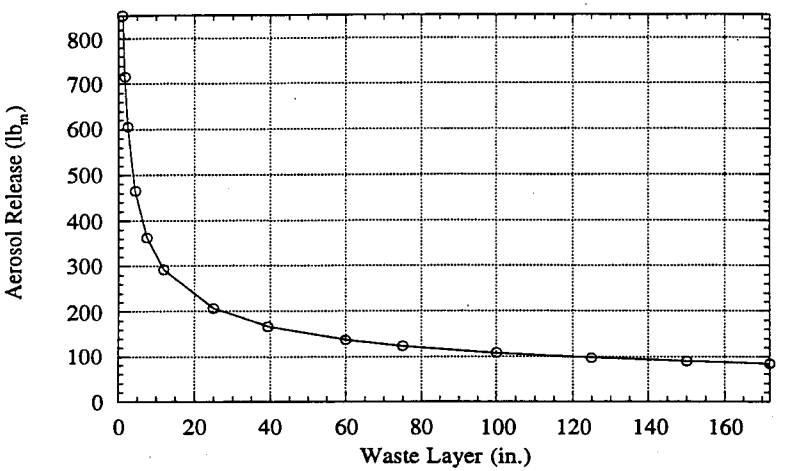


**Fig. I-5. Amount of aerosolized material as a function of an energy-absorbing layer.**

This gives a 132-kg (291-$lb_m$) airborne release. DOE-HDBK-3010-94 (page 3-4, Ref. 22) states that a bounding RF for a 3-m spill is 0.8. Ballinger's correlation for the aerodynamic MMD strongly increases as a function of impacting velocity. Consequently, an RF of 0.8 should be bounding for higher drop heights. Using an RF = 0.8 gives a respirable release of 106 kg.

### 5.2.2. Quasi-Mechanistic Considerations Assuming a Continuous Collapse

The analysis in Sec. 5.2.1 is unrealistic in that the simulated coherent collapse leaves no path through the debris allowing the aerosol to escape. An improved picture is to assume that the dome collapse in incoherent. Such a picture is shown in Fig. I-6. The main effect of the filling of the tank by the collapsing dome is to decrease the effective drop distance. (From the impact equations used to obtain the energy density in Sec. 5.1.2, the ratio of the impacting mass to waste mass may be assumed as approximately constant.) The Ballinger correlation depends on the drop height to the 1.35 power. By assuming the Fig. I-6 incoherent collapse, the correlation can be averaged (integrated) over the drop height, reducing the airborne release by a factor of 2.35. The RF is calculated by assuming 0.8 for fall heights greater than 3 m, and RF = 1.0 for that part of the fall height that is less than 3 m. This gives an average RF of 0.84. The respirable release is 0.84 x 132/2.35 = 47 kg.

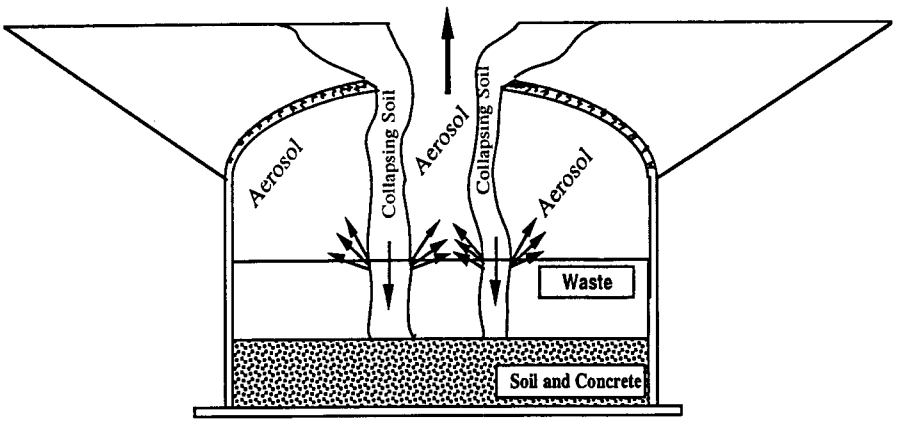


**Fig. I-6. Incoherent model of the collapsing dome.**

## 6.0. DOME COLLAPSE LONG-TERM RELEASES

The main concern is atmospheric entrainment of aerosol before post-accident recovery operations can contain the release. There are three situations that require consideration. First, the salt cake impact has produced airborne waste that may have settled outside the dome and can be resuspended. Second, the logical extension of the model shown in Fig. I-6 results in a pool of liquefied waste that can be entrained. Third, if buried waste has been ignited, the heat can release additional toxic or radioactive gases.

For the salt cake impact, the airborne release is approximately 1 kg/$m^3$ times the tank air volume of 3273 $m^3$ in Sec. 5.1.1. Conservatively, we could assume that ~3000 kg might settle onsite. Part could be resuspended as respirable particulate. The bounding release rate for aerodynamic entrainment and resuspension is 4E-5/h with an RF = 1.0 from DOE-HDBK-3010-94 (page 5-4, Ref. 22). Multiplication gives 0.12 kg/h, or about 20 kg for a 7-day release.

For the liquefied waste case, the volume of the collapsing soil and concrete is 227,800 $ft^3$ (6451 $m^3$). After collapse, only 12 ft (3.66 m) will exist between the bottom of the final soil surface and the ground surface even if collapse occurs into an empty tank. The most conservative configuration for long-term releases is to use the assumption that no waste is absorbed by the soil. Instead, a pool of waste is postulated to form on the top of the collapsed soil. Entrainment can occur from this pool. Assuming the volume of the pool is the volume of the waste in Tank A-101, the volume of the pool is 127,010 $ft^3$ (3597 $m^3$), the radius of the pool is 74.1 ft

(22.6 m), the depth of the pool center is 9.18 ft (2.8 m), and the surface of the pool is 2.82 ft (0.86 m) below the surface of the ground. The pool surface area is 17,300 $ft^2$ or about 1600 $m^2$.

With variable winds and property uncertainties, pool entrainment is a difficult problem. The approach was to take the bounding DOE-HDBK-3010-94 (page 3-5, Ref. 22) entrainment rate of $4 \times 10^{-6}$/h for outdoors, assessed as applicable to large pools and ponds with windspeeds to 30 mph (13.4 m/s). The RF is 1.0. This rate applies to the mass in a 1-cm active layer. The respirable aerosol released in 7 days is

$$(1600\ m^2)(0.01m)(1600\ kg/m^3)(4 \times 10^{-6}/h)(168\ h) = 17.2\ kg.$$

Gases released from a buried waste burn could not be assessed fully at this time. An adiabatic temperature rise is (300 cal/g)(4.184 J/cal)/(1.8 J/g-°C) ≈ 700°C. Potentially, vaporization of some cesium compounds would be possible. However, condensation of escaping gases on soil particles would appear to preclude release. At this time, the conservatism in the resuspension and entrainment calculations would seem sufficient to allow respirable releases from buried waste to be ignored as long as burial can be maintained.

## 7.0. CONCLUSIONS

During the dome collapse accident, the conservative estimate for the prompt release of respirable aerosol is obtained as follows:

| | |
|---|---|
| Initial dome loading: | 0.6 L |
| Entrainment during deflagration: | 1.8 L |
| Solid respirable aerosol from impact: | ~60.0 L |
| TOTAL | 62.4 L |

Because of the neglect of the rapid reduction phenomena from aerosol agglomeration and from possible aerosol scrubbing by incoming soil during the release from the tank, the prompt release would be bounded by 62.4 L of solid particulate during the dome collapse.

Using the receptor doses for 1 L release given in Appendix R, the onsite receptor dose for the prompt release may be calculated as 17,200 rem. The offsite receptor dose is 9.3 rem.

These numbers are conservative if one considers that maximum concentrations that can be sustained in a plume or a cloud. In order to receive 17,200 rem, the onsite individual must inhale $7.2 \times 10^{-4}$ L of waste. Sutter[9] states that the concentrations in dust storms range between 0.5 g/$m^3$ and 10 g/$m^3$. The concentration at the at the face of a mine would be 0.5 g/$m^3$ and, in smog, it would be 50 mg/$m^3$. If one assumes that, by expansion, dispersion, agglomeration and deposition, the concentration in the plume drops to the lower dust storm limit of 1 g/$m^3$ (or $6.3 \times 10^{-4}$ L of waste/$m^3$ of air), the onsite individual must inhale ~1 $m^3$ of

air. Using a $3.3 \times 10^{-4}$ $m^3/s$ breathing rate, the individual must remain in the dust cloud for ~50 min. It is highly unlikely that, an individual at 100 m from a catastrophic accident will remain in the cloud for such an extended period of time without protection or without leaving the premises. These calculations indicate that the doses resulting from the dome collapse accident are conservatively estimated. However, to remove some of the conservatism, a more detailed analysis of entrainment, dispersion, agglomeration, deposition and re-suspension must be performed under different weather conditions.

Releases from liquefied waste are on the same order of magnitude. The doses resulting from liquid releases are about an order of magnitude less than the doses resulting from an equal volume of solid releases (see Appendix R). Thus, the liquid releases are not further considered in the dome collapse accidents. Present analysis suggests that incoherence in the collapse may reduce the magnitude of the liquid release by a factor of 2. However, the extent of and effects from incoherence in a dome collapse pose questions that deserve more study.

The long-term entrainment from an open pool of waste following the dome collapse is bounded by 12.5 L/wk of solid resuspended respirable aerosol.

## 8.0. REFERENCES

1. W. Bohl and C. Unal, "Dome Collapse Accidents For Single-Shell Flammable Watch List Tanks," Los Alamos National Laboratory Calc-Note TSA6-CN-WT-SA-TH-108 (March 1996).

2. L. H. Sullivan et al., "A Safety Assessment for the Proposed Pump Mixing Operations to Mitigate Episodic Gas Releases in Tank 241-SY-101: Hanford Site, Richland, Washington," Los Alamos National Laboratory report, LA-UR-92-3196, Rev. 14 (March 31, 1995).

3. R. T. Perry, "Aerosol Mass in the Dome," Los Alamos National Laboratory Calc-Note TSA6-CN-WT-SA-TH-096 (December 1995).

4. K. O. Pasamehmetoglu, "Additional Dome Collapse Calculations For Single-Shell Flammable Watch List Tanks," Los Alamos National Laboratory Calc-Note TSA6-CN-WT-SA-TH-093 (December 1995).

5. J. D. Iverson, "Particulate Entrainment by Wind," Department of Aerospace Engineering, Iowa State University report Project 1699, ISU-ERI-Ames-85010, prepared for Los Alamos National Laboratory under Subcontract No. 9-X54-K9610-1 (July 1984).

6. D. R. MacFarlane, D. W. Stack, J. Kindinger, R. K. Deremer, S. R. Medhekar, and T. J. Mikschl, "Probabilistic Safety Assessment for Hanford High-Level Waste Tanks," Los Alamos National Laboratory report, LA-UR-95-1900, TSA-11-94-R110 (November 1995).

7. W. C. Hinds, *"Aerosol Technology, Properties, Behavior, and Measurement of Airborne Particles"* (John Wiley and Sons, New York, NY, 1982).

8. R. F. Schwab, "Dusts," Chapter 12, Section 3, from A. E. Cote, P. E., Editor-in-Chief, *Fire Protection Handbook* (National Fire Protection Association, Quincy, Massachusetts, 1992).

9. S. L. Sutter, "Accident Generated Particulate Materials and Their Characteristics—A Review of Background Information," Pacific Northwest Laboratory report NUREG/CR-2651, PNL-4154 (May 1982).

10. H. R. MacDougall, L. W. Scully, and J. R. Tillerson, "Preliminary Preclosure Radiological Safety Analysis," Appendix F in "Site Characterization Plan Conceptual Design Report," Sandia National Laboratory report SAND84-2641 (1987).

11. W. J. Mecham, L. J. Jardine, R. H. Pelto, G. T. Reedy, and M. J. Steindler, "Interim Report of Brittle-Fracture Impact Studies: Development of Methodology," Argonne National Laboratory report ANL-81-27 (October 1981).

12. L. J. Jardine, W. J. Mecham, G. T. Reedy, and M. J. Steindler, "Final Report of Experimental Laboratory-Scale Brittle Fracture Studies of Glasses and Ceramics," Argonne National Laboratory report ANL-82-39 (October 1982).

13. W. J. Mecham, L. J. Jardine, G. T. Reedy, and M. J. Steindler, "General Statistical Description of the Fracture Particulates Formed by Mechanical Impacts of Brittle Materials," *Ind. Eng. Chem. Fundam.*, **22**, pp. 384-391 (1983).

14. C. W. Young, "Equations for Predicting Earth Penetration by Projectiles: An Update," Sandia National Laboratory report SAND88–0013 (July 1988).

15. "Effects of Impact and Explosion," Summary Technical Report of Division 2, NDRC, Volume 1, Copy No. 247, U. S. Government War Department, Washington D. C. (Columbia University, Division of War Research, New York, New York, 1946).

16. L. J. Julyk, "Static Internal Pressure Capacity of Hanford Single-Shell Waste Tanks," Westinghouse Hanford Company report, WHC-SD-WM-TI-623 (August 1994).

17. E. A. Rodriguez, R. F. Davidson, and M. L. Walsh, "Comparison of ABAQUS and EPIC Nonlinear Transient Dynamic Models for a Hydrogen Burn Event of Hanford Site High-Level-Waste Tank 241-SY-101," Los Alamos National Laboratory report LA-UR-95-3441 (October 1995).

18. R. F. Davidson, M. L. Walsh, E. A. Rodriguez, "EPIC Hydrodynamic Code Modeling of Hanford Site HLW Tank 241-SY-101 for Bounding Hydrogen Detonation," Los Alamos National Laboratory draft report (December 1995).

19. D. A. Siebe, "Thermal Analysis of Rotary-Mode Core Drilling," Los Alamos National Laboratory Calc-Note TSA10-CN-WT-SA-TH-111 (February 1996).

20. M. A. Halverson and J. Mishima, "Initial Concepts on Energetics and Mass Releases During Nonnuclear Explosive Events in Fuel Cycle Facilities," Pacific Northwest Laboratory report PNL-5839, NUREG/CR-4593, US Nuclear Regulatory Commission (August 1986).

21. M. Y. Ballinger, J. W. Buck, P. C. Owczarski, and J. E. Ayer, "Methods for Describing Airborne Fractions of Free Fall Spills of Powders and Liquids," Pacific Northwest Laboratory report NUREG/CR-4997, PNL-6300 (October 1987).

22. U. S. Department of Energy, "Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities," U.S. Department of Energy Handbook DOE-HDBK-3010-94 (October 1994).

# APPENDIX J

# HYDROGEN DIFFUSION INTO DRILL STRING AND BURN/DETONATION ANALYSIS

## 1.0. INTRODUCTION

During the core-sampling operation, nitrogen will flow through the drill string and out the drill bit. The purpose of the nitrogen flow is to cool the drill bit, to provide the lift necessary to remove drill cuttings from the annulus bore, and to maintain a hydrostatic pressure at the drill bit to keep the waste out of the drill string during sampler change. During the sample retrieval process, the waste and flammable gases such as hydrogen, nitrous oxide, ammonia, and methane will flow into the drill string in case of loss of nitrogen flow. The gas concentration will reach the low flammable-gas limit, and a gas burn will occur if a spark is generated because of friction. The objective of this appendix is two-fold:

- To calculate the potential for flammable-gas accumulation in the drill string when the nitrogen purge system is lost; and
- To consider the possibility of transition from deflagration to detonation and to estimate the over-pressure ratio and the rate-of-pressure rise. The over-pressure ratio and the rate-of-pressure rise will be used as boundary conditions for the structure analysis.

## 2.0. HYDROGEN DIFFUSION INTO THE DRILL STRING

The following sections provide a summary of the analysis methodology and the results of the calculations for the hydrogen diffusion into the drill string.

### 2.1. Analysis

For constant density and diffusion coefficient and for no convective flow, Reference 1 gives the following governing equation for one-dimensional transient diffusion of species a into species b,

$$\frac{\partial c_a}{\partial t} = D_{ab} \nabla^2 c_a \quad , \tag{J-1}$$

where

$c_a$ = volumetric concentration of species a, kg-moles/$m^3$.
$D_{ab}$ = diffusion coefficient of species a into species b, $m^2/s$.

Given the assumptions above and for only one species diffusing into another, the volumetric concentration of the mixture will also be constant so that Eq. (J-1) can be rewritten in terms of mole fraction or volume fraction, assuming ideal gases.

$$\frac{\partial x_a}{\partial t} = D_{ab}\nabla^2 x_a \quad , \tag{J-2}$$

where

$x_a$ = mole fraction of species a.

If the flow area varies, but the diffusion process can be assumed to be one-dimensional, then Equation (J-2) can be rewritten as

$$\frac{\partial x_a}{\partial t} = \frac{D_{ab}}{\bar{A}}\frac{\partial}{\partial z}\left(A\frac{\partial x_a}{\partial z}\right) , \tag{J-3}$$

where

$A$ = flow area, which is a function of z, $m^2$ and
$\bar{A}$ = average flow area over the volume of interest, $m^2$.

For this problem, the initial condition is that the mole fraction of hydrogen in the drill string be zero. The boundary conditions are that the mole fraction of hydrogen at the bottom of the drill string (i.e. z = 0) be one and that the diffusion flux of hydrogen at the top of the drill string be zero, which implies the gradient of the mole fraction of hydrogen at z = L is zero.

Equation (J-3) is solved numerically.[2] An analytical solution to Eq. (J-2) with the initial conditions and boundary conditions given above exists. Comparison of the analytical solution with the finite-difference solution for constant flow area indicates that because of the numerical diffusion, the finite difference solution diffuses hydrogen faster than the numerical solution on the order of 10% absolute relative error, which is conservative.

The diffusion coefficient for hydrogen in nitrogen was obtained from curve fitting parameters to the CHEMKIN[3] database. These curve-fitting parameters indicate that the diffusion coefficient for hydrogen in nitrogen increases from 0.682 $cm^2/s$ at 20°C to 1.042 $cm^2/s$ at 90°C. A conservative value of 1 $cm^2/s$ was chosen for this analysis. The molecular diffusion coefficient varies as the inverse of the absolute pressure. For this analysis, a conservative pressure of 1 atm was chosen.

The diffusion of one species into another because of thermal gradients is governed by the thermal diffusion ratio. The mass flux of species a into species b because of a temperature gradient is given by Eq. (J-4) as,

$$j_a^{(t)} = -\left(\frac{c^2}{\rho}\right) M_a M_b D_{ab} k_T \nabla \ln T \ , \qquad \text{(J-4)}$$

where

$j_a^{(t)}$ = mass flux of species a into species b caused by a thermal gradient, $kg/m^2$-s,
$c$ = molar concentration of the mixture, kg-moles/$m^3$,
$\rho$ = density of the mixture, $kg/m^3$,
$M_a$ = molecular weight of species a, kg/kg-mole,
$M_b$ = molecular weight of species b, kg/kg-mole,
$k_T$ = thermal diffuse ratio, and
$T$ = gas temperature, K.

From Eq. (J-4) it can be seen that the sign of thermal diffusion ratio determines the direction of the thermal diffusion for a given species. If the thermal diffusion ratio is positive, then species a moves toward the colder temperature; when the thermal diffusion ratio is negative, then species a moves toward the hotter temperature. Experimental values for the thermal diffusion ratio for hydrogen diffusing into nitrogen caused by a thermal gradient are given in Reference 2 for 264 K as -0.0548 to -0.0663, depending upon the hydrogen mole fraction. The negative thermal diffusion ratio indicates that hydrogen caused by thermal gradients will diffuse toward a higher temperature region and nitrogen will diffuse toward the colder temperature region. Therefore, it is conservative to neglect this effect. Hydrogen will diffuse into a rotary-core drill string faster by neglecting the effect of diffusion caused by thermal gradients because the waste is anticipated to be at a higher temperature than the nitrogen gas in the drill string. An order of magnitude solution can be obtained based on a steady-state solution of the case in which the molecular diffusion is balanced by the thermal diffusion as,

$$\Delta x_a = -k_T \ln\left(\frac{T_2}{T_1}\right) \ , \qquad \text{(J-5)}$$

where

$T_2$ = hot gas temperature, K, and
$T_1$ = cold gas temperature, K.
$\Delta x_a$ = difference in steady-state hydrogen mole fraction at the hot temperature minus the hydrogen mole fraction at the cold temperature.

Evaluating Eq. (J-5) with experimental values in Reference 1 yields a difference in hydrogen mole fraction at a hot temperature minus the hydrogen mole fraction at a cold temperature at steady-state to be on the order of 1.4%. Therefore, the magnitude of the effect is not significant.

Based on past analyses, the buoyancy effect of hydrogen gas mixing with air or nitrogen is significant. The actual mixing of hydrogen with the drill-string nitrogen gas may be faster than the conservative diffusion calculation presented in this appendix. The actual mixing of retained gas with the drill-string nitrogen gas may be limited by how fast the retained gas can diffuse from the waste to the drill bit. However, if the drill bit is in a relatively large retained gas bubble, then diffusion and mixing of retained gas with the drill-string nitrogen gas will not be limited by diffusion of retained gas through the waste.

### 2.2. Results

Equation (J-3) was solved for two geometries. Both geometries were assumed to be 320 in., which represents the smallest length for the drill string to still be in contact with the waste. The small flow area geometry assumes that the seal in the bottom of the rotary-core drill string has failed completely and that the available flow area for diffusion of hydrogen into the drill string is an annulus with an o.d. of 1.82 in. and an i.d. of 1.78 in. Drill-string gas volume continues to be an annulus with a varying i.d. until the elevation is above the latching mechanism. For the bit-flow area geometry, the drill-string geometry is a cylinder at all elevations with a diameter of 1.91 in. and with an inlet flow for hydrogen diffusion equal to the available bit-flow area. The average hydrogen concentration in the rotary-core drill string as a function of time is given in Fig. J-1 for the small flow area geometry and the bit-flow area geometry. From Fig. J-1 it can be seen that for the bit-flow area geometry, the average concentration rises faster than for the small flow area geometry. The bit-flow area geometry case reaches an average flammable-gas concentration within 25 minutes, while the small-flow area case reaches an average flammable-gas concentration within 180.0 minutes.

Figure J-2 shows the results for hydrogen concentration versus axial level for selected times into the transient for the small-flow area case. You can see that the first few feet of the drill string that is an annulus for this case fills with hydrogen relatively quickly. The discontinuity in the slope of the results occurs when the geometry goes from an annulus to a cylinder. For the bit-flow area case, shown in Figure J-3, there is no discontinuity in the slope of the hydrogen concentration versus z curve, because the geometry is a uniform cylinder. By comparing Figs. J-2 and J-3, it can be seen that the larger inlet area for the bit-area case results in a larger diffusion rate of hydrogen into the drill string. Within 24 hours, both calculations indicate significant concentrations of hydrogen from the top to the bottom of the drill string.

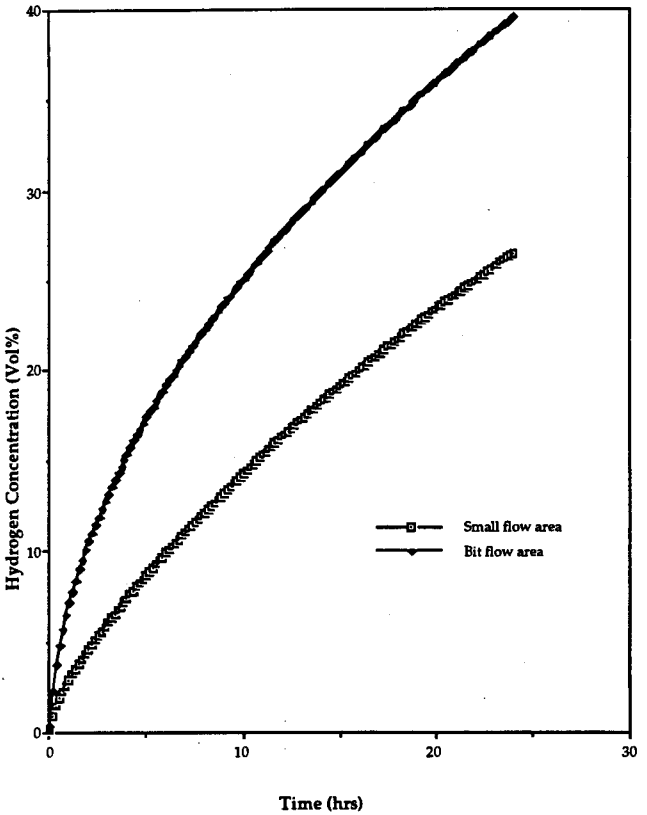


**Fig. J-1. Average hydrogen concentration in the drill string.**

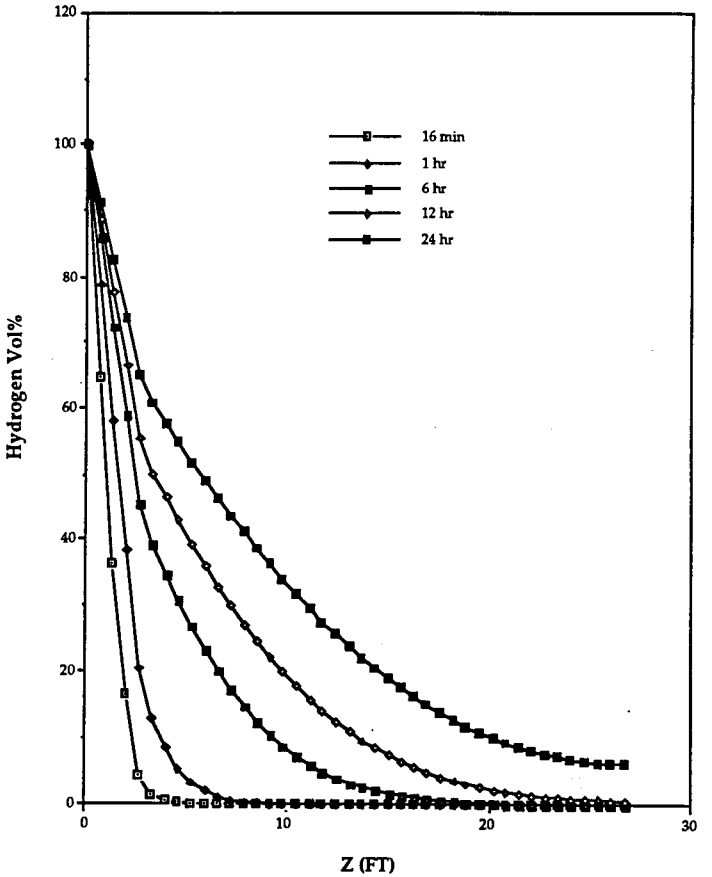


**Fig. J-2. Hydrogen volume fraction versus axial location for small flow area case.**

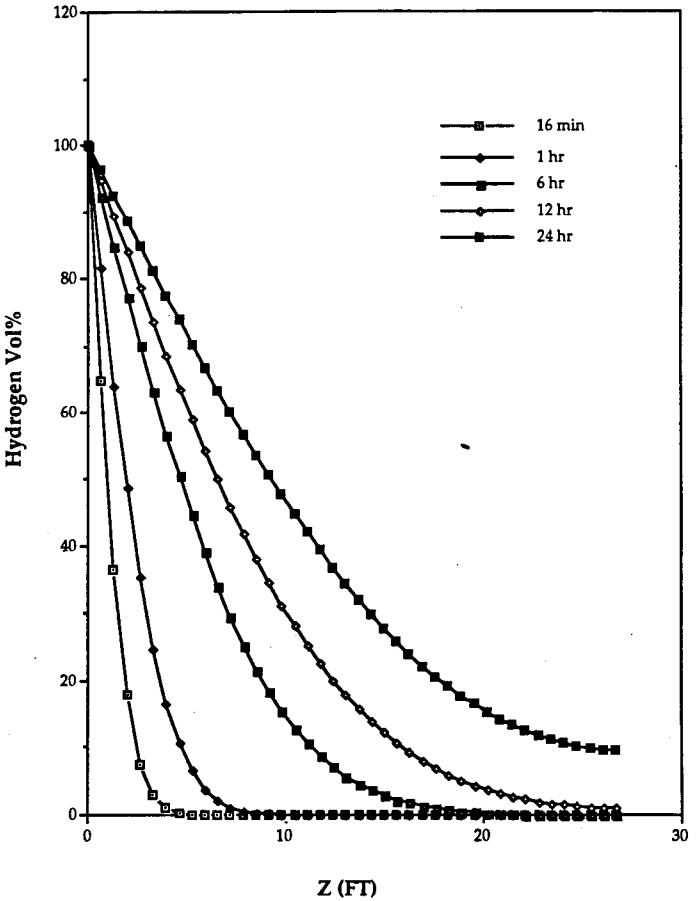


**Fig. J-3. Hydrogen volume fraction versus axial position for big flow area case.**

The maximum molecular mass-diffusion flux into the drill string occurs at the first-time step of each transient calculation. The following results were obtained for the maximum mass-diffusion volumetric flow of hydrogen into the rotary-core drill stream: (a) for a small-area case, 0.000122 cfm, (b) for a bit-flow area case, 0.000448 cfm.

An order-of-magnitude analysis can be used to verify these numbers. The mass-diffusion flux at the entrance to the drill string can be written as

$$j_a = -cM_a D_{ab} \nabla x_a \quad , \tag{J-6}$$

where $j_a$ = mass diffusion flux caused by the concentration gradient, $kg/m^2$-s.

Evaluating Eq. (J-6) for P = 1 atm, T = 303 K, a diffusion coefficient of 1 $cm^2/s$ and the gradient of the concentration profile on the order of -10 yields $j_a$ = 8.064e-05 $kg/m^2$-s or in terms of a volumetric flux yields, $q_a$ = 0.001 m/s of hydrogen.

For the small-flow area case, the inlet flow area is 0.000232 $m^2$ and for the bit-flow area case the inlet flow area is 0.00133 $m^2$, which results in a peak volumetric flow of hydrogen into the drill string caused by hydrogen diffusion of 0.000232 liters/s (0.000492 cfm) for the small-flow area case and 0.0009 liters/s (0.00019 cfm) for the bit-flow area case. These order-of-magnitude results are consistent with the numerical solutions to the transient diffusion equation.

Results obtained from Eq. (J-6) are independent of the pressure chosen because the molar concentration for an ideal gas mixture is proportional to the pressure, and the diffusion coefficient is inversely proportional to the pressure. However, the volumetric flux depends upon one over the density, and the density is directly proportional to pressure. Therefore, as pressure increases, density will increase, and the volumetric flow of hydrogen caused by diffusion will decrease.

## 2.3. Summary and Conclusions

A conservative estimate of the diffusion rate of hydrogen into the rotary-core drill string based on two different geometries indicates that within 20 minutes to 180 minutes, depending upon the inlet flow area, there will be a significant concentration of hydrogen within the drill string. It is a conservative assumption that the retained gas, which includes its own oxidizer, will diffuse as fast as hydrogen by itself. Based on this conservative analysis, the average retained-gas concentration within the rotary-core drill string following the failure of sampler chevron seal will exceed 4% within 180 minutes and following a nitrogen purge system failure with the test section removed, will exceed 4% within 20 minutes. Concentrations high enough to support a detonation (assuming an oxidizer is present) are reached within minutes in the first few feet of rotary-core drill string drilling for both cases, and the average concentrations for the rotary-core drill string reach detonation limits again, assuming an oxidizer is present within 3 to 11 hours.

The maximum diffusion flux of hydrogen into the rotary-core drill string occurs at the first-time step into the transient solution. The maximum volumetric flow of

hydrogen into the drill string was calculated for the bit-flow area geometry based on an order of magnitude analysis to be 0.00019 cfm.

## 3.0 BURN AND DETONATION ANALYSIS IN THE DRILL STRING

The assumptions for this analysis are as follows:

1. The nitrogen pressurization system failed to operate for more than 10 h;
2. A burn is generated by a spark resulting from metal friction in the drill string;
3. The gases in the drill string are well mixed; and
4. The fuel is hydrogen only; this assumption is reasonable because the hydrogen concentration may be very high, as discussed in Appendix C.

### 3.1. Burn Analysis

Burn can probably occur in two places in the drill string during a loss-of-nitrogen-flow accident. One is between the drill bit and the bottom of the universal sampler. The other one is between the top of the universal sampler and the ball valve. However, the geometry at both locations, which are the two closed ends of a pipe, is similar. Therefore, a 1D burn-combustion code can be used to analyze the problem and to estimate the overpressure and the-rate-of-pressure rise, dP/dt, in the drill string.

The problem was solved with GASBURN, which is a derivative of the GASFLOW code.[4] The code strips the chemical reaction subroutines in GASFLOW and solves the 1D hydrodynamic equations. The result calculated by GASBURN is given in Reference 5. The maximum overpressure is 30%, which is a little above the stoichiometric value of 29.5%.

In Reference 5, the pressure ratio calculated by the GASBURN code is compared with the data obtained by the Bureau of Mines (BOM).[6] The measured pressure ratio, which is defined as the ratio of maximum absolute explosion pressure to the initial pressure, is in good agreement with that calculated with the adiabatic constant-volume combustion model. If we convert the overpressure calculated by GASBURN to the pressure ratio, the pressure ratio calculated by GASBURN is in good agreement with that calculated by BOM. This comparison shows that the chemical reaction model in GASBURN is properly modeled.

We can either use the overpressure calculated by GASFLOW or the experimental data for the safety analysis. To estimate the overpressure in the drill string, we need to know the hydrogen concentration. In Section 2 of this appendix, we calculate a concentration of 30% when the axial position of the universal sampler is about 10 ft

above the rotary drill in about 12 h. The hydrogen concentration of 30% is the point at which maximum pressure occurs. The calculated overpressure is about 6.3 bars or 630 kPa.

For structure analysis, we need to estimate the rate of pressure rise in the drill string. The maximum rate-of-pressure rise, which is defined as $K_G = (dP/dt)V^{1/3}$ bar-m/s, is obtained from the BOM experiment. The maximum rate of pressure rise for 30% hydrogen is about 1120 bar-m/s (from the Appendix, "Detailed Listing of Flammability Test Data").[6] The i.d. of the test chamber is 2 ft. The volume of the test chamber is 4.1888 $ft^3$ or 0.118613 $m^3$. The rate-of-pressure rise is 2279.5 bar/s. It should be noted that the data of $K_G$ are scattered from 456 to 1120 bar-m/s.

The BOM data were obtained from a spherical chamber. However, the drill string is in cylindrical geometry. The BOM data may not be applicable to drill-string geometry. We used the GASFLOW code to calculate the over-pressure and the rate-of-pressure rise in a pipe of 1.91 in. in diameter and 10 ft in length. The over-pressure and the rate-of-pressure rise are ~9.0 bar and ~2280 bar/s. The results are similar to those calculated for a spherical chamber as above.

### 3.2. Detonation Analysis

Consider a tube with a very large length-to-diameter ratio (L/D) such as the drill string case containing a combustible mixture whose normal burning velocity is high relative to the velocity of sound of the unburned gas. With these circumstances, ignition at a closed end can cause the flame to accelerate to such an extent that a detonation eventually occurs in the tube. The phenomena of transition from deflagration to detonation is probably the least-understood aspect of detonation theory at this time. The critical parameters for controlling the transition are the tube diameter, the tube length, and fuel concentration. Detailed discussions of these parameters are given in Reference 7 and are summarized below.

The critical cell size in a detonation is a fairly easy quantity to measure. It ties with the chemical reaction rate having the gross macroscopic propagation behavior of detonations. The further a mixture is from stoichiometric, and hence the less energetic the chemical reaction, the larger is the detonation cell size. In Reference 8, the detonation cell size for a hydrogen-to-air mixture at atmospheric pressure is measured.[8] The minimum detonation cell width is about 0.6 inches. The required diameter for propagating the detonation wave is about one-third of the detonation cell width. Therefore, it only needs a 0.2-in.-diameter tube to propagate a detonation wave generated by a stoichiometric mixture. The i.d. of the drill string is much larger than that value. Hence, if any detonation generates in the drill string, it may propagate in the drill string.

The induction distances (the distances from the igniter to the location in the detonation tube where the flame propagation rate first attains detonation velocity)

are an important parameter to control wave propagation. If the tube is too short, then the wave never reaches it maximum velocity. Bollinger performed an experimental study to measure the induction distances in hydrogen nitrous oxide mixtures.[9] For a 79-mm i.d. tube, the induction distance for 30% hydrogen is about 200 cm. The ratio of induction distance to the tube diameter is about 23. The L/D for the drill string is about 60, which is much longer than the above ratio. Therefore, in the drill string, the wave speed may reach the detonation wave speed, which is about 2000 m/s for the stoichiometric mixture.

Hydrogen and air mixtures near stoichiometric ( ~ 29.5% hydrogen) are known to be detonable. Mixtures departing from stoichiometric, either in the hydrogen-lean or hydrogen-rich direction are increasingly more difficult to detonate. It has been generally believed that beyond certain mixture ratios of about 18% and 58% hydrogen, hydrogen and air mixtures could not be detonated. As shown in Section 2 of this appendix, the hydrogen concentration in the drill string reaches 30% in 16 minutes at 2 ft above the rotary drill. One operation of drilling takes about 30 minutes. By that time, the hydrogen concentration is already above 18%. Therefore, any burn in the drill string may detonate.

Akbar and Shepherd performed an experiment to study deflagration-to-detonation transition (DDT) using the gas mixture similar to the 101-SY waste gas mixture (42.8% $H_2$, 36.4% $N_2O$, and 28.8% $N_2$) with various dilutions.[10] This study shows that the waste gas mixture produced DDT up to 50% of dilution with air. The waste gas composition may contain higher concentrations of hydrogen (see Appendix C). Therefore, DDT may be produced in the drill string.

Theoretical detonation pressure for hydrogen-to-air mixtures in a pipe can be calculated through a numerical method by solving the differential equation for isentropic compression in the burn gas. Reference 8 shows the theoretical detonation pressure and temperature, and reflected detonation pressure and temperature for hydrogen-to-air mixtures. The pressure ratio is about 15 at 30% $H_2$ before the pressure wave is reflected back from the tube end. The final over-pressure is about 15 bars. Using the detonation velocity 2000 m/s (see page 2-50, Ref. 7) and a detonation cell with 10 mm, the rate-of-pressure rise is about $3 \times 10^6$ bar/s. It should be noted that we did not use the reflected pressure because an increase in the rate of first compression pressure is high enough to fail the structure of the drill string.

### 3.3. Conclusions

From the above analysis, the overpressure and the rate-of-pressure rise during a burn in the drill string are 630 kPa and 2279.5 bar/s, respectively. During a detonation in the drill string, the overpressure and the rate-of-pressure rise are 15 bars ($1.5 \times 10^6$ Pa) and $3 \times 10^6$ bar/s, respectively. A DDT may occur in the drill string. Therefore, any burn in the drill string may result in a detonation because the rate of

pressure rise is very high ($3 \times 10^6$ bar/s) during the detonation. Consequently, the structure of the drill string may fail and cause partial dome failure.

## 4.0. REFERENCES


1. R. B. Bird, et.al., "Transport Phenomena," (John Wiley & Sons, New York, NY 1960).

2. J. W. Spore, "Bounding Hydrogen Diffusion Analysis in Rotary Core Drill String," Los Alamos National Laboratory TSA-10 Calc-Note TSA-CN-WT-SA-GR-048 (December 1995).

3. R. J. Kee and J. A. Miller, "A Structured Approach to the Computational Modeling of Chemical Kinetics and Molecular Transport in Flow Systems," Sandia National Laboratory report SAND86-8841 (December 1993).

4. J. R. Travis, K. L. Lam, and T. L. Wilson, "GASFLOW: A Three-Dimensional Finite-Volume Fluid-Dynamics Code for Calculation of the Transport, Mixing, and Combustion of Flammable Gases in Geometrically Complex Domains," Los Alamos National Laboratory report LA-UR-94-2207 (July 11, 1994).

5. J. C. Lin, "Drill String Detonation," Los Alamos National Laboratory Calc-Note TSA10-CN-WT-SA-GR-050 (January 1996).

6. K. L. Cashdollar, et. al., "Laboratory Flammability Studies of Mixtures of Hydrogen, Nitrous Oxide, and Air," Westinghouse Hanford Company report WHC-SD-WM-ES-219, Rev. 0 (June 1992).

7. A. L. Camp, et. al., "Light Water Reactor Hydrogen Manual," Sandia National Laboratories report NUREG/CR-2726, SAND82-1137 (June 1983).

8. C. M. Guirao, et. al., "Hydrogen-Air Detonations," presented at the 1982 International Combustion Symposium, Haifa, Israel (1982).

9. L. E. Bollinger, J. A. Laughrey, and R. Edse, "Experimental Detonation Velocities and Induction Distances in Hydrogen-Nitrous Oxide Mixtures," *ARS Journal*, Vol. 32, 81-82 (1962).

10. R. Akbar and J. E. Shepherd, "Detonation in N2O-H2-N2-Air Mixtures," Rensselaer Polytechnic Institute, Department of Mechanical Engineering report prepared for Los Alamos National Laboratory under contract C-4836 (June 18, 1993).

# APPENDIX K

# TOXICOLOGICAL CONSEQUENCE ANALYSIS METHODOLOGY

## 1.0. INTRODUCTION

This appendix discusses the methodology used in quantifying the toxicological consequences of accidental releases during rotary-mode core sampling (RMCS) operations.

## 2.0. METHODOLOGY

The methodology provided in References 1 and 2 are adopted for consistency with other safety basis documents used at the Hanford Site Tank Farms.

### 2.1. Release of Toxic Gases

For gaseous releases, the receptor doses are obtained as

$$C = \frac{\frac{\chi}{Q}}{1 + V \times \frac{\chi}{Q}} \times S \times V \quad , \tag{K-1}$$

where C is the receptor dose,
$\chi/Q$ is the atmospheric dispersion factor given in Table K-1,
V is the gas-release volume (puff release) or gas-release volume flow rate (continuous release), and
S is the species concentration at the source.

For $(V)(\chi/Q) << 1$, which is the case for the accidents analyzed in this safety assessment (SA), Eq. (K-1) reduces to

$$C = \frac{\chi}{Q} \times S \times V \quad . \tag{K-2}$$

The atmospheric dispersion coefficients are obtained using the computer code GXQ, which uses the methods in the Nuclear Regulatory Commission (NRC) Regulatory Guide 1.145 (Ref. 3). The atmospheric dispersion coefficient is the time-integrated normalized air concentration at the receptor for toxicological releases. For puff releases, the atmospheric dispersion coefficient is the instantaneous maximum concentration at the receptor. Only the plume meander correction was used in the calculations. The coefficients used to calculate dose or concentration are presented in Tables K-1. The acute release values were developed for weather

conditions that result in downwind concentrations exceeded only 0.5% of the time in the maximum sector (16 sectors) or 5% of the time for the overall site. The larger of the two values was used as the integrated bounding value for on-site and off-site individuals. The chronic annual average $\chi/Q$ values were obtained by calculating chronic annual average values for each sector and using the highest one for calculation purposes. The value is suitable for long-term releases but not for accidents. All the releases analyzed in this safety assessment (SA) are either puff releases or releases that occur in less than 1 h. Thus, the plume meander correction or the chronic annual average values for the atmospheric dispersion coefficients are not used.

TABLE K-1
DISPERSION COEFFICIENTS

| RECEPTOR | Continuous Release $\chi/Q$ ($s/m^3$) | Puff Release $\chi/Q$ ($1/m^3$) |
|---|---|---|
| On-site | 3.44 E-02 | 9.85 E-03 |
| Off-site | 1.88 E-05 | 4.45 E-08 |

Reference 2 suggests that releases with a duration of less than 3.5 s must be treated as puff releases for the on-site receptor. Likewise, releases less than 420 s must be treated as puff releases for the off-site receptor.

This SA is also interested in releases from a 5-m (15-ft) tall stack. The atmospheric dispersion coefficients for this problem are not provided in References 1 and 2. The AI-RISK model,[4] which was previously used in the Tank 101-SY Mixer Pump SA,[5] was used to obtain the atmospheric dispersion coefficients for the stack releases.

For a ground point source release with no initial momentum and buoyancy, the 95% atmospheric dilution coefficient for a 100-m receptor is obtained as 3.26 E-02 using AI-RISK.[6] Thus, the AI-RISK results are in good agreement with the atmospheric dilution coefficient given in Table K-1 for an on-site receptor. There is no concern about off-site values because for toxic-gas releases analyzed in this SA, the off-site consequences are always less than 1 ppm (Sec. 5) and taking credit for the stack release in the calculation is not necessary. Table K-2, obtained from References 6 and 7, summarizes the AI-RISK results for the conditions of interest.

The receptor doses for a 1 $m^3$ or 1 $m^3/s$ release of a pure toxic gas and summarized Table K-3 were obtained using the atmospheric dilution coefficients given in Tables K-1 and K-2.

### 2.2. Release of Toxic Solid/Liquid Waste

To determine the acceptance limits for liquid/solid waste material, WHC uses different types of composite waste for different tank groupings.[2] The risk associated

with waste releases is divided into three categories: particulate, toxic effects, and corrosive effects. The chemical species in the composite waste are divided into toxic and corrosive bins. Within each bin, the allowable releases are computed using the "sum of the fractions" methodology. The minimum among the three categories (particulate, toxic, and corrosive) is chosen in each frequency range. For further details on the methodology used in determining the maximum acceptable waste releases, the readers are referred to Reference 2. The resulting maximum acceptable releases for single-shell tank liquid and solid releases are given in Table 5-4 in Section 5 of this SA. Note that the values reported in Table 5-4 represent the release quantities at the source because the atmospheric dispersion coefficients already are factored in arriving at these magnitudes.

**TABLE K-2**
**ATMOSPHERIC DISPERSION COEFFICIENTS OBTAINED FROM AI-RISK**

| Release Type | $\chi/Q$ ($s/m^3$) |
|---|---|
| GROUND RELEASE, D = 0 m, V = 0.1 m/s, T = 300 K | 3.26 E-02 |
| STACK RELEASE (15 ft), D = 0 m, V = 0.1 m/s, T = 300 K | 5.12 E-03 |
| STACK RELEASE (15 ft), D = 0 m, V = 1 m/s, T = 300 K | 5.12 E-03 |
| STACK RELEASE (15 ft), D = 0.3 m, V = 0.1 m/s, T = 300 K | 5.03 E-03 |
| STACK RELEASE (15 ft), D = 0.3 m, V = 1 m/s, T = 300 K | 4.24 E-03 |
| STACK RELEASE (15 ft), D = 0.3 m, V = 10 m/s, T = 300 K | 1.05 E-03 |
| STACK RELEASE (15 ft), D = 0.1 m, V = 15 m/s, T = 300 K | 2.20 E-03 |
| STACK RELEASE (15 ft), D = 0.1 m, V = 23 m/s, T = 300 K | 1.31 E-03 |

D: source diameter, V: source vertical velocity, T: source temperature

**TABLE K-3**
**RECEPTOR DOSES FOR A 1-$m^3$ or 1-$m^3$/s TOXIC-GAS RELEASE**

| | ON-SITE (ppm) | | OFF-SITE (ppm) | |
|---|---|---|---|---|
| RELEASE TYPE | Cont. | Puff | Cont. | Puff |
| Ground, D = 0 m, V = 0.1 m/s | 34,400 | 9850 | 19 | 5 |
| Stack, D = 0 m, V = 0.1 m/s | 5120 | 5120 | 19 | 5 |
| Stack, D = 0.3 m, V = 0.1 m/s | 5030 | 5030 | 19 | 5 |
| Stack, D = 0.3 m, V = 1 m/s | 4240 | 4240 | 19 | 5 |
| Stack, D = 0.3 m, V = 10 m/s | 1050 | 1050 | 19 | 5 |
| Stack, D = 0.1 m, V = 15 m/s | 2200 | 4240 | 19 | 5 |
| Stack, D = 0.1 m, V = 23 m/s | 1310 | 1050 | 19 | 5 |

## 3.0. REFERENCES

1. "Tank Waste Composition and Atmospheric Dispersion Coefficients for Use in Accelerated Safety Analysis Consequence Assessment," Westinghouse Hanford Company report WHC-SD-WM-SARR-016, Rev. 1 (October 1995).

2. "Toxic Chemical Considerations for Tank Farm Releases," Westinghouse Hanford Company report WHC-SD-WM-SARR-011, Rev. 1 (October 1995).

3. "Atmospheric Dispersion Models for Potential Accident Consequence Assessments at Nuclear Power Plants," US Nuclear Regulatory Commission Regulatory Guide 1.145, (USNRC, Washington, DC 1982).

4. Y. Y. Chien, and D. MacFarlane, "AI-RISK: A Computer Program for Calculating Doses and Health Risk from Accidental Release of Radioactive Materials," Los Alamos National Laboratory report LA-UR-92-2636, (July 1992).

5. L. H. Sullivan et al., "A Safety Assessment for the Proposed Pump Mixing Operations to Mitigate Episodic Gas Releases in Tank 241-SY-101: Hanford Site, Richland, Washington," Los Alamos National Laboratory report LA-UR-92-3196, Rev. 14 (March 31, 1995).

6. C. Unal, "Evaluation of Atmospheric Dispersion Coefficients at Elevated Discharge Temperatures, Velocities, Diameters and Release Heights by Using AI-RISK Computer Program," Los Alamos National Laboratory Calc-Note TSA10-CN-WT-SA-TH-078 (August 1995).

7. C. Unal, "Toxicological Consequences of Ammonia and Nitrous Oxide Releases During Rotary Mode Core Sampling," Los Alamos National Laboratory Calc-Note TSA10-CN-WT-SA-TH-104 (January 1996).

# APPENDIX L

# PROBABILITY OF GAS-RELEASE EVENTS DURING INTRUSION

## 1.0. BACKGROUND

In this appendix, a probabilistic model is developed to determine the gas-release event (GRE) characteristics during an intrusive operation in flammable-gas single-shell tanks (SSTs). Undoubtedly, some SSTs may have a GRE likelihood and consequences that are much lower than the ones obtained in this appendix. However, a tank-by-tank analysis was not the intent of this appendix.

As discussed below, there is very limited empirical information to develop such a probabilistic model based on data alone. Consequently, the model incorporates "expert judgment" combined with

- the limited data during intrusive activities in flammable-gas tanks,
- the information gained from laboratory experiments with simulants, and
- a general understanding of gas retention and release mechanisms in SSTs.

Because the approach has limited empirical support, the current model must not be used for eliminating safety features or defense-in-depth controls until further knowledge can be gained. The probabilistic model is merely intended for use in comparing the bounding consequences against the Westinghouse Hanford Company (WHC) Risk Guidelines (RGs) that require a realistic estimate of frequencies and allow for qualitative estimates for phenomena for which there are a lack of data. This safety assessment (SA) was developed using the following step-wise approach:

1. The most important issue is to develop a spark-management strategy that is appropriate for a hazardous flammable-gas environment such as the one summarized above and detailed in Appendix B of this SA.

2. The quantification of the reliability of the equipment used to protect against burns also must provide reasonable assurance that all practicable preventive measures are taken against burn accidents. It is believed that the equipment failure probabilities on the order of $10^{-4}$ to $10^{-5}$ per operation is acceptable, considering the type of operation. Appendices D and E show that this objective also is achieved in this SA.

3. The probabilistic GRE model discussed in this appendix was introduced only after the completion of these first two steps in order to derive realistic accident frequencies.

The order in which these steps are taken is identical to the order in which this SA was developed. This order should not be reversed until further data and understanding for SST gas retention and release mechanisms are available.

In SSTs, burn accidents result in unacceptable consequences because even a small pressurization in the dome may result in dome failure, potentially followed by a catastrophic collapse. In order to meet the RGs, one must demonstrate that such burn accidents have a frequency of less than $10^{-6}$/yr. However, burn accidents are not the only accidents that may result in dome failure. The design basis earthquake (DBE) has a return period of 7500 yr (frequency > $1 \times 10^{-4}$/yr). SSTs are designed to withstand a 0.20-g ZPA (zero-period acceleration), but there is high probability that a DBE of magnitude 0.20 g may produce structural failure of the dome because of potential cracks that occurred immediately after back-filling. Thus, the baseline dome collapse frequency for the SSTs is ~$10^{-4}$/yr, and this frequency is independent of rotary-mode core sampling (RMCS). Even if one assumes that the failure frequencies are equivalent to burn and dome collapse frequencies, the dome collapse risk is less than the base-line risk associated with a DBE as discussed above. Introducing the GRE probability only demonstrates that the incremental risk is negligible compared to the base-line risk.

The next stage is to convert the failure probabilities into accident frequencies. The major accidents in the flammable-gas tanks are burn accidents that require the existence of a flammable-gas mixture combined with an equipment failure resulting in a spark. In order to obtain realistic accident frequencies, one needs to know the probability of experiencing flammable-gas atmosphere in the regions where sparks can exist. Unfortunately, the potential gas-release volume, gas-release rate, and gas composition data necessary to develop such a model for SSTs are scarce. Likewise, the gas retention and release mechanisms for SSTs are not fully understood so that one may develop a realistic or bounding model of an expected GRE during waste intrusive activities. On the other hand, through the limited data obtained during similar intrusive activities, through educated estimates of the waste contents and properties pertinent to gas retention and gas release, and through laboratory experiments conducted with simulants, it is possible to obtain an expert opinion on the likelihood of GREs during intrusive activities.

In order to determine the GRE probability model, the recent data available from intrusive operations in flammable-gas SSTs and double-shell tanks (DSTs) was considered. The data and the conclusions are summarized in the next section. In Section 3, the probability distributions are obtained based on the implications of the limited data and "expert interpretation" of the existing knowledge. Section 4 summarizes and concludes this appendix.

## 2.0. AVAILABLE SOURCE OF INFORMATION

There are some data obtained during intrusive activities in SSTs that can be used to develop likelihood arguments for the GREs. Likewise, there is a limited amount of modeling performed for the gas retention and release mechanisms in the SSTs. However, given the uncertainty of the physical and chemical properties of the waste, such theories also must be used in accounting for large uncertainties associated with the quantitative results.

### 2.1. Summary of Available Data

WHC Characterization Field Engineering screened the recent flammable-gas concentration data obtained during and after intrusive activities in flammable-gas DSTs and SSTs.[1] A total of 49 intrusive sampling events (core sampling and auger sampling) alone were evaluated for 21 tanks sampled. One possible evidence of a GRE was observed in tank level data (A-103). Waste surface or liquid level drops for 34 of the sampling events showed no GRE. During 12 of the events, the plots had insufficient or non existent data on which to draw a conclusion. During two of the events, minor changes were observed during sampling activities, but the changes were well within the normal data scatter. Only one change for Tank A-103 during March of 1986 was questionable. The waste surface showed a 2.4 in. drop between March 24 and March 31, 1986. The level drop occurred when the lower segment samples were removed on March 25 to March 26, 1986. During the second core taken on March 31 through April 3, no level drop was observed.

No GREs were evident based on temperature data. Twenty-six of the activities' plots showed no evidence of a GRE activity. For 23 events the plots either had either insufficient or nonexistent data on which to draw a conclusion. If a rollover type of GRE were to have occurred, that would have been observed in the temperature data.

Tank vapor space monitoring data indicated three of the seventeen tanks monitored using a combustible gas meter (CGM) or other hydrogen monitoring equipment during waste-intrusive activities showed a very minor increase in the flammable-gas concentration during the sampling event. Three events showed small gas releases estimated to be ~50 $ft^3$. The dome vapor space never exceeded 9% of the lower flammability limit (LFL) during any of these events.

All the sampling activities contained in the database took place in tanks from the Flammable Gas Watch List (FGWL) or tanks recommended for the FGWL. Seventeen of these tanks are SSTs.

Reference 1 also provides observations during 38 liquid observation well (LOW) installations in SSTs in 1984. The database includes LOW installation in all the Flammable Watch List tanks except AX-103, which currently has a waste level of 42 in. During these activities, no flammable-gas monitoring was done. The temperature data are all insufficient to draw any conclusions, or are nonexistent. Waste surface level

drop data showed that a GRE did not occur in 23 of the 38 installations. During seven events, the data were insufficient to draw any conclusions. During another seven events, small variations (well within the normal data scatter) were observed. Only one level change for SX-104 on May 24, 1984, was questionable. The waste surface showed a 2.1 in. drop. The data show that the level dropped on 1 to 8 days before the LOW installation. However, the potential exists that the data logs might have been off for a couple of days, and that the level drop actually occurred during the LOW installation.

Typically, ammonia can be smelled at 20 ppm. At higher concentrations, the smell can cause discomfort. No strong ammonia odor problem was reported during these activities. Because the SSTs typically do not have an active ventilation system, even small concentrations of ammonia in the dome space may result in exceeding the smell detection levels above an open riser. However, considering most of these activities took place more than ten years ago, it is likely that such occurrences (if they existed) are not in the data logs.

Likewise, no complete or partial temperature inversion (typical of rollovers) was observed during these activities. Also, no perturbations in the local temperature that would indicate waste motion were observed.

Unfortunately, these data cannot be formalized into a complete statistical model. The benefit of these data is to suggest that, qualitatively, a large GRE resulting in hazardous flammable-gas concentrations in the dome space is not a likely event during the intrusive activities. Quantitatively, the data may be used in a number of different ways:

It can be stated that 2 out of 87 activities resulted in a detectable GRE, suggesting a frequency of $2.3 \times 10^{-2}$. Accounting only for the activities in the SSTs, the probability becomes 2 out of 77 ($2.6 \times 10^{-2}$). Also subtracting the activities in which the level data were inconclusive, the probability becomes 2 out of 58 ($3.4 \times 10^{-2}$). However, this approach does not apply to a bounding tank, and at best it provides an overall probability of a GRE in the flammable-gas tanks. The SOWs are installed in A-101 (waste level ~345 in.) and AX-101 (waste level 278 in.), which have the largest waste volumes in the SSTs that are on the original FGWL. If one were to postulate that the retained gas volume is proportional to the waste volume, no GRE during intrusion into these tanks would be interpreted as encouraging. Tank A-103, which showed a 2.4 in. level drop between March 25 and March 26, 1986, also has a large waste volume (waste level ~370 in.). The other possible 2-to 3-in. level drop corresponds to Tank SX-104 that has less than 240 in. of waste.

A 3-in. level drop would correspond to 1600 $ft^3$ of gas release, assuming that the gas is originally compressed at 1.5 atm. Unfortunately, the level measurements were not taken frequently enough to estimate the release rate. No dome pressure data were reported in Reference 1 to assess the gas-release rate based on dome pressurization.

Another pertinent set of data analysis is provided in Reference 2. In this study, all the data from the original FGWL tanks were screened for GRE behavior. The study concluded that the tanks can be categorized in four groups:

Category 1: The tanks that exhibit neither periodic release behavior nor waste growth. Tanks 103-AX, 111-S, 112-S, 103-SX, 106-SX and 109-SX are in this category.

Category 2: The tanks that do not exhibit waste growth, but periodic release behavior is indeterminate. Tanks 101-AX, 101-SX, 102-SX, 103-SX, 104-SX and 105-SX are in this category.

Category 3: Tanks that exhibit periodic release behavior. Only Tank 101-A is in this category. These tanks exhibited 2-to 3-in. surface level variations between 1988 and 1993 that may be indicative of slow periodic releases.

Category 4: Tanks that exhibit waste growth but do not exhibit periodic release behavior. Tanks 102-S, 110-T, 103-U, 105-U, 107-U, 108-U, and 109-U are in this category.

It must be noted, however, that Reference 2 was primarily interested in natural GRE behavior as opposed to a GRE during an intrusion. Recent detailed analysis of the waste level history in Tank A-101 indicates that the observed level fluctuations are possibly not a result of periodic releases. They are likely to be caused by random measurement errors. [3]

## 2.2. Summary of Available Simulant Experiments

The experience with SST waste simulants is primarily developed at Pacific Northwest National Laboratory (PNNL). The discussion below provides a summary of the PNNL experience to date with SST simulants.** The simulants are aimed at simulating the physical characteristics of SST waste (sludge and salt cake) as opposed to chemical properties. The simulants are typically prepared using various clay, bentonite, and water mixtures, and gas is generated with the use of hydrogen peroxide.

Simulant experiments have been conducted to measure the retained fraction of gas generated within a simulant as a function of shear strength. These experiments were conducted without an overlying supernatant layer, which is typical of many SSTs. The results show that essentially all the generated gas is retained until a maximum retention capacity of the sludge is reached. Beyond the point of maximum retention, which is about 35% void, any additional generated gas and some of the retained gas is released. The results show that the maximum gas retention depends on the sludge shear strength.

** Private communications with P. Gauglitz (PNNL) and K. Pasamehmetoglu (LANL) (February 1996) and a desk-top demonstration by P. Gauglitz (PNNL) at the January 17, 1996, Flammable Gas Data Review meeting.

For the strongest sludges, the maximum retention is about 30% void. The maximum retention increases to a peak value of about 40% void as the sludge strength decreases. Together, these data show that sludges are quite capable of retaining a high void fraction of gas, and it can be inferred that it is difficult to release bubbles trapped in the sludge. To date, a few very qualitative experiments have been conducted in which small rods are inserted into the waste to initiate a release. These experiments have shown that the intrusion releases a small amount of retained gas, and that the release comes out of a region immediately adjacent to the intrusion.

Another interesting set of simulant experiments conducted by PNNL is related to the effect of the supernate thickness on the rollover strength. Some SSTs show a thin layer of supernate on top of the sludge layer. The experiments show that with thick supernate layers the rollover is quite energetic, and a substantial amount of gas is released. On the other hand, the rollovers with thin supernate layers are very un-energetic, and very little gas (if any) is released during the rollover.

While developing a rigorous statistical model based on simulant experience alone is not appropriate, the simulant data are quite valuable in developing a best-estimate prediction for the GRE behavior in SSTs.

### 2.3. Summary of Available Models

The DSTs on the FGWL all indicate that there may be a convective layer over the nonconvective layer where the gas is trapped. The prompt gas-release mechanism is postulated to be the density inversion or the Rayleigh-Taylor instability.[4] The observation of the axial temperature profiles and the waste types that are in the SSTs do not support the Rayleigh-Taylor instability as being a likely gas-release mechanism. Likewise, the waste-level history of the SSTs does not show rather rapid level increases followed by sudden level drops that were observed, for instance, in Tank 101-SY during and after a rollover.

A necessary condition for a rollover is the existence of a density inversion, where a layer becomes less dense than the layer above it. This implies that the layer above has been able to release gas generated in it, while the layer below is retaining the generated gas. In an SST with a significant supernatant layer or convective layer (CL), then most of the gas generated in that layer will be released. If the layer below the supernatant or CL has sufficient strength to retain most of the generated gas, a density inversion can develop. A rollover will result when the hydrostatic forces between the two layers are sufficient to cause the lower layer to flow as a fluid. This illustrates the second condition necessary for a full tank rollover; the lower layer waste strength must be large enough to retain gas, but not large enough to preclude fluid flow under hydrostatic forces. If the lower layer strength is too large, then a full tank rollover does not occur and gas is released through local eruptions and/or mini-rollovers. Without a significant supernatant level or CL, it is possible in an SST that there be significant variations in waste properties between two layers so that the upper layer releases gas while the lower layer retains gas. However, if this were occurring, then a continuous

level growth would be observed until the rollover of the lower layer. Also, even during an unlikely event of a rollover in an SST, the rollover is expected to progress very slowly, and gas-release rates are expected to be much smaller than the gas-release rates observed in DSTs (e.g., 101-SY).

A semi-qualitative evaluation of gas-release mechanisms in SSTs is provided in Reference 5, which suggests that while rollover is possible in the SSTs, it is not a likely mechanism. Because of the limited volume of the supernatant liquid, during an unlikely rollover event, the gas releases would be small. Also unlikely is a mechanism whereby large bubbles (1 m diameter) are stored in the waste and released during an intrusion. Intrusion into the largest expected bubble based on conservative estimates of waste properties, indicates that 350 $ft^3$ of retained gas could be released over an ~20 minute time period. The total release during this unlikely mechanism also is postulated to be small. The most likely mechanism that could lead to a large gas release appears to be a "mud pot" fed by dendritic bubbles if a chimney is opened to the dendritic bubble region as a result of the intrusion. The calculations reported in Ref. 5 indicate that 700 $ft^3/h$ releases may be expected through this "unlikely" mechanism. Finally, the fracture of a dry sludge or dry salt cake are other possible, but unlikely, mechanisms quoted in Ref. 5. Releases through this mechanism are estimated to be at a smaller rate than the 700 $ft^3/h$ value obtained for the "mud pot" mechanism.

During RMCS operations, the drill string is rotated at 55 rpm and a nitrogen purge flow of 30 $ft^3/min$ is used. If it is assumed that the drill string disturbs a region that is 20 times its diameter (4 in.) and is inserted at 2 in./min, the gas volume disturbed would be ~1 $ft^3/min$ (assuming a conservative void of 20% in the waste) resulting in a total release of less than 200 $ft^3$. However, nitrogen purge also may scrub soluble ammonia out of the waste. Conservatively, assuming that the ammonia partial pressure in the waste is 0.6 atm and that ammonia comes in equilibrium with nitrogen instantaneously, an ammonia release rate may be obtained as 45 $ft^3/min$. This value is in agreement with the conservative magnitude obtained in Ref. 6. However, such a high ammonia release rate would be possible until the liquid immediately around the drill string is depleted and a mass transfer resistance to ammonia forms in the liquid. Thus, the total release volume would be < 500 $ft^3$ (Ref. 6). Based on these discussions, one could argue that the release rates during RMCS would be ~1 $ft^3/min$ for insoluble gases. Large ammonia releases rates are possible for a short period during drilling.

Among the 19 SSTs that are on the original FGWL, A-101 has the largest waste volume. Based on the available data, a data reconciliation analysis for the gas inventory of A-101 was performed.[3] The results indicate that the gas inventory estimate for A-101 is 6300 $ft^3$ with a standard deviation of 1300 $ft^3$. Thus, the gas inventory for this tank, at two standard deviations level, would be less than 9000 $ft^3$.

The gas-release mechanisms during salt well pumping (SWP) of A-101 are discussed in Reference 7. During SWP operations, liquid waste will drain from the waste into the salt

well and reduce the effective hydrostatic head as seen by the retained gas bubbles. The reduced hydrostatic head and liquid level in the waste can be related to the gas-release volume and rate. Gas-release rates for a given liquid drainage rate depend upon the assumed bubble size and distribution. Based on a range of assumed conditions the calculated gas-release rate was typically less than 1 to 2 $ft^3$/min.

## 3.0. PROBABILISTIC MODEL

In this section, the knowledge developed by the limited data, limited modeling results, and the expert-judgment are set into a probabilistic model. In order to develop a probabilistic model of reaching or exceeding hazardous conditions in the dome space, one needs probabilistic models for the gas-release rate, the gas-release volume, and the gas composition. These models may then be combined into a hydrodynamic model of dome space to compute the consequences of different-sized gas releases.

First, the discussion provided in the previous section is cast into a qualitative model. The qualitative likelihood matrix is provided in Table L-1.

TABLE L-1
QUALITATIVE LIKELIHOOD MATRIX FOR GAS-RELEASE VOLUMES AND RATES

| | Volume ($ft^3$) | | | |
|---|---|---|---|---|
| Rate ($ft^3$/min) | 100 | 500 | 2500 | 10,000 |
| 1 | Expected | Unlikely | Very Unlikely | Extremely Unlikely |
| 10 | Unlikely | Unlikely | Very Unlikely | Extremely Unlikely |
| 100 | Very Unlikely | Extremely Unlikely | Extremely Unlikely | Extremely Unlikely |
| 1000 | Extremely Unlikely | Extremely Unlikely | Nearly Impossible | Nearly Impossible |

The gas-release volume break-down in Table L-1, is based on unnoticeable level drop (100 $ft^3$), 1 in. level drop (~500 $ft^3$), 5 in. level drop (2500 $ft^3$) and nearly 20 in. level drop (10000 $ft^3$). The data that is considered in Section 2.1. shows that a level drop > 2.5 in. was not observed in any of the intrusive activities covered in the database.

The rate range shown in Table L-1 is obtained by considering the orders-of-magnitude, based on the discussions provided in the previous section. Even at slow release rates, larger release volumes are less likely because:

1. Typically release will occur from the waste volume immediately around the intrusive device, and

2. Flammable gas monitors will detect the gas release and terminate waste penetration, which is expected to stop the induced gas release.

For release volumes that are never observed in the SSTs, a qualifier of "very unlikely" is assigned. The existing models do not predict release volumes corresponding to very unlikely and less likely categories, except for a rollover and seismic event that can liquefy the waste by vigorous shaking. Even for these very unlikely events the release volume is limited by the fraction of total retained gas. The maximum values shown in Table L-1 (10,000 $ft^3$) corresponds to the largest GRE volume observed in Tank 101-SY before mitigation. Similar events have not been observed in any of the SSTs.

The rate range shown in Table L-1 is obtained by considering the orders-of-magnitude, based on the discussions provided in the previous section. Only rollovers and seismic shaking may result in release rates on the order of 100 $ft^3$/min or greater, while resulting in large release volumes. There is a remote possibility of tapping into a high pressure gas region which may result in large release rates but a very small volume. Thus, while small volume releases at high releases rates are believed to be extremely unlikely, large volumes with large releases rates are nearly impossible.

The qualitative matrix may be quantified for the gas-release volume and gas releases rates assuming that these two are independent parameters. In the quantification process, the following probabilities were assigned: a probability of 1 for expected events, $10^{-1}$ for unlikely events, $10^{-2}$ for very unlikely events and $10^{-3}$ for extremely unlikely events. Thus, the quantitative results may be approximated as a logarithmic distribution given by

$$P(Q' \geq Q) = \left(\frac{Q}{100}\right)^{-1.5} \quad \text{for} \quad Q \geq 100\ ft^3. \tag{L-1}$$

Likewise, the release rate may be approximated by a logarithmic distribution given by

$$P(q' \geq q) = (q)^{-1} \quad \text{for} \quad q \geq 1\ ft^3/min. \tag{L-2}$$

### 3.1. Effect of Release Volume and Release Rate on Dome Concentrations

This section, the relationship between the gas-release rates and the peak dome concentrations are quantified. In order to quantitatively assess the reduction in the flammable-gas inventory, the following simple mathematical model is used for the dome space waste gas concentration: [8]

$$V\frac{dX}{dt} = q - X \cdot f \quad , \tag{L-3}$$

where V is the dome volume = 1416 $m^3$ (50,000 $ft^3$),

X is the dome-averaged waste gas concentration,
t is the time,
q is the waste gas-release rate into the dome, and
f is the ventilation flow rate.

For simplicity, it is assumed that the gas-release rate is constant and the gas release is modeled as a pulse function as illustrated in Fig. L-1. Thus, the gas release is characterized by the following parameters (only two of them are independent): q: gas-release rate, T: gas release duration, and Q: total gas-release volume (Q = q x T).

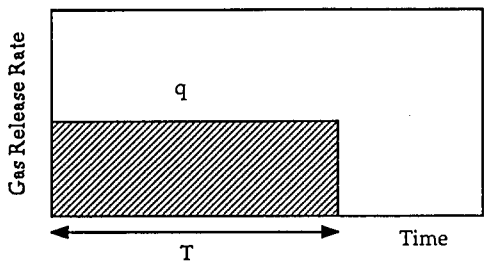


**Fig. L-1. Gas-release rates as a function of time.**

The solution for Eq. (L-3) is obtained as

$$X(t) = \begin{cases} \frac{q}{f}\left[1-\exp\left(-\frac{f}{V}t\right)\right] & \text{if } 0 \le t \le T \\ \frac{q}{f}\left[1-\exp\left(-\frac{f}{V}T\right)\right]\exp\left[-\frac{f}{V}(t-T)\right] & \text{if } t > T \end{cases} \qquad \text{(L-4)}$$

where it is assumed that the initial concentration in the dome (before the beginning of the gas-release event) is zero. The peak dome concentration is obtained as

$$X_{max} = \frac{q}{f}\left[1-\exp\left(-\frac{f}{V}T\right)\right] = \frac{q}{f}\left[1-\exp\left(-\frac{f}{q}\frac{Q}{V}\right)\right] . \qquad \text{(L-5)}$$

If q > f (which is always the case when active ventilation is not available), the discharge rate is set equal to the gas-release rate during a gas-release event. Thus, the solution of Eq. (L-3) becomes

$$X(t) = \begin{cases} 1-\exp\left(-\frac{q}{V}t\right) & \text{if } 0 \le t \le T \\ \left[1-\exp\left(-\frac{q}{V}T\right)\right]\exp\left[-\frac{f}{V}(t-T)\right] & \text{if } t > T \end{cases} \quad \text{(L-6)}$$

The peak concentration for this case becomes

$$X_{max} = 1-\exp\left(-\frac{q}{V}T\right) = 1-\exp\left(-\frac{Q}{V}\right) \quad . \quad \text{(L-7)}$$

As shown by Eq. (L-7), when the gas-release rate is greater than the ventilation flow rate, the peak concentration is independent of the release rate and is a function of the release volume only. This is also illustrated in Fig. L-2 that shows the peak dome concentrations for Q = 2000 $ft^3$ (Q/V) = 0.04 as a function of q/f. As shown in this figure, for q/f > 0.4, the peak concentration is nearly independent of the gas-release rate. At q/f < 0.4, the peak concentration rapidly decreases with decreasing q/f. But even at q/f = 0.1, the peak concentration decreases to 3.3% compared to the maximum value of 3.9%.

Based on these discussions, one could argue that, for a ventilation flow rate of 200 $ft^3$/min, for gas releases > 10 $ft^3$/min, the gas-release rate has a minimum effect on the final results. On the other hand, for gas releases around 1 $ft^3$/min, the ventilation flow substantially suppresses the peak concentration for an extended period of time. The peak concentration in the dome for a 1 $ft^3$/min gas-release rate would be 5000 ppm, regardless of the release volume.

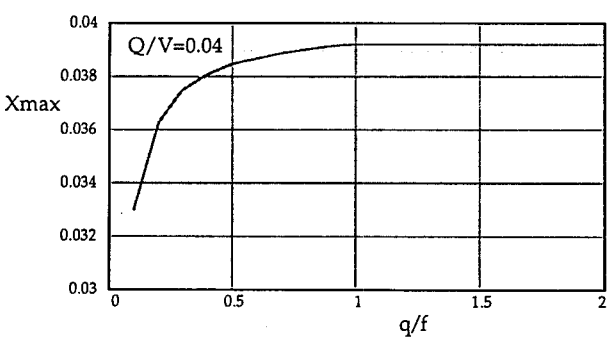


**Fig. L-2. Peak dome concentration as a function of gas-release rate.**

### 3.2. Gas Composition

There is considerable uncertainty in the gas composition as discussed in Appendix C. The maximum hydrogen concentration may be as high as 90% (App. B). However, that estimate assumes that there is no nitrogen, ammonia, or water vapor in the release gas (all of those species are known to exist in the waste gases). Without any ammonia, the LFL for this hydrogen-rich mixture would be 4%. Based on discussions provided in Appendix C, a bounding ammonia fraction of 60% may be used for the SSTs.

Adding ammonia (that is also known to exist) reduces the LFL but reduces the amount of hydrogen volume in the release. The net effect is that the most conservative case is the maximum hydrogen in the waste gas even though the LFL for that mixture is the highest. While it is still bounding, the use of 50% hydrogen in the waste gas would be a good estimate for probability calculations. In the subsequent analysis, a uniform distribution is used for hydrogen between 50% and 90% and conservatively assume that the rest of the gas is ammonia. Neglecting the other gas species, which are also known to be generated in the waste, provides an additional degree of conservatism in the above calculations.

### 3.3. Time-at-Risk Estimates

Another important parameter for the burn probability estimates is the time-at-risk. The time-at-risk is the period of time when the dome volume remains above the LFL. The results of the ventilation study documented in Ref. 8 are shown in Fig. L-3 for different release volumes. For this example, it is assumed that the ventilation flow rate is 250 $ft^3$/min and that the dome volume is 50000 $ft^3$. The hydrogen concentration in the release gas is 90%, and the LFL is 4%. Figure L-3 is provided as an example without crediting the expected low release rates. The results of more detailed calculations are given in the next section.

## 4.0. RESULTS

A code was written to perform the following tasks:

(1) perform Monte Carlo sampling from probability of frequency distributions for: gas-release rate, gas volume, and gas composition,
(2) calculate dome gas thermodynamic properties for each set of sampled gas release values, and
(3) bin the calculated thermodynamic gas properties into various bins to provide probability of frequency distributions for these thermodynamic properties.

Equation L-1 was used for the probability of frequency distribution for the gas-release volume. Equation L-2 was used for the probability of frequency distribution for the gas-release rate. The exhauster was assumed to run continuously through the GRE. Stopping the drilling operations upon detection of flammable gases and potentially stopping the gas release is not modeled. Using information from WHC, the exhauster

flow rate was set at 200 $ft^3$/min and the initial tank pressure was set at -0.5 in. w.g. Nitrogen cooling flow to the drill bit was set at 35 $ft^3$/min. The details of the analysis are provided in Ref. 9.

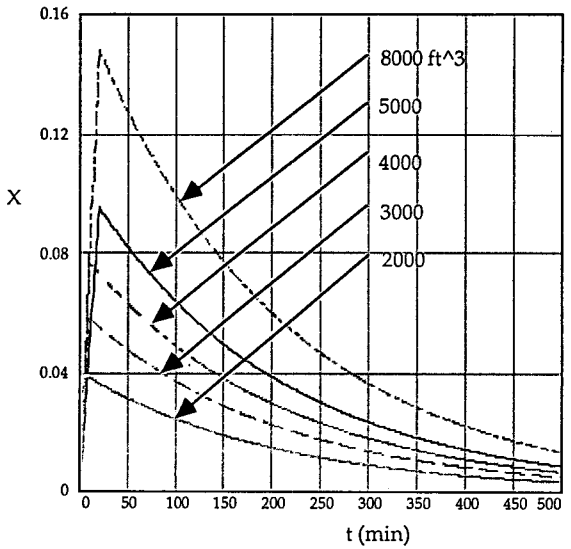


**Fig. L-3. Dome space concentration as a function of release volume and time.**

A uniform probability density function was used for the fraction of hydrogen in the gas between a lower limit of 0.5 and an upper limit 0.9. The fraction of the gas that was not hydrogen was assumed to be ammonia.

In these calculations, a uniform dome mixing was assumed. Three-dimensional analysis show that for ventilation flow rates ≥ 200 $ft^3$/min, the release gases mix fairly uniformly in the dome space.[10]

### 4.1. LFL Results

A sample size of 400,000 was used. The probability that LFL is exceeded in the dome and that the tank pressure is positive was calculated to be 7.0E-5. The probability of exceeding twice the LFL is 3.5E-5.

The mean time that LFL was exceeded in the dome was calculated to be 0.12 minutes. Using a mission time of 144 hours, this implies that the probability that LFL is exceeded during an event that is random in time is: 0.12/(144*60) = 1.4E-5.

In these calculations, a conservative estimate of the LFL is used to define the hazardous conditions because the calculations given in Ref. 10 shows that the release gases mix fairly uniformly in the dome space with a ventilation flow rate ≥ 200 $ft^3$/min. Thus, as long as the ventilation is operable, the probability of a plume burn in or above the dome space is very unlikely. However, if the ventilation system fails, the probability of a plume burn in the dome increases as uniform mixing in the dome may not occur.

There are two accident scenarios for failed ventilation:

1. Ventilation fails without tripping the drilling operations which subsequently causes a GRE;

2. Ventilation fails during a GRE; and

3. Ventilation is intentionally shutdown because of high flow (> 250 $ft^3$/min)

The simple calculations given in Appendix C show that, the dome pressure limit may be exceeded a waste gas volume of 1000 $ft^3$ is burned in the dome space. This volume corresponds to a dome concentration greater than 25% of the LFL. Using the above models, the probability of exceeding 25% of the LFL in the dome space is < 5E-2. The combined probability of ventilation failure (conservatively estimated as 0.1/activity) and failure to shutdown the drilling operations (1.4E-3) is estimated as 1.4E-4 per activity. Thus, the frequency of exceeding 25% of the LFL during RMCS operations without ventilation is 7E-6/activity, which is an order of magnitude smaller than the frequency of exceeding the LFL.

For the second scenario, the mean time above the LFL and 25% of the LFL are obtained as 0.12 min and 5 min, respectively, during an activity. Using the conservative estimate of 0.1 failure per activity (144 h), the failure probability during the time period while the dome is above the LFL is 1.4E-6. The failure probability while the dome is above 25% of the LFL is 5.8E-5. These numbers are smaller than the probability of exceeding the LFL while the ventilation is operable.

Finally, the intentional exhauster trip is considered in the analysis. The exhauster trips if the flow rate exceeds 250 $ft^3$/min. During a rapid gas release event, the exhauster flow rate is expected to exceed the nominal 200 $ft^3$/min flow rate. The probability of exceeding the 250 $ft^3$/min flow rate is calculated as 2.5E-3. The probability of exceeding the 250 $ft^3$/min flow rate for more than 1.5 min is calculated as 4E-5. The exhauster trip is delayed by 5 minutes once the 250 $ft^3$/min limit is exceeded. This design feature minimizes the possibility of loss of exhauster resulting from excessive flow during a GRE.

### 4.2. Toxic Gas Releases

To provide information for evaluating release of toxic gas, the code was run with a fixed concentration of 60% ammonia and a sample size of 50,000. The results are summarized in Table L-2.

TABLE L-2
PROBABILISTIC RESULTS FOR DOME SPACE AMMONIA CONCENTRATIONS

| Concentration Bins | Positive Dome Pressure | Negative Dome Pressure |
|---|---|---|
| 0 - 6000 ppm | 6.2E-03 | 9.7E-01 |
| 6000 - 10,000 ppm | 5.2E-04 | 1.8E-02 |
| 10,000 - 25,000 ppm | 2.4E-04 | 5.9E-03 |
| 25,000 - 50,000 ppm | 1.0E-04 | 5.6E-04 |
| > 50,000 ppm | 2.0E-05 | 1.0E-04 |

### 4.3. Conclusions

In this appendix, a quantification of the GRE probabilities are presented based on the best-estimate interpretation of the state of knowledge of gas releases during intrusion in the SSTs. The probability values quoted in this appendix may be used in evaluating the best-estimate accident frequencies in comparing the conservative accident consequences with the risk guidelines. An uncertainty analysis is not performed because such an analysis is not required for accident frequency estimates. However, although point estimate GRE probabilities are combined with failure rate frequencies in Section 4 of this SA, the GRE probabilities must be viewed as order of magnitude estimates. At least an order of magnitude uncertainty must be considered in making decisions critical to the safety of the RMCS operations.

In the accident analysis (Section 4 of the SA), two probability numbers were used. For potentially continuous (if the GRE is undetected) spark sources, the probability of exceeding the LFL is used as 7E-5. For spark sources that are random in time, the ratio of mean time at risk to the total mission time (144 hrs) is used as 1.4E-5. This analysis is based on the assumption that a waste intrusive event triggers a large enough GRE to result in exceeding hazardous conditions. Without intrusion, a natural release that exceed LFL is assumed to be less likely than an event during intrusion. A detailed analysis of Tank 101-A level data indicate that periodic natural releases in that tank are very unlikely[3] and the maximum level changes are not sufficient to result in a GRE that exceeds the LFL. However, all the tanks are not analyzed to the same level of detail as tank A-101. Consequently, GRE probability is a checklist item that must be addressed for each specific tank (see Section 7 of this SA).

## 5.0. REFERENCES


1. J. S. Schoefield, "Evidence of Release Events During Waste Intrusive Activities in Flammable Gas Watch List (FGWL) and Proposed FGWL Tanks," Westinghouse Hanford Company internal memorandum to B. Barton (February 21, 1996).

2. B. D. Nichols, S. W. Eisenhawer, and J. W Spore, "Bounding Gas Release Calculations of Flammable Gas Watch List Single-Shell Tanks," Los Alamos National Laboratory report, LA-UR-94-1323 (1994).

3. W. L. Kubic, "Summary, Review and Analysis of Data for Tank 241-A-101," Los Alamos National Laboratory Calc-Note, TSA10-CN-WT-SA-DA-001 (January 1996).

4. L. H. Sullivan et al., "A Safety Assessment for the Proposed Pump Mixing Operations to Mitigate Episodic Gas Releases in Tank 241-SY-101: Hanford Site, Richland, Washington," Los Alamos National Laboratory report LA-UR-92-3196, Rev. 14 (March 31, 1995).

5. R. T. Allemann, "A Discussion of Some Mechanisms for Sudden Gas Release from Single-Shell Waste Tanks," Pacific Northwest Laboratory letter report PNL-WTS-101095 (October 1995).

6. J. D. Hudson, B. J. Palmer, and C. W. Stewart, "The Potential for Flammable Concentrations of Ammonia Resulting from Core Drilling Operations," Pacific Northwest National Laboratory letter report PNL-WTS-112295 (November, 1995).

7. J. W. Spore, "Conservative Gas Releases for Tank 241-A-101," Los Alamos National Laboratory Calc-Note, TSA10-CN-WT-SA-GR-046 (January 1996).

8. K. O. Pasamehmetoglu, "Issues Associated with the Use of An Exhauster During Saltwell Pumping Activities in Single-Shell Tanks that are on the Flammable Gas Watchlist" Los Alamos National Laboratory Calc-Note, TSA10-CN-WT-SA-TH-107 (January 1996).

9. J. L. Darby, "Monte Carlo/Thermodynamic Model for Dome Gases", Los Alamos National Laboratory Calc-Note TSA10-CN-WT-SA-TH-114 (February 1996).

10. P. Sadasivan, "Effects of Exhauster Flow Rates on Consequences of a GRE in 101-A," Los Alamos National Laboratory Calc-Note, TSA10-CN-WT-SA-GR-054 (February 1996).

# APPENDIX M

# UNFILTERED RELEASES AND NITROGEN ADDITIONS

## 1.0. INTRODUCTION

In this appendix, the unfiltered releases are quantified and the effect of nitrogen addition are discussed during rotary-mode core sampling (RMCS) operations. First, in the next section, the amount of aerosol that is suspended in the dome space during RMCS operations is discussed.

## 2.0 DOME LOADING DURING RMCS OPERATIONS

During drilling operations, aerosols will be carried into the dome. Some will be transported to the high-efficiency particulate air (HEPA) filter, while others will settle out on the crust. In this appendix, an estimate is given of the bounding value for the mass of aerosols to be found in the tank dome during drilling operations.

The TRAC-TE code was developed by Science Applications International Corporation to calculate the mass of aerosols that would be carried to the HEPA filter during drilling operations. Part of the results output from the code is the mass of aerosols found in the dome under various operating conditions. This code and the results of calculations are discussed in Reference 1; however, this code is not available to us at this time. Thus, the analysis presented in these notes is based on the results of analyses using the TRAC-TE code found in Reference 1.

In Appendix G of Reference 1, the results for two relevant bounding cases of salt drilling, calculated using TRAC-TE, are presented. The two relevant cases presented are based on 700 scfm flow. The results are based on a total drilling depth of 266 inches and a schedule of 40 minutes of drilling (19 inches) followed by 60 minutes delay before starting the next drilling period. In Case 1, Appendix G-1 of Reference 1, the exhauster is on only during drilling, but in Case 2, Appendix G-2 of Reference 1, the exhauster is on continually. The results take into account the settling of the aerosol created and the flow of material up the stack to the HEPA filter. The cases are referred to as bounding because they maximize the amount of material transported to the stacks. The results for the first 700 minutes, i.e., seven drilling and waiting periods for these two cases are given here in Table M-1. Note that equilibrium has been reached.

The results in Table M-1 have simply been extracted from Appendix G-1&2 of Reference 1. The results given are the amount of material in the dome, up the stack, or cumulative grams made airborne at the end of the time period given. The amount of material made airborne in any 40 minute drilling period, 3106 grams, is the total amount drilled minus the 1 in. diameter sample. This would be a 2.5 in. diameter and 19 in. long cylinder less the 19 in long and 1 in diameter sample.

TABLE M-1
GRAMS OF AEROSOL IN THE TANK DOME AND GRAMS TRANSPORTED UP TO STACK FOR 700-scfm FLOW

| Time (minutes) | Total (grams made airborne) | Case 1 on during drilling (grams in dome) | Case 2 continuous exhauster (grams in dome) | Case 1 on during drilling (grams up stack) | Case 2 continuous exhauster (grams up stack) |
|---|---|---|---|---|---|
| | | | | | |
| 40 | 3106 | 249 | 249 | 131 | 131 |
| 100 | 3106 | 44 | 17 | 0 | 59 |
| 140 | 6212 | 262 | 254 | 149 | 138 |
| 200 | 6212 | 52 | 19 | 0 | 62 |
| 240 | 9318 | 266 | 255 | 152 | 138 |
| 300 | 9318 | 55 | 19 | 0 | 62 |
| 340 | 12424 | 267 | 255 | 154 | 139 |
| 400 | 12424 | 56 | 19 | 0 | 62 |
| 440 | 15530 | 267 | 255 | 154 | 139 |
| 500 | 15530 | 56 | 19 | 0 | 62 |
| 540 | 18636 | 267 | 255 | 154 | 139 |
| 600 | 18636 | 56 | 19 | 0 | 62 |
| 640 | 21741 | 268 | 255 | 154 | 139 |
| 700 | 21741 | 57 | 19 | 0 | 62 |

An exhaust flow of 250 scfm (rather than a flow of 700 scfm) with continuous exhauster flow is closer to actual operating conditions. The amount of material going into the stack over the entire time period, i.e., 1440 minutes, for the 250 scfm case is given in Table 2 of Reference 1, but the amount of material in the dome is not presented. In Table 2 of Reference 1, the same information is given for 700 scfm and has been taken from the results presented in Appendix G-2 of Reference 1. However, it is the equilibrium material in the dome at 250 scfm that is of interest here, and this value will be determined below.

The material given that goes into the stack, according to Reference 1, contains only those particles with a diameter less than 5.5 μm. Reference 1, page 11, states, "These values assume that the low transport velocities in the exhaust riser can carry only smoke sized particle, 5.5 μm and less, out the riser." Note that this is conservative since the objective here is to determine the maximum amount of material in the dome.

From Table 2 of Reference 1, the amount of material going up the stack is 901 grams for the 250-scfm case and 1741 grams for the 700-scfm case at the end of 1440

minutes. Thus, when the flow is 250-scfm, only 52% of the material flows out the stack when compared with the flow in the 700-scfm case for continuous exhauster flow.

Referring to Table M-1, note that for Case 2 at equilibrium there are 255 grams in the dome and 139 grams going up the stack. If the flow is reduced to 250 scfm, then it is assumed that 48% (100%-52%) of this 139 grams will remain in the dome. Because some of this material will also settle, a conservative first estimate value of material in the dome is:

$$255g + 0.48 \times 139\ g = 322\ g.$$

Note that there is a compounding factor. Table 2 of Reference 1 is based only on those particles less that 5.5 μm. However, Table M-1 here assumes that all size particles flow up the stack. Referring to Table G-2 of Reference 1, it is found that 39% of the mass of airborne particles calculated to escape are larger than 5.5 μm at the end of the 700 minutes. It is expected that this mass to remain in the dome. Thus, as a bounding value, this mass should also be added to the mass in the dome. Thus, the bounding value for the material in the dome is:

$$255\ g + 0.39 \times 139\ g + 0.48\ (0.61 \times 139\ g) = 350\ g.$$

This calculation states that 39% of the material that is calculated to go up the stack will not do so because of size, and it is assumed that it will remain in the dome. Of the remaining 61% that would go up the stack in the 700-scfm case, 48% will remain in the dome in the 250-scfm case of interest here. This material that was earlier calculated to go up the stack is assumed not to settle out of the dome.

A less conservative value may be found by assuming a fraction of this material now remaining in the dome will settle out. An estimate of the amount that may settle out is 94%, which is based on the results given in Appendix G-2 in Reference 1. Thus, the less conservative, but more realistic, value is

$$255\ g + 0.06[\ (0.39 \times 139\ g + 0.48(\ 0.63 \times 139\ g)] = 261g.$$

Hereafter, the bounding value of material found in the dome during drilling operations is 350 g for the continuous exhauster operation at 250 scfm. Prior to RMCS operations, there may be additional suspended waste in the dome. To bound the background concentration, 600 g (1.32 lb) of aerosol in the tank dome is used. This number is used in the safety assessment of mixer pump operations[2] in the 101-SY tank and is based on a very conservative fog limits during a rollover. Typically, quasi-steady particulate concentrations less than 100 $mg/m^3$ are expected for SSTs. For a 1416-$m^3$ (50,000-$ft^3$) dome, the maximum amount would be 142 g (0.31 lb). Note that the unfiltered releases discussed in the next section are inversely proportional to the dome volume. Consequently, they are directly proportional to

the concentration and the releases would not be affected by the larger dome volumes. Thus, total aerosol in the dome during RMCS operations may be bounded conservatively by ~0.6 kg (1.3 lb).

## 3.0. UNFILTERED RELEASES

The following unfiltered releases are considered in this appendix:

- Release as a result of a gas-release event (GRE) during operation or removal (including material entrained from the drill string as a result of decontamination system failure);
- Continuous release from the exhauster after HEPA failure; and
- Continuous releases during open riser period with ventilation failure.

Releases from spill accidents or HEPA filter failures are considered separately.

### 3.1 Unfiltered Releases Caused by a GRE

Unfiltered releases can occur in operation and removal. During installation, before intruding into the waste, a gas release event is not expected; therefore, only the operation and removal phase will involve unfiltered material releases.

One can estimate the amount of material entrained out of the tank during a GRE using the following simple equation:

$$M_T = M_o \frac{Q}{V} \quad , \qquad \text{(M-1)}$$

where Q is the total gas release into the dome, $M_o$ is the initial dome loading [0.6 kg (1.3 lb)], and V is the dome volume [1415.8 $m^3$ (50,000 $ft^3$) based on Reference 3]. This simple model is based on the following assumptions:

1. The aerosol waste generated by the drilling and the waste gas released during a GRE are homogeneously mixed in the dome space;
2. The waste gas mixes homogeneously in the dome during a GRE;
3. The gas release rates are high enough to pressurize the dome [which is conservative for GREs expected in the single-shell tanks (see App. L)]; and

4. All the suspended material flows out of an open riser that is not protected by a HEPA filter (this is also very conservative because the inlet and exhaust headers are equipped with HEPA filters).

Using the probabilistic model developed in Appendix L combined with the conservative assumptions listed above, the resulting waste release from an open riser is tabulated as a function of the gas release as shown in Table M-2.

TABLE M-2
UNFILTERED AEROSOL RELEASE AS A FUNCTION OF GAS RELEASE

| Frequency (per activity) | GRE Volume ($ft^3$) | Material Release (g) | Release Rate (g/s) |
|---|---|---|---|
| $10^{-2}$ (anticipated) | 1000 | 12 g | 0.013 |
| $10^{-4}$ (very unlikely) | 5000 | 60 g | 0.07 |
| $10^{-6}$ (extremely unlikely) | 10000 | 120 g | 0.13 |

The release rates are computed for toxicological consequence analysis which require a 15-min average value. Thus, it is assumed that the total release occurs over a 15-min period. This assumption is conservative because the release rates for the three cases analyzed about would be greater than 66 $ft^3$/min, 333 $ft^3$/min, and 666 $ft^3$/min, which are comparable to 101-SY rollover releases.[2] Such high release rates are not expected for the SSTs (see Appendix L).

These releases are applicable to removal and operation time periods. During operation, however, the nitrogen purge system must fail for an unfiltered release to occur through the open riser. Thus, the likelihood of an unfiltered release during operation is much lower than a release during removal.

Another scenario is concerned with a GRE during removal with a contaminated drill string. The amount of waste on the drill string (inside or outside) during removal could vary. Under normal conditions, waste should not be inside, and the outside is decontaminated. If the decontamination is not effective or failed and a GRE occurs during removal, additional waste would be entrained from the contaminated drill string. To estimate the entrainment, it is assumed that there is a 3-mm-thick waste layer on one 19-in. drill rod. Note that each drill rod is removed individually. The total amount of waste on one drill rod becomes 370 g. It is assumed that 1% of this amount would be entrained resulting in an additional 3.7 g. This scenario assumes the failure of decontamination and seal or sampler latching. Thus, the frequency of the additional release is much lower than the frequencies listed in Table M-2. Considering the conservative assumptions made in obtaining the results in Table M-2, any additional releases resulting from decontamination failure combined with a GRE are neglected.

### 3.2. Continuous Release through the Exhauster After HEPA Failure

This scenario is concerned with the releases through the exhauster if the HEPA filters fail. The failure of the HEPA filters will be detected by the high flow or low pressure drop readings. Failure to shut down the exhauster will result in unfiltered material release. The frequency of this accident is dominated by the failure to shut the exhauster down following a HEPA failure, which is in the unlikely to extremely unlikely range. The maximum ventilation flow rate is 250 $ft^3$/min (0.12 $m^3$/s). Based on a 1-kg (2.2-lb) dome loading, a continuous release of 0.08 g/s will be experienced. Thus, the consequences of material release caused by a GRE bounds this accident.

### 3.3. Continuous Release with Ventilation Failure

If the riser is open and the gauge pressure inside the tank becomes positive, an unfiltered release will occur. Ventilation system failure with open-tank conditions has been identified as one of these conditions. Controls are established to help ensure that this kind of release is minimized. No operation can be started if the ventilation system is not working properly. However, the ventilation system can fail during the periods when the riser is open. If the ventilation system were to fail to maintain pressure inside the tank at less than atmospheric pressure, the continuous generation of gases in the tank would cause a release. In comparison to other releases driven by a GRE, this release is small. The gas release out of an open riser as a result of natural convection and steady-state gas release out of the waste is expected to be bounded by 0.03 $m^3$/s (60 $ft^3$/min), resulting in a material release of 0.02 g/s. The frequency of this accident is also small (in the unlikely to extremely unlikely range). The consequences of material release caused by a GRE bounds this accident.

## 4.0. NITROGEN ADDITIONS

Nitrogen addition is of concern because it may (1) result in dome pressurization, and/or (2) cause a gas release.

Nitrogen gas is added to the tank during normal RMCS operations. Nitrogen is added to the waste at a rate of 30 to 50 $ft^3$/min. Each sampling may take from 2 to 38 minutes. It is assumed an average drilling period of 10 minutes in the reliability study. This safety assessment (SA) assumes that two full sampling activities will be performed in a tank per year. Each sampling activity would include 11 samples. Thus, the drilling time per year per tank would be 220 minutes. The total nitrogen addition into waste during drilling is 11,000 $ft^3$ per year using a maximum flow rate of 50 $ft^3$/min.

The hydrostatic head also supplies nitrogen with a flow rate of 0.3 $ft^3$/min. Removing samples is assumed to take 2 hours. For two samples, the total nitrogen

addition per day would be 72 $ft^3$. This is a relatively small amount added during drilling. The riser will be purged with about 5 $ft^3$/min. However, this will be added to the tank dome.

Past experience in air additions to Tank 101-SY can be used in understanding the expected response of the tank caused by nitrogen injection.[4] From 1987 to 1989, Tank 101-SY was air-lanced periodically. In 1989, the air lancing was performed almost daily. This air-lance data from each air-lancing operation was examined that introduced 28.3 $m^3$ (1000 $ft^3$) of air into the waste. Examination of the level data indicates that there is no systematically observed pattern, in terms of change of waste level, with respect to the air lancing. The level does not always increase or decrease after each air-lancing operation. Generally the level continued to increase (in an average sense) until a small or a big GRE occurred. In some cases, the level tended to stay constant or decreased slightly after several days following the air lancing. However, these small changes were insignificant because they did not change the level-time plot significantly.

The observations above suggest that introducing air in the waste does not immediately cause a rollover with a significant gas release. Adding air to the waste is expected to increase the level growth rate. This conclusion assumes that some fraction of added air will remain entrapped in the waste as bubbles. The added nitrogen can stay in the waste or rise to the surface depending upon the yield stress of the waste. In a worst-case condition, the released nitrogen can form large bubbles (Ref. 5) and gives criteria for a spherical bubble to move.

The bubble diameter-yield stress relation is plotted in Fig. M-1. This figure illustrates that large bubbles can be created if the yield stress of the waste sludge is high (and if it exists). There is a possibility that released nitrogen can be held in the waste, especially at the bottom of the tank where the yield stress is thought to be relatively high. The total amount of nitrogen added during RMCS is significant. If this nitrogen is somewhat retained in the waste, a GRE initiated by a rollover could be observed. However, note that the daily gas-generation rate in a full tank is expected to be around 100 $ft^3$/d using 101-SY data resulting in a rate of level rise of 0.15 to 0.2 in./d. None of the SSTs experience large level growth rates, suggesting that they have reached a steady state whereby the gases that are generated are being released to the dome. Thus, it is very likely that the additional nitrogen also would be released continuously to the dome through the release paths that are available for the generated gas. It is even more likely that the nitrogen would be released from the hole created by the drilling. However, while flowing into the dome space, nitrogen may entrain some of the retained gas. The most likely gas-release mechanism would be the scrubbing of ammonia by the nitrogen flow. Initial ammonia releases as high as 34 $ft^3$/min are predicted by Reference 6. However, Reference 6 also suggests that such high release rates will not last forever as the waste near the drill string will be quickly depleted of its dissolved ammonia. Furthermore, the flammable gas monitors would stop the operations if high

ammonia concentrations are detected at the exhauster. Ceasing the nitrogen flow will stop the ammonia release.

One of the purposes of the use of nitrogen is to remove the waste from the drill bit. The nitrogen carries the waste chips. The flutes on the drill string also help the transportation of waste chips. Because of nitrogen addition and aerosol created by drilling, an exhauster is required to be operated during RMCS operations. The exhauster operation will also remove the small amounts of waste gas that may be entrained into the dome during nitrogen purging. It is believed nitrogen remaining trapped in the waste and subsequently triggering a large GRE is an unlikely occurrence.

The nitrogen addition can cause the dome to be pressurized if the exhauster fails. Thus, the nitrogen flow must be stopped upon exhauster failure.

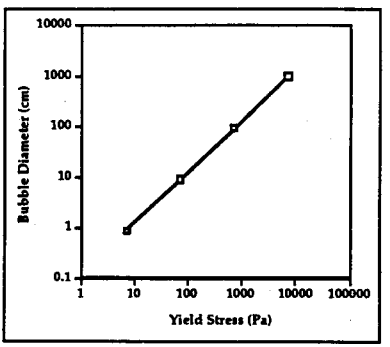


**Fig. M-1. Bubble-diameter to yield-stress relation at the initiation of a bubble motion.**

## 5.0. REFERENCES

1 P. M. Francis, "Aerosol Study for the Rotary Mode Exhauster," Westinghouse Hanford Company report WHC-SD-WM-ES-225, Rev. 0 (1993).

2. L. H. Sullivan et al., "A Safety Assessment for the Proposed Pump Mixing Operations to Mitigate Episodic Gas Releases in Tank 241-SY-101: Hanford Site, Richland, Washington," Los Alamos National Laboratory report, LA-UR-92-3196, Rev. 14 (March 31, 1995).

3. K. O. Pasamehmetoglu, "Single Shell Tanks Dome Volume Calculations," Los Alamos National Laboratory Calc-Note TSA10-CN-WT-SA-TH-086, (November 1995).

4. C. Unal, "Concerns with Uncontrolled Reactions Caused by Rapid Pressurization and Depressurization of the Voidmeter Sampler," Los Alamos National Laboratory Calc-Note, TSA6-CN-WT-SA-TH-044, (May, 1994).

5. A. N. Beris, J. A. Tsamopoulos, R. C. Armstrong, and R. A. Brown, "Creeping Motion of a Sphere through a Bingham Plastic," *J. Fluid Mech.* **158** (1985) pp. 219–244.

6. J. D. Hudson, B. J. Palmer, and C. W. Stewart, "The Potential for Flammable Concentrations of Ammonia Resulting from Core Drilling Operations," Pacific Northwest National Laboratory letter report PNL-WTS-112295 (November 1995).

# APPENDIX N

# STRUCTURAL ISSUES ASSOCIATED WITH ROTARY MODE CORE DRILLING OPERATIONS

## 1.0. INTRODUCTION

In this appendix we discuss structural issues associated with the operation of rotary-mode core sampling (RMCS). There are six different issues examined. Some of the issues are related to the ignition hazards, and others are breach of containment issues. They are not discussed in a particular order.

## 2.0. DOME LOADING

RMCS operations for single-shell tanks will impose an increase in the dead weight over the tank dome. Section 2 describes all the equipment that is necessary to perform the sampling operation.

### 2.1. Static Dome Loading

In this section, we consider static and dynamic dome loading. Reference 1 indicates that dome loading must be controlled by the dome-loading limits for single-shell tanks (SSTs) as specified in OSD-T-151-00013 (Ref. 2 ). The RMCS System Weights Table N-1 lists the weights of the various components that possibly will be imposed simultaneously on the dome surface. This additional tank dome loading is considered to be a live load in the Westinghouse Hanford Company (WHC) evaluation of the tank structural integrity.

The static load capacity of the tank dome is monitored carefully, and an overload state that could precipitate a structural failure must be avoided. The equipment required on the surface of the tank to support RMCS sampling operations qualifies as a live load. The tank loads study permits a 50-ton live load on the tank dome. The weight of the RMCS equipment is <50 tons; thus, this limit is not exceeded.

### 2.2. Dynamic Dome Loading

In case a truck were to fall on the tank dome, the dome would be subjected to dynamic dome loads. Reference 2 considers this scenario and analyzes the consequences of the dynamic loading caused by the truck dropping onto the dome. The truck weight is estimated to be 30,000 lb. The drop height for the truck was selected as 3 ft from the raised platform, and the truck is assumed to land on the minimum of 7 ft of fill.

TABLE N-1
RMCS COMPONENT WEIGHT BREAK-DOWN

| Component | Weight (lb) |
|---|---|
| Core sample truck (includes grapple hoist assembly and shielded receiver assembly) | 30,000 |
| Truck platform | 6,000 |
| Universal sampler (11 @ 10.3 lb) | 113 |
| Drill String (50 ft @ 4 lb/ft) | 200 |
| Change-out assembly | 45 |
| Riser adapter and drill rod washer | 280 |
| Riser liner | 200 |
| Support truck | 7,000 |
| Cask truck | 8,000 |
| Cask stand | 300 |
| Casks (5 @ 480 lb) | 2,400 |
| Mobile X-ray system | 5,000 |
| Exhauster system | 10,000 |
| Light plants (2 @ 1000) | 2,000 |
| Video vehicle | 5,000 |
| Tent | 7,000 |
| Tent weights | 33,000 |
| People (10 total) | 2,000 |
| Total Potential Weight | 118,538 |

The analysis examines the worst case in which the platform disappears and the truck lands on its tires. (The greater likelihood is that the truck would fall off the platform and land on its side, thereby affecting a greater area.)

The kinetic energy of the dropping mass is assumed to work by the resistance representing the impact. The work is estimated by integrating the load deflection diagram. (Details of calculations are available in Reference 3.) The deflection calculation considered the impact and static contributions. The dynamic load is calculated as 525,000 lb. Assuming that the load is spread over a $60^{\circ}$ cone angle as it passes through the minimum 7 ft of soil until it reaches the dome, a projected bearing surface area on the dome is calculated as 29,860 $in^2$. The allowable load on the dome is given as 5540 lbf in Reference 4. Considering 3 in. of water vacuum in the dome, the net allowable dome load is estimated as 4,680 lbf.

This conservative analysis shows that the dome will withstand the impact force of the 30,000-lb truck dropping on it from the 3-ft-high platform. The analysis in Reference 3 is conservative in that it uses the smallest conceivable projected area of the dome in the calculation. If the truck were to fall on its five jacks, or on its side, the projected reacting area of the dome would be greater, and the margin of safety larger. Further, it is not likely that the truck will fall at the same time the dome is subjected to a vacuum equivalent to 3 in. of water.

## 3.0. BUCKLING OF THE DRILL STRING

The failure of the drill string during drilling is evaluated as a fire hazard. The downward force is limited to prevent drill bit overheating. The other limit on the down force should be based on the buckling limit. In this section, we discuss the structural buckling limit under various boundary conditions.

The drill string has an outer diameter (o.d.) of 2.25 in. and an inner diameter (i.d.) of 1.91 in., and these dimensions will be used in all of the calculations discussed in this appendix. The effects of torsion on the drill string have not been considered, and the weakening effects of the multiple threaded joints have been ignored.

Three different cases have been considered. In each case, it is assumed that the upper end of the drill string is fixed. The lower end may be free, pinned, or fixed. The formulas for allowable buckling load for long columns in these three conditions are given in References 3 and 5. Calculated buckling limits are shown in Fig. N-1 as a function of drill string length.

It is difficult to predetermine which set of end conditions should be applied as bounding boundary conditions. There are two different cases to consider; (1) the drill bit entering the crust, and (2) the drill bit penetrating the crust or waste. Reference 6 documents the case of a drill-string failure at a length of 41.7 in. under a vertical load of 2,600 lb (the drill bit was in the waste). This falls exactly on the fixed-fixed curve of the above graph. However, it does not necessarily follow that waste entrance should be treated as such. It is conceivable that when a new drill first bites into the hard salt cake surface, the string will behave as fixed-fixed. It is also possible that the drill will wander along the salt cake, and behave as fixed-free.

The first core sampler has a centering spike attached to the bottom of the core sampler. The use of centering spike ensures that the drill bit does not wander along the salt cake as it tries to penetrate. Therefore, it is reasonable to assume that the boundary conditions are fixed-pined as the drill string penetrates the waste or when it is in the waste. We have establish a control requiring that the first core sampler must include the centering spike.

Based on the above discussion, the downward force during crust penetration should be evaluated from Figure N-1 using fixed-pinned boundary conditions. We could not put a limit that could bound all lengths. For drill string lengths less than 45 ft, the downward force limit is quite high. However, the downward force in this range is also limited with 750 lbf established by the envelope testing to eliminate the waste ignition hazard. Thus, the downward force will be set to 750 lbf when the drill-string length is less than 45 ft. For drill string lengths higher than 45 ft, this limit should be lowered to 650 lbf because of buckling concerns.

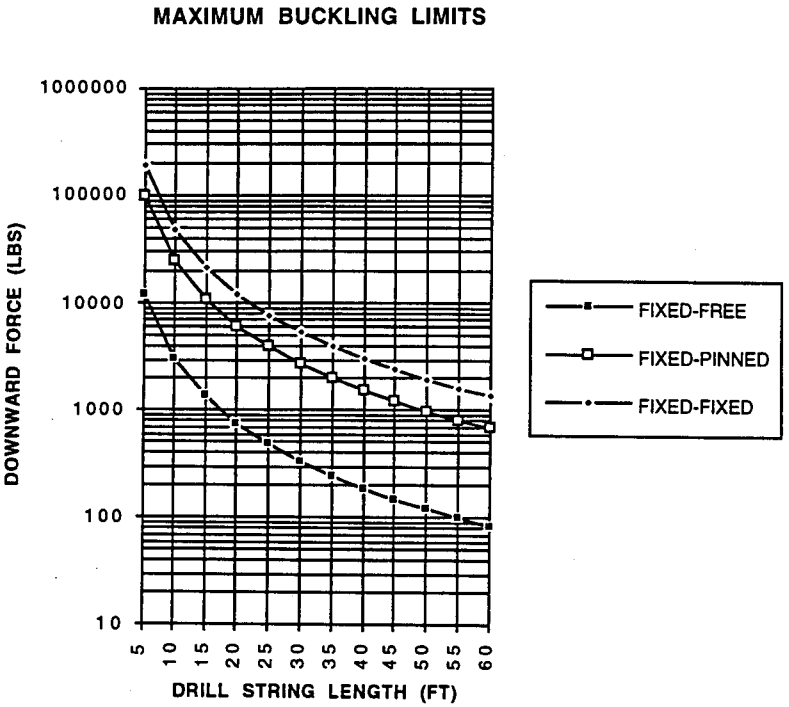


**Fig. N-1. Buckling limits for drill strings considering three boundary conditions.**

## 4.0. MAXIMUM BEARING FORCE CALCULATIONS OF DRILL STRING AGAINST SLEEVE

The major concern is the frictional spark when the drill string rotates in the sleeve and periodically bangs into flutes on the conductive sleeve. In this section, we determine the horizontal force that could be applied to the drill string during contact with the sleeve.

Figure N-2 is an illustration of the operation of the drill string in the conductive sleeve. The objective is to determine the absolute maximum force that the drill string could exert against the sleeve before the failure of the drill string. This

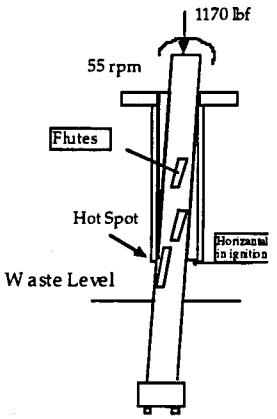


**Fig. N-2. Sketch of a drill string in riser.**

maximum force can occur when the end of the sleeve is the shortest distance from the salt cake.

The following assumptions are proposed. The tube material is steel with an ultimate tensile strength of 90 ksi. The weakness caused by the threads is ignored in order to compute the highest possible bearing force. The sleeve is 15 ft long and is totally rigid. Among the tanks considered, Tank U-108 has the shortest distance from the bottom of the sleeve to the top of the salt cake. That distance is 80 in. Upon touching the waste, the drill experiences a lateral force, sufficient to fracture it at the point where it leaves the sleeve.

The bending moment required to fracture the drill string is given in Reference 5 as $M = s_u \times I/c = F \times 80$ in. From this equation, the bearing force is estimated as 610 lb against the sleeve before the drill string fails. This particular case will develop the highest possible bearing force. The deflection at this force is found as 5.7 in. in Reference 3. It has been assumed that the sleeve is completely rigid. In reality, some deflection of the sleeve will occur, and the drill string may not necessarily fail where it leaves the sleeve. Furthermore, the particular tank chosen has the shortest distance between the sleeve and the salt cake. These two factors combine to give the maximum contact force of 610 lb.

## 5.0. DRILL STRING DROP ACCIDENT

A potential hazard to the tank structural integrity exists if the RMCS drill string were to fall and impact the tank bottom. The drill string is restrained from falling and impacting the tank bottom by the pneumatic foot clamp. After numerous

sections of the drill string have been added, the suspended weight will cause the drill string to fall if the clamp is released because the force of gravity exceeds the frictional forces. Initially, the frictional force developed at the riser seal interface exceeds the string weight. The frictional force is produced by the rubber seal that girths the outside diameter of the drill string shell. This constant force eventually is overcome by the column weight as the sections are added. The long drill string extending nominally halfway into the tank poses the largest hazard to the integrity of the tank bottom from an impact. We evaluated the impact force that would occur if the drill string were released.[3]

Among the tanks considered, Tank AX-103 has been chosen as a worst case because the low level of waste (42 in.) is insufficient to absorb a significant amount of energy from the falling drill string. Consequently, the effects of drag and buoyancy will be ignored.

Assumptions made in evaluating the drop accidents are as follows. The tank has a cylindrical height of 390 in. and is topped by an elliptical dome that is 144 in. high. The minimum waste level is 42 in. (Ref. 7). There are 84 in. of fill on top of the tank. The first rod section of drill weighs 6.3 lb (Ref. 8).

The methodology is based on the ballistic impact on the tank bottom. The drop distance from the ground to the tank bottom is 618 in. (Ref. 8). The impact velocity is 17.6 m/s (57.6 ft/s). The maximum impact kinetic energy for one drill rod of 6.3 lb becomes 325 ft-lbf.

If the steel bottom corroded 4.5 mils per year for 40 years (Ref. 9), the remaining thickness would be 0.195 in. (Ref. 9). From the analytical techniques of Reference 8, we found $t/D = 0.086 < 0.35$. The critical velocity at which 50% of the cases would have penetration is found to be 218 ft/s. This is greater than the 57.6 ft/s calculated above; therefore, penetration is not likely for the single section of drill string.

As another check, it has been customary to convert a body that does not have a ballistic shape to an equivalent body by solving for an effective diameter. This has been considered as discussed in Reference 3 and the same conclusion is found; penetration is not likely if a single drill rod is dropped.

However, if we examine the case where the drill string is 340 in. long, the weight becomes 113 lb. The drop distance then becomes 278 in. Using the same ballistic impact analysis for higher weights, we found the critical velocity at which 50% of the cases would have penetration as 34.6 ft/s. It appears likely that the base would be penetrated if the whole drill string were to be dropped.

Another method is based on stresses induced in the steel liner from the impact as it was done in Reference 8. We equate the work done by the liner in absorbing the kinetic energy of the dropped drill string to the kinetic energy.

The impact velocity of the drill string is expressed as a function of the number of the drill rod ($V = (2gh)^{0.5} = [(2\ g\ (618 - 19n)]^{0.5}$, where n = the number of 19-in. drill sections). The kinetic energy becomes ($324n - 10n^2$) (Ref. 3). The kinetic energy peaks at 16 sections for a string length of 16 x 19 = 304 in.

Taking Poisson's ratio as 0.25 and the radius of the bottom plate that responds to the impact as 60 in., the equivalent spring constant for the plate is found as 6,370 lb per in. The impact force is calculated as 20,100 lb. The deflection at this load is found at 3.15 in. The developed moment can be calculated as 8164 in. lb. This results in a stress level of 1.3E6 psi. It is clear that this is more than an order of magnitude higher than the ultimate strength of the material. Thus, bottom liner penetration could occur if the drill string were dropped.

## 6.0. STRUCTURAL FAILURE OF THE ROTARY CORE DRILL STRING UNDER PURE TORSION

If the drill string becomes embedded in the waste because of debris in the waste, torque will continue to be applied to the drill string at a constant rate. If such a condition occurs, there is a possibility that the drill string will partially fail. Partial failure of the drill string will then result in a nitrogen flow bypass through the area that is partially failed with a leak path. Providing the necessary nitrogen flow to the drill bit protects the drill bit from overheating. Thus, waste or flammable-gas ignition is prevented. The flow rate is measured in the nitrogen instrumentation box. If a partial drill-string failure occurs because of applied torque, this condition will never be detected. Therefore, the likelihood of ignition in the waste becomes uncertain. In other words, providing nitrogen flow if there is a leak path on the drill string would not prevent the drill bit from overheating.

In this section we examine the scenario in which the drill string is considered to be torque from the upper end while the rotation of the lower end is not allowed. If the drill string fails in a short period of time under the over-torque conditions, we can conclude that the drill bit does not have enough time to overheat itself. Thus, the purpose of this section is to examine whether or not the drill string will fail in the short period of time when a torque is applied.

This issue is examined in Reference 10. The method applied and results will be briefly summarized here. An analysis in Reference 10 assumes that the drill string is jammed in the waste while torque is applied at a maximum rate of 55 rpm. Linear elastic methods are applied as a first approximation to obtain the lower bound failure estimate. Secondly, strain energy methods are used to upper bound the solution by assuming that the ultimate shear strain in the drill rod is proportional to the shear modulus. This is a very conservative approximation but will provide the upper limit of failure and will estimate the maximum time-to-failure.

Material is manufactured from ASTM A-518 carbon steel (its properties are given in Reference 10). Linear elasticity analysis estimates the shear stress as Tc/J (where T = torque, c = distance from the point of rotation to the maximum outer fiber on the cylinder under shear, and J = polar moment of inertia). The torque results in an angle of rotation for pure torsion as given by $\theta = TL/JG$ where, G = shear modulus, $\theta$ = angle of rotation, and L = length. The shear modules are calculated as 11.2E6 psi using a Poisson's ratio of 0.3. Assuming the shear stress developed under torsion is brought to the limit of the material, that is, the shear ultimate strength of the pipe, then the maximum angle of rotation can be determined. This is conservative because the theory is applicable to linear elastic bodies, and obviously this assumption does not account for the ductility of the material. The angle of rotation is calculated as 126° in Reference 10. This corresponds to about one-third of a full revolution. In terms of a time-to-failure determination, the rod will fail in 0.38 seconds for a rotational speed of 55 rpm. The time period to failure becomes 2.1 seconds for a rotational speed of 10 rpm and 4.2 seconds for 5 rpm. The lower speeds are not usually selected because sampling becomes poor. However, even in the case of low rotational speed, the drill rod will fail in a few seconds.

The second method that upper-bounds the torsional resistance is based on the strain energy method. Shear failure is assumed to occur when the materials' total strain energy equals the work done by the applied torque. Then, the strain energy can be written in terms of the shear stress and shear strain. However, in this case, the assumption is that the shear strain is the "ultimate" shear strain capacity of the material based on a linear elastic relationship. Using this method, the angular rotation to cause failure is estimated as 5208°. For a rotational speed of 50 rpm, this corresponds to a time period of 15.8 seconds. The time becomes 43.4 seconds for a rotational speed of 20 rpm. This second method is only provided to show an upper bound, and by no means will this be a reasonable failure angle or time-to-failure of the drill string under pure torsion. Because linear-elastic methods do not account for ductility or the strain hardening/softening of materials, the strain energy calculated is grossly conservative. Furthermore, the ultimate strain used in the calculations is also overly conservative because for this specific material, typically, there is virtually no ductility.

In reality, the drill string will fail somewhere between 0.5 and 2 seconds for a drill bit rotational speed of 55 rpm and between 2 to 8 seconds for a rotational speed of 20 rpm. The most important notion to consider is that this material does not have much ductility, as evidenced by the lack of strain hardening. The fact that the yield strength is only 10 ksi lower than the ultimate strength shows negligible strain hardening capability. In fact, one may consider this material somewhat brittle. Therefore, the assumption that the material attains 15% ultimate shear strain at failure is very conservative. In addition, no stress concentration factor (or effective area) is considered for threads between the drill rods. The threaded rods allow the drill string to fail in much smaller time periods.

## 7.0. DRILL-STRING RESONANCE

A torque and axial load will be applied to the drill string during drilling. Excitation of the drill string with a natural frequency is of concern. In this section, we evaluate the resonance rotational speeds under various boundary conditions. However, the weakening effects of the multiple threaded joints have been ignored.

Consider first the case of torsional resonance. The equation for the first mode of torsional resonance is given in Reference 3. Limiting rotational speed is plotted in Fig. N-3 as a function of the drill string length.

The maximum rotational speed is 55 rpm. From Fig. N-3, it is clear that the torsional resonance speed is extremely high. Figure N-4 plots the first- and second-mode resonance rotational speed as a function of the drill string length for the fixed-free, fixed-pinned, and fixed-fixed boundary conditions. Curves with fixed-pinned boundary conditions are suggested for the cases where the drill bit penetrates the waste and where the drill bit is in the waste. We tabulated the suggested range of speeds in Table N-2.

When the drill string is in the waste, a rotational speed of up to a maximum of 55 rpm can be used when the drill string length is less than 45 ft. Above 45 ft, the speed should be either 40 rpm. The second excitation frequency is much higher than the maximum allowable speed of 55 rpm.

## 8.0. DRILLING THROUGH THE BOTTOM OF THE TANK

Buckling of steel liner bottom plates in underground single-shell tanks (SSTs) and double-shell tanks (DSTs) has been observed in about three instances and documented in one specific case that we are aware of. DST SY-101 has a known buckle that extends inwardly about 4.5 to 5.0 inches, which was caused by the stress-relieving operations immediately after heat-treating the shell liner to 1100°F. Documentation of this specific case is extensive, also providing contour maps of the actual buckled shape.

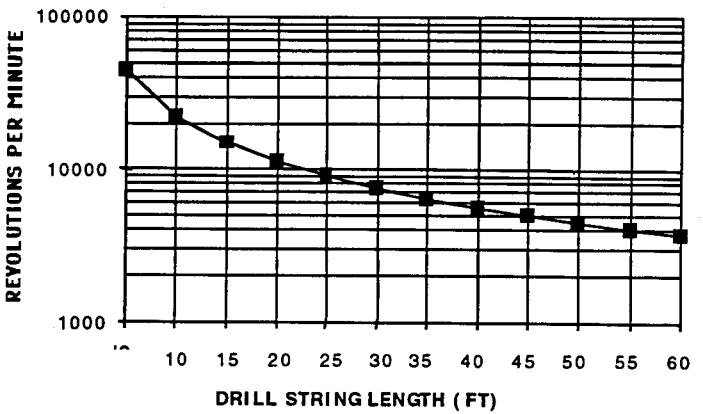


Fig. N-3. Resonance speed caused by torsional load.

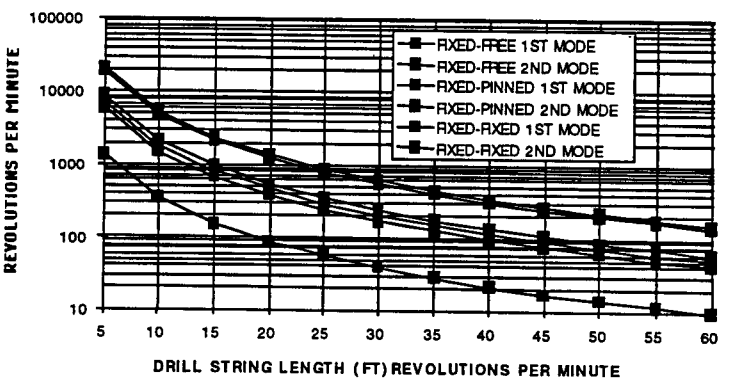


Fig. N-4. Transverse resonance rotation speed as a function of the drill string length.

TABLE N-2
ROTATIONAL SPEED LIMITS

| Drill String Length (ft) | Force (lbf) | Rotational Speed (rpm) |
|---|---|---|
| L<45 | <750 | <55 |
| 45<L | <650 | <40 |

Other cases in SSTs that are known to exist but have not been documented pose a potential concern when installing equipment through the risers that extend to near the bottom of the tank. The inward deflection created by the buckles may prevent equipment from fully seating on the riser. Other more important concerns are with RMCS equipment, which is required to obtain samples from the complete depth of tank waste. The potential for drilling through the steel liner is evident if the steel bottom plate has a deformation from lateral buckling. Therefore, limiting the drill string height to a safe distance above the bottom plate is justified.

This analysis evaluates nominal deformations in the bottom plate caused from effects related to tank construction practices. Because very little is known about the post-fabrication condition of some SSTs, one can only depend on the structural deformation created from the construction phase, such as the loads imposed on the tank walls after soil backfilling and shrinkage loads created during the curing period of the reinforced concrete shell.

### 8.1. Analysis

Using dimensions of Tank A-101 for the typical SST, Figure N-5 shows the approximate soil depth and tank characteristics. The tank liner is 3/8-in. thick carbon steel with a 75-ft diameter and the depth of soil to the tank bottom plate is approximately 54.5-ft. The waste temperature currently is taken as 135°F.

The lateral soil pressure is assumed as the "at-rest" soil pressure for retaining-type structures. The hydrostatic load at the base of the wall is shown[11,12] as

$$P = \gamma H K_o$$

where, $\gamma$ = Soil density ($lb/ft^3$),
$H$ = Depth of soil (ft), and
$K_o$ = Coefficient of soil pressure at rest.

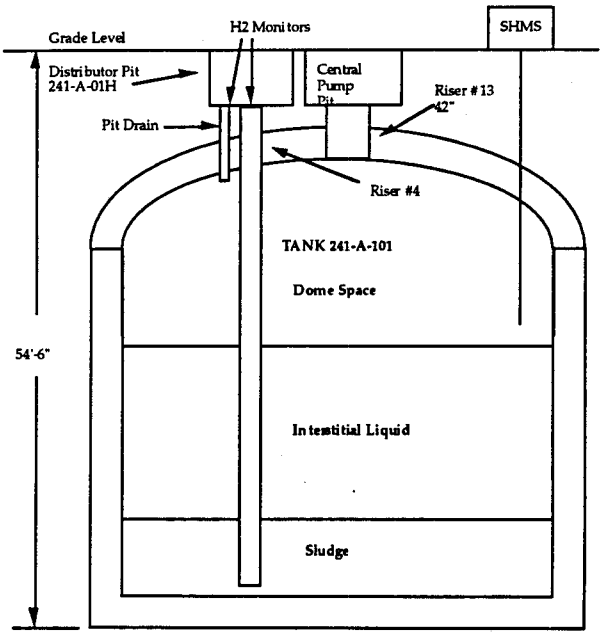


**Fig. N-5. Cross-sectional view of A-101.**

The maximum soil pressure, assuming a moist, dense soil, typical of the Hanford Tank Farm region is

$$P = 6500 \text{ lb/ft}^2 \quad \text{or} \quad P = 45 \text{ psi}.$$

The lateral soil force per unit circumference on the 3/8-in. bottom plate is

$$F_s = 17 \text{ lb/in.}$$

Concrete shrinkage and creep is very common, and design practices allow for some shrinkage; however, structures are often slightly deformed because a small margin was allowed for deformation-type strains. For 3000 psi compressive strength concrete, typical of A-101 construction, Ferguson[13] provides the nominal shrinkage to be approximately 2.0E-4 in./in.

Obviously, there is some appreciable gap between the concrete and the steel liner after construction before shrinkage begins. This gap cannot be fully quantified.

Thus, nominally, a 1/4 in. gap is assumed to exist between the steel and concrete immediately after construction.

The bottom plate radial deformation, based on a concrete shrinkage coefficient of 2.0E-4 in./in. is

$$\Delta R = \alpha R ,$$

where, $\alpha$ = 2.0E-4 in/in.,
$R$ = 450 in., and
$\Delta R$ = 0.09 in.

Thermal expansion deformations of the tank bottom, caused by heat loads from the waste, will comprise about

$$\Delta R_{th} = \alpha_{stl} R \Delta T ,$$

where, $\alpha_{stl}$ = 6.5E-6 in/in/°F,

and the temperature difference is from 75°F to the current waste temperature of 135°F, or $\Delta T$ = 65°F. The 75°F temperature is assumed to exist at the time of construction with no appreciable deformations. The maximum thermal expansion of the tank bottom is

$$\Delta R_{th} = 0.175\text{-in.}$$

Accounting for the 1/4-in. initial gap between the steel and concrete, the maximum lateral deflection of the plate after concrete shrinkage and thermal expansion, would be 0.015 inches. The difference between the radial gap and the concrete shrinkage plus thermal expansion is an interference fit, that is, the radial contraction imposed on the tank plate. Thus, there exists a radial force per unit of circumference such that the proportionality of the following relationship must hold true in the elastic region

$$\frac{\Delta R}{\alpha R} = \frac{\sigma}{\alpha E} ,$$

where, $\sigma$ = Stress, (psi)
$E$ = Modulus of elasticity, (psi)

or, $$\Delta R = \frac{\sigma R}{E}$$

The applied stress from the shrinkage and thermal effects is

$$\sigma = 1000\text{-psi} ,$$

or a radial force per unit circumference of

$$F_{cs} = 375\text{-lb/in.}$$

Comparing this value to the critical buckling load of the 450-in. diameter plate assuming a clamped condition is[14,15]

$$\sigma_c = 1.22\frac{E}{1-\nu^2}\left(\frac{t}{a}\right)^2, \text{ and}$$

the critical stress is

$$\sigma_c = 28\text{-psi} \quad \text{or a radial load of} \quad F_{cs} = 10.5\text{-lb/in.}$$

The compressive load from the concrete shrinkage and thermal expansion is much greater than the critical buckling load of the plate. Given these large loads, the plate would have undergone local plastic deformation and therefore would never achieve such high radial forces. Obviously, the actual gaps and conditions are unknown, and any other assumption as to the actual state of construction is an estimate.

Therefore, in order to achieve a physical meaning, a conservatively critical buckling load representative of the circular plate plus additional load from the lateral soil pressure is used in calculating the maximum deflection of the buckled form.

This rationale assumes that soil pressure will always be present on the tank walls, and that thermal and concrete shrinkage loads will cause local plasticity, thus allowing for relieving of strains. Thus, the maximum load is taken as

$$F_t = 27\text{-lb/in.}$$

The out-of-plane deformation of the bottom plate for the compressive load shown above is approximated using a differential strip element of plate along its diameter. This is a conservative assumption because it assumes a rectangular strip of length L and not a radial segment of a circular plate. In order to obtain a buckled shape deformation with a compressive radial load, a very small out-of-plane perturbation load is applied to initiate buckling, where the perturbation load is Q. Let Q equal 1% of the compressive load, and the deformation is found as[14]

$$w = \frac{Q}{2Pk}\left(\tan\frac{kL}{2} - \frac{kL}{2}\right),$$

where, $w$ = Deflection (in.),
$P$ = Lateral compressive force (lb),

$k = \sqrt{\frac{P}{EI}}$,
$L$ = Elemental strip length (diameter), and
$I$ = Moment of inertia (in.$^4$)

The solution to the maximum deflection is

$w$ = 2.2 in.

It should be understood that this calculation only provides an "estimate" of the buckling deformation. It presents a simplistic argument for a complex condition and makes assumptions on the state of construction. There are numerous unknown conditions that may exist, which if conservative assumptions are used, would yield unreasonable results of the buckling deformation. Furthermore, because actual observations of DST buckling are documented (e.g., SY-101) with maximum heights of about 4 to 5 inches, this calculation provides a basis for the order of magnitude.

### 8.2. Conclusions

A 3-in. minimum distance is recommended for limiting the lowering of the drill string to the tank bottom. This limit is established from the best-estimate analyses provided above. One may estimate larger deformations using more conservative assumptions that those used in this analysis. Obviously, the 3-in. limit does not guarantee that the drill bit will never contact the tank bottom. However, it reduces the probability of drilling through the bottom without sacrificing valuable sample data near the bottom of the tanks. As mentioned before, one documented case of bottom buckling is for 101-SY. For that case, the peak deflection is measured as ~4 in., which covers less than a few percent of the total surface area.

## 9.0. REFERENCES

1. N. Milliken, "Safety Analysis for the Push Mode and Rotary Mode Core Sampling," Westinghouse Hanford Company report WHC-SD-WM-SARR-031, Rev. 1 (June, 1995).

2. V. C. Boyles, "Operating Specifications for Single-Shell Waste Storage Tanks," Westinghouse Hanford Company report OSD-T-151-00013, Rev. D-4 (1994).

3. B. Weinstein, "Structural Analysis of Rotary-Mode Core Sampling Operations," Los Alamos National Laboratory Calc-Note TSA10-CN-WT-SA-ST-086 (December, 1995).

4. K. J. Lawrance, "Dome Analysis," Los Alamos National Laboratory Calc-Note N6-CN-WT-SA-ST-024 (August, 1992).

5. R. J. Roark and W. C. Young, *Formulas for Stress and Strain*, 3rd edition, (McGraw Hill Co., New York, New York, 1975)

6. H. H. Ziada, "Axial Failure Food Estimates for Push Mode Drill String," Westinghouse Hanford Company memorandum H5-52 (October 18, 1995).

7. K. O. Pasamehmetoglu, "Single-Shell Tanks Dome Volume Calculations," Los Alamos National Laboratory Calc-Note TSA10-CN-WT-SA-TH-086 (December 1995).

8. W. O. Miller, "Retained-Gas Sampler Drill-String Drop Analysis," Los Alamos National Laboratory Calc-Note TSA6-CN-WT-SA-075 (November 30, 1994).

9. J. P. Strehlow, "Drill-Bit Punch Through Single-Shell Tank Liner," Westinghouse Hanford Company memorandum CSA:JPS:ggb:92/32 (1992).

10. E. Rodriguez, "Structural Failure of the Rotary-Core Drill String Under Pure Torsion," Los Alamos National Laboratory Calc-Note TSA10-CN-WT-SA-ST-085 (December 1995).

11. G. B. Sowers and G. F. Sowers, *Introduction to Soil Mechanics*, 3rd Edition (Macmillan Publishing Co., New York, New York, 1970).

12. J. E. Bowels, *Foundations Analysis and Design*, 3rd Edition (McGraw-Hill Book Co., New York, New York, 1982).

13. P. M. Ferguson, *Reinforced Concrete Fundamentals*, 3rd Edition (John Wiley & Sons, Inc., New York, New York, 1973).

14. S. P. Timoshenko and J. M. Gere, *Theory of Elastic Stability*, 2nd Edition (McGraw-Hill Book Co., New York, New York, 1961).

15. R. J. Roark and W. C. Young, *Formulas for Stress and Strain*, 5th Edition (McGraw-Hill Book Co., New York, New York, 1975).

# APPENDIX O

# ENERGY AND WATER ADDITIONS/REMOVALS

## 1.0 INTRODUCTION

In this appendix, the issues associated with energy and water addition to the tank during sampling are addressed.

## 2.0. WATER ADDITIONS

These accidents address the possibility of excessive water additions to the tank that would cause the level to rise above that allowed by safety controls. In the limit, flooding could result from the release of tank materials into the environment caused by hydrostatic failure of the tank. This appendix also addresses the effect of the water addition on the waste temperature and gas releases.

The maximum quantity of water available for decontamination during operation and removal is 5.7 $m^3$ (1500 gal.), which is physically controlled by the size of the water supply. Adding this quantity of water increases the tank level by a maximum of 1.4 cm (0.55 in.). Per activity, water additions are limited to 0.95 $m^3$ (250 gal.). Flooding of the tank by adding a maximum 1500 gal. of water is impossible. Numerous 1500-gal. tanks of water would have to be added in violation of the 1500-gal. total addition limit. The maximum quantity of water available for decontamination during operation and removal is 250 gal., which physically is controlled by the size of the water supply. The water addition to an assumed leaky single-shell tank (SST) must be reduced to 100 gal.

One of the reasons for keeping the water addition to minimum amounts is the danger of interim-stabilized tanks jeopardizing the interim-stabilized status. A tank must contain less than 50,000 gal. of drainable interstitial liquid and less than 5000 gal. of supernatant liquid in order to maintain its interim-stabilized status.

These numbers are predicated on the flow rate, duration of operation of the decontamination system, and maximum number of anticipated decontamination operations. Any addition of water beyond this total level must be approved by the test review group (TRG) with consideration for overall effects on the tank waste. To ensure that the water is sufficiently provided to the check valve for the purpose of cleaning, the water level in the water supply tank will be monitored.

Water addition has several more effects: (a) changes the waste temperature, (b) releases gases, (c) changes the waste pH level, and (d) increases the activity of radiolysis.

Farley[1] investigated the water addition effect. Roughly, unit change in waste pH would require an order-of-magnitude change in volume to sufficiently affect the hydronium ion concentration. Assuming water will affect a 1-ft radius, the minimum waste volume can be found as 82 gal. that are calculated for Tank AX-103 that has a minimum waste level of 42 in. A unit change in pH for this tank would require 820 gal. of water. The water addition is limited to 250 or 100 gal. per activity. The small amount of water added to the tank will dissolve salts and will be saturated. The pH change is not expected. The water-addition limit is 100 gal. for assumed leaky tanks to minimize the release to the environment.

Hydrogen is generated by the radiolysis of water. The water addition would reduce radioisotope concentration. However, the volume would be increased by water addition. Therefore, hydrogen generation per unit volume would not be affected with water addition. Small amount of water addition in comparison to the total volume would imply insignificant effects. Generation of other gases would be affected in the same way. Water addition, however, may cause gas release, reducing the gas retention capability. During rotary-mode core sampling operations, water will be added at the waste surface, and a gas release triggered by water addition is not expected.

## 4.0. STEAM GENERATION CAUSED BY ENERGY ADDITION

In Reference 2, a steam-release accident is postulated for high-heat tanks. High heat was considered to generate and retain steam in the waste. However, an analysis specific to high-heat Tank C-106 demonstrated that the condition of this tank is not sufficient to initiate a steam-release event. This was believed because there is sufficient heat transport to cool or condense the steam bubbles, and the sludge-shear strength was not enough to retain steam bubbles in the saturated region. The steam generation caused by heat generation is not a concern in the single-shell flammable-gas tanks having waste temperatures less than 93°C, and the waste level does not significantly change to indicate a great deal of accumulation.

In this safety assessment (SA), the concern is the generation of steam caused by drill bit frictional heating that could remove moisture from the tank. The energy addition to the tanks is discussed above for two limiting cases: frictional heating with no penetration and efficient cutting with penetration.

The bounding energy input caused by drilling is estimated as $8.66 \times 10^6$ J for frictional heating and $5.6 \times 10^7$ J for smooth penetrating drilling operations. Reference 3 gives the amount of water that can be evaporated for the tanks that are on the Flammable Gas Watch List. The maximum amount of water is estimated as 27.3 kg. These results are very conservative because all the drilling energy is assumed to result in evaporation. Nonetheless, the amount of evaporation is negligible and will not change the moisture content and waste level significantly in any of tanks listed in the table. The vapor volume is 22.84 $m^3$ (807 $ft^3$). Considering

that the minimum dome volume is 1416 $m^3$ (50,000 $ft^3$) and that the steam will be generated over hours of operation, the temperature increase in the dome will not be significant.

## 3.0. WATER REMOVAL CAUSED BY EXHAUSTER

Another way to remove the moisture in the tank is by operating the exhauster. Among the original Flammable Gas Watch List tanks, the maximum tank dome temperature is found to be 37°C (98°F) in Tank 101-A. This temperature is used to calculate a conservative moisture removal. The exhauster has a relative humidity requirement of 70%. Above this value, normal exhauster operation is not allowed unless there is a gas-release event.

Reference 3 calculates the time of operation necessary to observe a noticeable waste-level decrease, 0.5 in., as ~15 days if the relative humidity in the dome were 70%. These results are very conservative because they do not account for the water vapor partial pressure suppression in highly concentrated salt solutions. In reality, the waste (especially if the surface is dry) is likely to act like a desiccant and absorbs moisture from the dome. Nevertheless, the rotary-mode core sampling (RMCS) operation is assumed to involve roughly about 10 days per year per tank in this SA (App. E). This period considers two full samplings each, including 10 to 11 samples. Note that each full sampling may occur at different times. Thus, during RMCS, water removal as a result of continuous ventilation is not a safety concern.

## 4.0. REFERENCES

1. W. G. Farley, "Safety Assessment for Thermocouple Tree System Installation and Operation in Ferrocyanide Waste Tanks," Westinghouse Hanford Company report WHC-SD-WM-SAD-014, Rev. 3 (November 1993).

2. N. Milliken, "Safety Analysis for Push-Mode and Rotary Mode Core Sampling," Westinghouse Hanford Company report WHC-SD-WM-SARR-031 (July 1995).

3. C. Unal, "Calculation of Water Removal From Single Shell Tanks Due to Exhauster Operation," Los Alamos National Laboratory Calc-Note, TSA10-CN-WT-SA-TH-092 (December 1995).

# APPENDIX P

# ANALYSIS OF FRICTIONAL HEATING IN ROTARY-MODE CORE SAMPLING

## 1.0. INTRODUCTION

It is possible that the rotating drill string may contact the conducting sleeve during drilling operations. Because this contact involves potentially high horizontal loads and dry metal-to-metal sliding, an analysis of the temperature rise caused by frictional heating was performed. In addition, a scoping analysis of frictional heating in the event of exhauster-fan-to-case contact was performed, as discussed in Section P-8 of this appendix. The analyses presented in this appendix should be viewed in light of statements in the literature such as

> *"The actual surface temperatures achieved during dry friction are virtually impossible to measure, and both the temperatures themselves and the methods used to obtain them are matters of continuous controversy."*[1]

Rabinowicz[2] notes that

> *"...In consequence of the difficulties involved in this situation, hardly anyone ever tries to calculate the temperature rise produced in sliding. Instead, if the author's experience is typical, reliance is generally placed on one or another of two widely established but mutually exclusive maxims:*
>
> *1. The flash temperature at a sliding surface is usually only a little greater than the average temperature of the contacting surfaces.*
> *2. The flash temperature is usually the melting temperature of the lower melting of the two sliding materials."*

Because reliance on either of the statements above provides a poor basis for a safety case, an attempt was made to develop a defensible calculation.

The concept of "flash temperature" mentioned by Rabinowicz is important to understanding the phenomenon of frictional heating and the analyses presented in this appendix. In sliding situations, contact is not made over the whole of the apparent contact area, $A_a$, but over a few isolated junctions (which together form the real contact area, $A_r$). Because these junctions are small and they receive substantial thermal energy, their temperatures may be much higher than that of neighboring surface regions (that is, the local macroscopic surface temperature). The flash temperature is defined as the hot-spot temperature associated with these junctions. During sliding, junctions continue to be made and broken, and the "hot spots" on

the surfaces shift their location throughout the apparent contact area. There seems to be general agreement, however, that the flash temperature reached at any of these hot spots tends to be reasonably constant under constant sliding conditions. Figure P-1 provides a schematic view of an interface, showing the apparent and real areas of contact.

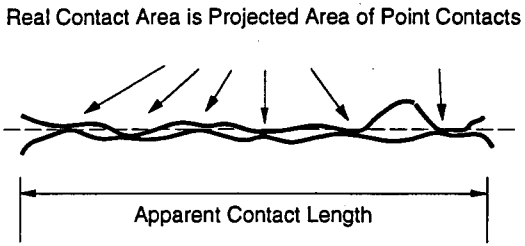


**Fig. P-1. Schematic view of a sliding interface between real materials, showing the apparent and real areas of contact.**

For a given dry-sliding problem, estimation of peak temperatures is, therefore, the combined problem of calculating the nominal surface temperature distribution resulting from frictional heating over the entire apparent contact area, and the "flash temperature rise," which are then added together. The first difficulties arise in determining appropriate areas and in estimating the flash temperature rise.

The real contact area depends on the characteristics of the surfaces in contact, namely the size and shape of the apparent area of contact, the surface roughness of the two materials, and the way they are placed together. Fortunately, it is possible to estimate the real contact area based on simple limit analyses assuming ideally plastic deformation. If the surfaces that are placed in contact are rough (not prepared bearing surfaces), the contact area of a localized region of material under an imposed load will depend on the stress that such a region can carry without plastic yielding. This property is known as the penetration hardness, and is about three times the yield stress. This argument is plausible based on the similarity between the load carried by a surface high point (called an asperity in the friction literature) and the load imposed by the indenter used in performing the surface hardness test. It also yields results consistent with experimental measurements, such as electrical contact resistance measurements with precious metals. The simple limiting values obtained by this approach are often modified to account for shear forces (always present in sliding) and surface energy considerations.

The apparent contact area consists of the real contact area of the junctions and the area of those regions that appears as if contact might have been made there (but was not). Again, this can be very difficult to estimate for other than simple (for example,

planar) geometry. It can be conservatively estimated from the real contact area estimate, based on the generalization in the literature that "the real contact area is *no more than* 10% of the apparent contact area" (emphasis added).

When surfaces slide together, almost all of the energy dissipated in friction appears in the form of heat at (or near) the interface. Historically, it was a friction experiment that proved the equivalence of mechanical energy and heat. As implied above, some of this energy can be deposited just below the surface because the plastic and elastic deformations occur throughout a volume. The material properties and characteristics of the surfaces can change as a result of this surface "working," changing the subsequent frictional characteristics, including heating. Several formulas for use in estimating the *expected* flash temperature rise have been developed based on simplified assumptions. The expected flash temperature rise results from distributed contact over many contact points. The limiting case of a single asperity with an area equal to $A_r$ yields the *worst-case* flash temperature rise.

## 2.0. DRILL-STRING-TO-SLEEVE FRICTIONAL HEATING

As described in Section 4, the drill string moves within a conducting sleeve placed in the tank penetration. Information provided indicates that the drill string is 1100-series carbon steel and the sleeve is stainless steel. The sleeve is a Schedule 80S 3-in. nominal pipe,[3] which has an i.d. of 2.90 in. with a wall thickness of 0.3 in. and is nominally 15 ft long. The drill string has a 2.25 in. o.d. and a 1.906 in. i.d. The drill sections themselves are fluted on the o.d. and are nickel plated. It has been reported that the portion of the string not penetrating the waste is not fluted, and it is not assumed to be plated. A scale drawing of the drill-string-in-sleeve cross section is shown in Fig. P-2. Coolant nitrogen for the drill bit is fed through the drill string at a nominal rate of 30 scfm. A nitrogen purge flow is introduced into the annulus between the sleeve i.d. and the drill-string o.d. at a nominal rate of 5 scfm.

Contact between the drill string and sleeve is possible. An analysis provided in Appendix N determined that a horizontal load of up to 610 lbf could be applied before the drill string would break at the point where the string exits the sleeve. The figure in Appendix N illustrating this situation is greatly exaggerated, however. Because the nominal clearance between the drill string and sleeve is small compared to the 15 ft sleeve length, the contact angle is quite shallow (see Fig. P-3). The bounding frictional heating analysis presented here assumes the limiting load of 610 lbf is applied horizontally (incipient drill-string failure). It further assumes a drill rotational speed of 55 rpm and initial temperatures of 38°C. This analysis conservatively assumes contact at only one region (sleeve exit) and that the contact region remains stationary on the sleeve. It would be expected, in reality, that bending would cause the drill string to rotate eccentrically, sweeping the contact region around the sleeve periphery. Bending might distribute real horizontal loads over two regions of

contact. Also, a minimum penetration rate must be maintained for continued drilling, which would "feed" colder drill-string material into the contact region.

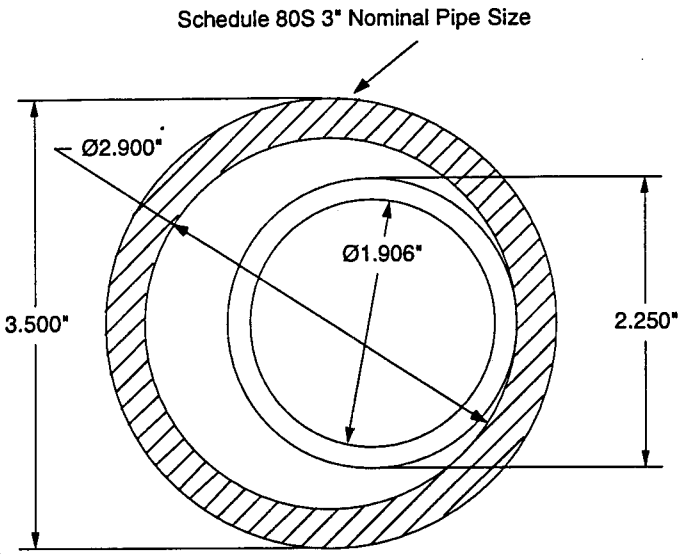


**Fig. P-2. Cross-sectional view of the drill string in the conducting sleeve (to scale).**

## 3.0. ESTIMATING CONTACT AREAS

Rabinowicz[2] suggests estimating the real contact area from the following relationship based on a limiting plastic-deformation analysis,

$$A_r = \frac{L}{p}, \qquad \text{(P-1)}$$

where L is the applied load acting normally and p is the penetration hardness. Because sliding applies shear forces at the surface, the limiting value obtained by Eq. (P-1) is usually modified to account for shear as

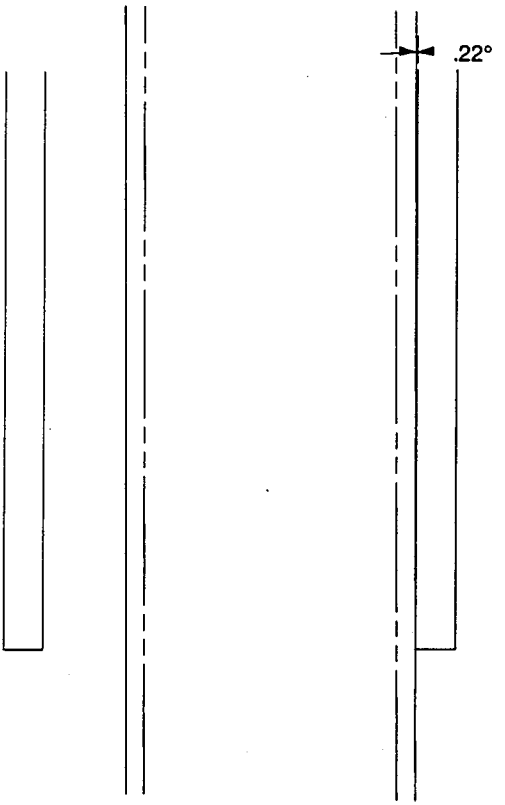


**Fig. P-3. Vertical section of the drill string in the conducting sleeve (to scale).**

$$A_r = \frac{L}{p}\sqrt{1+\alpha f^2}, \qquad \text{(P-2)}$$

where f is the coefficient of friction and $\alpha$ is an empirical constant.[4] When applied to the problem conditions described in Section P-2 above, the real contact area $A_r$ is estimated to be 13.1 $mm^2$ (see Reference 5 for calculation details).

The apparent contact area is needed to specify the area over which frictional heating occurs to enable calculation of the nominal surface temperature distribution.

Because the problem geometry involves both curved and straight surfaces (see Figs. P-2 and P-3), determination of the apparent area is not straightforward, and a conservative approximation of ten times the real contact area is used (131 $mm^2$). The contact area in the problem considered here is probably elliptical.[6] To convert the area above to an ellipse, the major axis length is assumed to be four times the minor axis height. The resulting elliptical area has a major axis length of 12.9 mm and a minor axis height of 3.2 mm.

## 4.0. FLASH TEMPERATURE RISE

Rabinowicz[2] summarizes the state of the art in estimating the flash temperature rise, and offers the following choices:

$$\theta = \frac{v}{2} \pm (\text{a factor of 3}), \qquad \text{(P-3)}$$

described as "an order of magnitude realistic" method, where $\theta$ is the flash temperature rise (°C) and v is the sliding velocity in cm/s. For our problem, this method yields an estimate of 8°C, with a range of 0°C to 33°C.

For the simplification of one circular junction of diameter $2r_j$ sliding on another material at moderate speed v, the interface attains an equilibrium mean temperature rise $\theta_m$ above the nominal surface temperature of

$$\theta_m = \frac{f\Delta L v}{4r_j(k_1 + k_2)}, \qquad \text{(P-4)}$$

where $r_j$ is the junction radius taken from the literature for dry steel on steel, and L is the applied load per junction, where the number of junctions is obtained by dividing the area of one junction of radius $r_j$ into the real contact area $A_r$. The thermal conductivities of the two materials in contact are denoted $k_1$ and $k_2$. For this problem, $\theta_m$ is estimated by Eq. (P-4) to be 3°C.

Finally, a method is presented based on surface energy considerations, yielding "an order of magnitude" estimate for $\theta_m$ of

$$\theta_m = \frac{7800 f W_{ab} v}{(k_1 + k_2)}, \qquad \text{(P-5)}$$

where $W_{ab}$ is the surface energy of adhesion. For our problem, this method yields the most conservative estimate of 46°C. This value was added to the maximum value calculated for the nominal surface temperature to estimate the peak surface temperature.

## 5.0. PEAK SURFACE TEMPERATURE CALCULATION

### 5.1. Nominal Surface Temperature Scoping Calculation

A scoping calculation was performed earlier, based on two semi-infinite bodies subjected to a sudden heat flux at the surface. This calculation used a different set of assumptions (fluted drill geometry in contact with the sleeve and a lower horizontal loading), but the results are qualitatively interesting. The calculation, described in Reference 5, concluded that a surface temperature rise on the order of several hundred degrees centigrade would require approximately 200 s. A corresponding steady-state interface temperature was calculated, with some general assumptions about convective heat transfer to the nitrogen drill-bit cooling and sleeve purge flow, at about 350°C.

### 5.2. Detailed Numerical Calculation of Nominal Surface Temperature

A detailed numerical model, with a two-dimensional drill string in contact with a three-dimensional sleeve was developed and applied. The string was modeled in two dimensions because the rotation smears any instantaneous azimuthal differences. The sleeve was modeled in three dimensions to account for the considerable heat capacity of the relatively thick wall and the extended area for convective heat transfer. Axial meshing was the same for both the string and the sleeve in the upper part of the model (through the contact region), and the drill string model extended below the sleeve. Approximately 1.45 m of overall drill string length was modeled, with the sleeve model just over half that length. The model axial ends were assumed adiabatic. Although the outer surface of the sleeve would be cooled by natural convection and could radiate heat to the cold tank interior, the outer surface of the sleeve and the outer surface of the drill string below the sleeve were conservatively considered to be adiabatic.

The finite-difference meshing can be varied, depending on the problem definition and expected thermal gradients. The axial meshing used to date is quite fine in the region of contact, being about one-fourth the thermal diffusion length for one revolution of the string. The axial nodes get courser as they get farther from the contact region. Both the drill string and the sleeve had three radial nodes for the calculations discussed here, with the outer drill-string-node thickness and the inner sleeve-node thickness kept equal. The azimuthal noding of the sleeve was relatively fine, as can be seen in Fig. P-4. The resulting model had 903 separate nodes. Frictional heating was applied to the contact region based on the elliptical

contact area described earlier. Because frictional heating occurs throughout the volume "worked" in sliding contact and because the material properties of the sleeve and drill string are similar, half of the heat was applied to each component. The contact region was coupled with a conduction model with contact resistance, allowing heat to flow across the interface in either direction as dictated by the instantaneous temperature distribution. Convective cooling (or heating farther down the string interior) was included in both the drill string and the sleeve-to-drill annulus. The annulus convection model included the effect of ten different temperature surfaces (nine azimuthal sleeve nodes and the drill string outer surface).

The model was developed and solved within the architecture of the Los Alamos Systems Analysis (LASAN) code package.[7] LASAN materials properties and convective cooling routines were applied directly. The resulting model had 903 nonlinear ordinary differential equations that were solved simultaneously with a fully implicit integration algorithm. Temperature-dependent material properties were used throughout. The maximum surface temperature and its location were saved at each time step along with user-defined list variables and plot variables. Details of the model can be found in Reference 5.

### 5.3. Peak Surface Temperature Estimates

Figure P-5 presents the estimate for the peak surface temperature as a function of time after initial contact. The lower curve is the maximum temperature calculated with the numerical model described above. The conservative flash temperature rise from Eq. P-5 is added to yield the estimated peak surface temperature as a function of time. This is the peak surface temperature calculated with very conservative assumptions, which should bound the "expected" temperatures. The conservative estimate of the maximum possible "worst-case" surface temperature can be found in the following section.

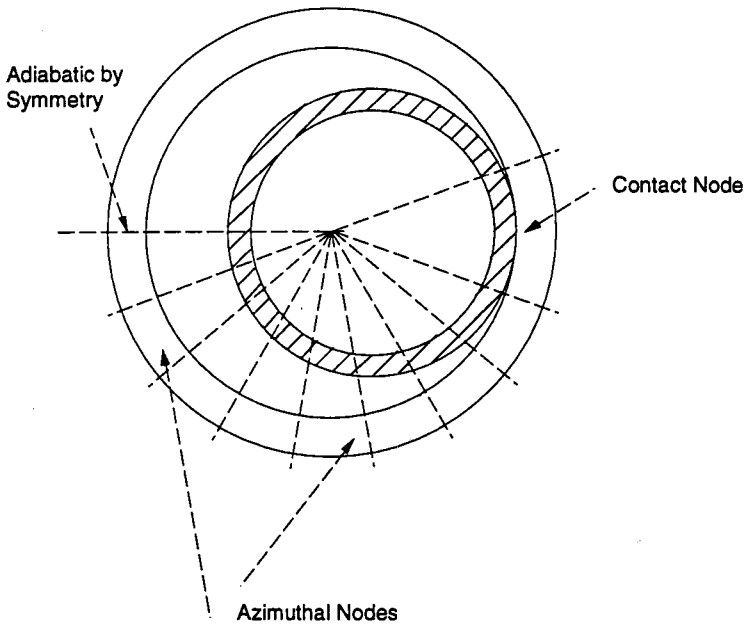


**Fig. P-4. Azimuthal noding of the sleeve. Nine azimuthal nodes are actually calculated (symmetry gives the effect of 17 nodes with an adiabatic boundary opposite the contact region).**

## 6.0. WORST-CASE HOT-SPOT TEMPERATURE, AREA, AND LIFETIME

The literature presents an equation for the "worst-case temperature rise." This equation results from applying Eq. (P-4) with a *single* asperity of area $A_r$. Application to our problem results in an estimated worst-case temperature rise above the nominal surface temperature of 577°C. The area of the hot spot is the real contact area, $A_r$, or 13.1 $mm^2$. This small volume would be expected to cool rapidly to the nominal surface temperature. Because the "single asperity" would be plastically deformed in sliding while carrying the *entire* applied load, it is reasonable to assume that this condition could only occur early in the dry sliding contact of two surfaces.

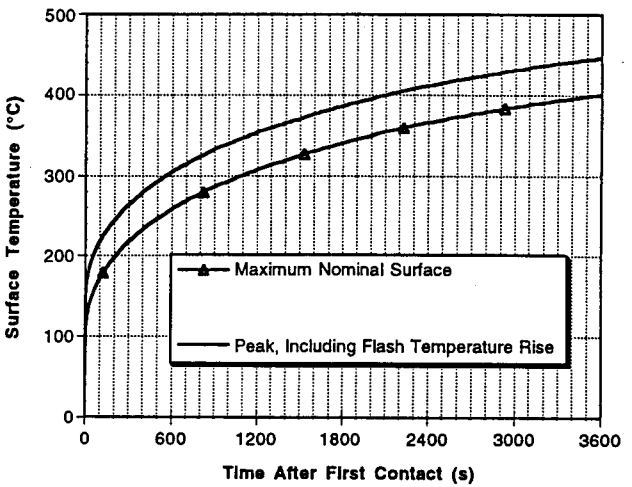


**Fig. P-5. Estimated peak surface temperature as a function of time after initial contact. The lower curve is calculated with the numerical model described. The upper curve results when the conservative "flash temperature rise" is added to the numerical results.**

To determine the lifetime, or time-temperature history, of this hot spot, a numerical calculation was performed. It was assumed that the spot was formed on the first revolution in contact, so the nominal surface temperature was the initial temperature (assumed to be 38°C). When this 13.1 $mm^2$ spot is swept out from under the contact area, heating stops and cooling begins. Because conduction is expected to dominate, convective and radiative heat removal were ignored.

The average surface roughness (from ANSI B46.1-1978) for cold rolled or drawn materials ranges from about 1-10 μm.[1] The asperity height chosen for this analysis (100 μm) ensures that the contact point is well above the nominal surface. The analysis is quite sensitive to the assumed height of the contacting asperity, because the volume of the hot spot and the conduction length to the cooler surface both depend directly on the height. Using temperature-dependent material properties

and the LASAN solver described above, the profile shown in Fig. P-6 was calculated. It can be seen that the hot spot drops below 400°C within 0.6 ms.

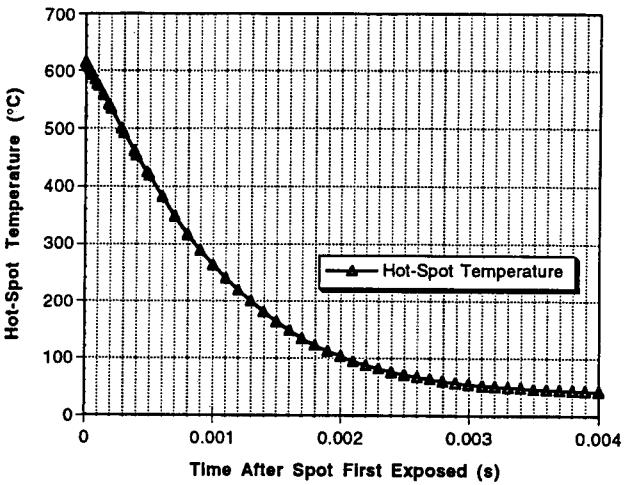


**Fig. P-6. Transient cooling curve for a "worst-case" hot spot. It can be seen that the very small (13.1 mm²) hot spot cools to below 400°C in less than 0.6 ms when exposed from under the contact area.**

## 7.0. CONCLUSIONS FOR DRILL-STRING-TO-SLEEVE CONTACT

The analyses above show that frictional ignition from a drill-string-to-sleeve contact event is unlikely. Even for a very conservative set of boundary conditions and loading assumptions (which probably could not be physically sustained for a long period), it takes on the order of 2100 seconds to reach surface temperatures of 400°C (500°C is not reached in 1 hour of contact). Although the possibility of a worst-case hot spot with a rapid, higher temperature rise cannot be precluded, analysis has shown the lifetime above 400°C to be very short, and the area is very small. With the nitrogen purge between the sleeve and the drill string, the presence of a combustible mixture in the vicinity of the hot spot is not likely. Consideration of the minimum surface temperature and the necessary area and induction time for

ignition indicate that ignition is not expected even if a combustible mixture happens to be present.

An experimental and theoretical study of the ignition of hydrogen/oxygen/nitrogen mixtures by hot surfaces, done for Canadian (CANDU) reactor licensing, provides methods for estimating both the minimum ignition surface temperature (MIST) and the induction time for ignition by surfaces with temperatures above the MIST.[8] For "20% and 30% hydrogen in air," the MIST was determined to be 916.2 K (643°C), which is higher than any of the temperatures calculated above. For temperatures below the MIST, the induction time is infinite (that is, ignition is not expected to occur, and did not occur in the experimental program).

However, as noted in the introduction to this appendix, there is considerable controversy about the ability to estimate the temperatures arising from dry metal-to-metal sliding. In order to conclude that ignition caused by drill string frictional contact with the sleeve is not likely with a high degree of confidence, it is necessary to obtain experimental verification by performing prototypical ignition testing. As test results are factored in, the predictive capability of the analysis will improve and the associated uncertainty will be reduced.

## 8.0. FRICTIONAL HEATING IN FAN-TO-CASE CONTACT

### 8.1. Scoping Calculation

A question has been raised about the possibility of frictional ignition by the exhauster fan during rotary-mode core sampling operations. The fan and its case are both made of aluminum. It is possible, using surface energy methods, to estimate the flash temperature rise above the nominal surface temperature resulting from dry metal-to-metal sliding as a function of sliding velocity.

Rabinowicz[2] develops an equation for the flash temperature rise based on surface energy considerations, presented earlier as Eq. (P-5). It can be noted that all parameters in this expression are material constants, with the exception of the sliding velocity. It is, therefore, particularly attractive for scoping estimates where a specific "event sequence" has not been postulated.

For aluminum, Table 2.1 of Reference 2 gives a value for the surface energy, $\gamma$, of 900 $mJ/m^2$ (0.9 $J/m^2$). The surface energy of adhesion for two materials in contact, $W_{ab}$, is defined as[2]

$$W_{ab} = c_m \left(\gamma_a + \gamma_b\right), \qquad \text{(P-6)}$$

where the compatibility parameter, $c_m$, is 1.0 for identical metals, yielding a value for $W_{ab}$ of 1.8 J/m$^2$. The coefficient of friction, f, for dry sliding of aluminum on aluminum is quite high. Marks' Handbook[3] gives a value of 1.4, confirmed by Figure 4.16 in Reference 2. The thermal conductivity for "generic" aluminum[9] is about 200 W/m °C.

Using the values listed above, Eq. (P-5) yields a unit-velocity flash temperature rise of about 49°C per m/s of sliding velocity. This value is only one-sixth of the comparable value for the drill-string-to-sleeve (carbon-steel/stainless-steel) problem above of 288°C per m/s of sliding velocity, but the potential sliding speeds in fan-to-case contact are much higher. Assuming an initial temperature of 38°C, any sliding velocity above about 12.7 m/s will produce melting using this simple model. (The drill-string-to-sleeve contact has a surface sliding velocity of only 0.16 m/s).

The exhauster ventilation fan has a 0.381-m (15-in.) o.d. and a maximum rotational speed of about 2400 rpm (estimated at the 60% power limit, 4.5 hp point — typical operating point is 28% power).[10] These fan characteristics give a tip speed of almost 48 m/s. Together with the unit-velocity flash temperature rise calculated above, this sliding speed gives a temperature well above the melting point of aluminum (conservatively
660°C, reported values for different material specifications range from 643°C to 657°C). In such cases, the temperature rise is limited to the melt temperature by the phenomenon of melt lubrication, which greatly reduces the coefficient of friction. This reduction in friction reduces the subsequent heating rate and limits the total quantity of material melted.

### 8.2. Discussion of Exhauster Fan-to-Case Frictional Heating

The first thing to remember is that the above estimate is an order of magnitude estimate for the mean flash temperature rise in equilibrium. Here equilibrium presumably means contact and constant sliding speed and because heat capacity does not appear in Eq. (P-5), thermal equilibrium of the "junctions" is expected. However, the junctions involved in the flash temperature *rise* (above the nominal surface) are *very* small and will reach thermal equilibrium quickly (assumed instantaneously in the friction and wear literature). But, a short duration "impact" could be different. Also, Eq. (P-5) gave the highest temperatures, by far, of three methods used in the drill-string-to-sleeve problem.

A second, and perhaps more important, consideration is what conditions are required for ignition of a hydrogen/air mixture by a hot surface. As mentioned in Section P-7 above, an experimental and theoretical study of ignition of hydrogen/oxygen/nitrogen mixtures by hot surfaces, done for Canadian reactor

licensing, provides methods for estimating both the minimum ignition surface temperature and the induction time for ignition by surfaces with temperatures above the MIST.[8] For "20% and 30% hydrogen in air," the MIST was determined to be 916.2 K (643°C), or very close to the melt temperature of aluminum. For temperatures below the MIST, the induction time is infinite (that is, ignition is not expected to occur, and did not occur in the experimental program).

The relationship between the surface temperature, $T_s$, and induction time, $t^*$, was given as

$$T_S = T_{S\infty} e^{A/t^*}, \qquad \text{(P-7)}$$

where $T_{S\infty}$ is the MIST and A is an empirical characteristic time constant. For "20% and 30% hydrogen in air," A was reported to be 5.08e-5 s.

Rearranging Eq. (P-7) to solve for $t^*$ given $T_s$,

$$t^* = \frac{A}{\ln\left(\frac{T_S}{T_{S\infty}}\right)}. \qquad \text{(P-8)}$$

For $T_s$ at the melting point of aluminum, the induction time $t^*$ calculated with Eq. (P-8) is 2.77 ms.

To determine the hot-spot lifetime above the MIST, a simple 1D transient heat transfer calculation was performed. The hot-spot thickness was taken to be 20 μm, as measured in experimental studies of methane ignition by a molten metal smear produced by worn coal-mining bits.[11] In a one-dimensional calculation, the area drops out if the calculation is based on the enthalpy per unit area (the time derivative is the heat flux). Because conduction was expected to dominate, other heat-transfer mechanisms such as convection to the ventilation flow and radiation to the ambient-temperature environment were ignored. The system was assumed to be initially at 38°C. The thermal conductivity and heat capacity of the melt were assumed to be equal to that of solid aluminum. The simple model was solved numerically with the LASAN code package.[7]

Figure P-7 displays the transient cooling of the melt smear to the ambient temperature surface. The plateau represents the time required to remove the heat of fusion from the melt. It can be readily seen that the hot smear is very short lived, with the time above the MIST temperature less than 4 μs and the time above 400°C less than 7 μs.

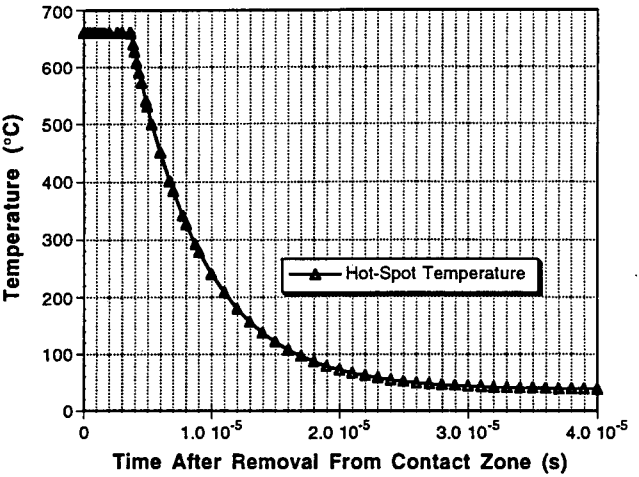


**Fig. P-7. Transient cooling curve for a 20-μm-thick hot-melt smear as a function of time after the melt is swept out of the contact zone. At that point, heating stops and conduction to the cool surface begins. The plateau represents the time required to remove the heat of fusion from the melt.**

This transient cooling is quite sensitive to the assumed melt-smear thickness, because both the volume of hot material and conduction length to the cooler surface depend directly on the assumed thickness. To assess the sensitivity, the problem was rerun with the assumed melt-smear thickness increased by a factor of 10 to 200 μm. Results for this parametric sensitivity calculation are shown in Fig. P-8. While the lifetimes are much longer than the base case, they are still short compared to the calculated induction time of 2.77 ms. Examination of Fig. P-8 shows the time above the MIST temperature is less than 0.4 ms, and the time above 400°C is less than 0.65 ms. At a sliding velocity of 48 m/s, this 0.65 ms lifetime would produce a smear above 400°C about 3 cm long (width depends on geometry of contact).

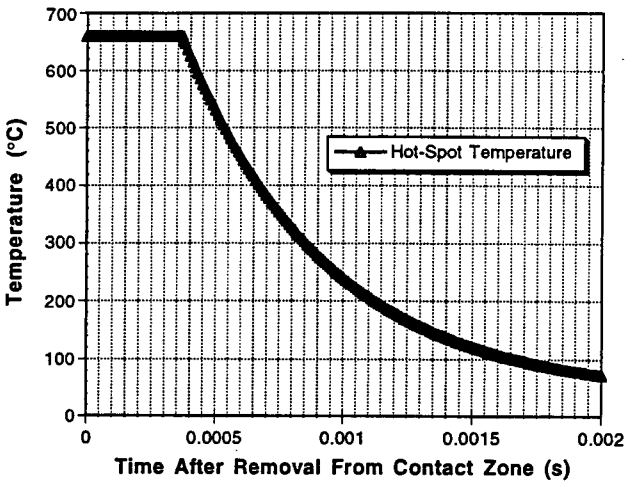


**Fig. P-8. Transient cooling curve for a 200-μm-thick (10 x expected) hot-melt smear as a function of time after the melt is swept out of the contact zone. At that point, heating stops and conduction to the cool surface begins. The plateau represents the time required to remove the heat of fusion from the melt.**

### 8.3. Conclusions for Exhauster Fan-to-Case Frictional Heating

Based on the simple analysis above, it appears unlikely that ignition would result from short-term contact between the exhauster fan and case, even though quite high local temperatures can be generated. The question of surface temperatures resulting from long-term rubbing is more difficult and would require detailed modeling of the fan and case to address. However, it requires a mechanical failure for fan-to-case contact to occur; therefore, sustained powered fan operation with contact is unlikely. If sustained rubbing is determined to be possible, the high thermal conductivity of aluminum provides some time to sense contact and interrupt fan power. Because the hot spots are quite localized, but at high temperatures, an optical temperature measurement (for example infrared) might be possible (depending on case geometry and "view factors"). This analysis is further documented in Reference 12.

## 9.0. REFERENCES


1. H. E. Boyer and T. L. Gall, editors, *Metals Handbook Desk Edition*, (American Society for Metals, Metals Park, Ohio, 1985).

2. E. Rabinowicz, *Friction and Wear of Materials*, 2nd ed., (John Wiley and Sons, New York,New York, 1995).

3. T. Baumeister and L. S. Marks, editors, *Standard Handbook for Mechanical Engineers*, 7th ed., (McGraw-Hill, New York, New York, 1978).

4. J. S. Courtney-Pratt and E. Eisner, "The Effect of a Tangential Force on the Contact of Metallic Bodies," *Proc. Royal Soc.* A, Vol. 238, 529-550 (August 1956).

5. K. R. Stroh, "Analysis of Frictional Heating in Drill-String-to-Sleeve Contact," Los Alamos National Laboratory Calc-Note TSA10-CN-WT-SA-ST-092, (March 1996).

6. J. Bos and H. Moes, "Frictional Heating of Tribological Contacts," Journal of Tribology, Vol. 117, 171-177, (January 1995).

7. K. R. Stroh, G. J. Willcutt, Jr., M. L. Walsh, and A. G. Barker-Wohletz, "LASAN-3 - A General Purpose Code for the Simulation of Large-Scale Complex Systems," Los Alamos National Laboratory report, DRAFT November 1992.

8. R. K. Kumar and G. W. Koroll, "Ignitability of Hydrogen/Oxygen/Diluent Mixtures in the Presence of Hot Surfaces," *Nuclear Safety*, Vol. 36, No. 1, (January-June 1995).

9. J. P. Holman, *Heat Transfer*, 3rd Ed., (McGraw-Hill, New York, New York, 1972).

10. J. Robinson, Westinghouse Hanford Company, personal communication, February 22, 1996.

11. R. Blickensderfer, "Methane Ignition by Frictional Impact Heating," *Combustion and Flame*, Vol. 25, 143-152, (1975).

12. K. R. Stroh, "Analysis of Frictional Heating in Exhauster-Fan-to-Case Contact," Los Alamos National Laboratory Calc-Note TSA10-CN-WT-SA-ST-093, (March 1996).

# APPENDIX Q

# SAMPLE PROBLEM FOR THE COMPUTATION OF THE SITE-WIDE RISK

## 1.0. INTRODUCTION

Rotary-mode core sampling (RMCS) operations will be performed in a number of tanks during the course of the year. In this safety assessment (SA), the bounding accident consequences and frequencies are computed. In doing so, a bounding tank was chosen in such a way that both the consequences and frequencies of a given accident were computed conservatively. For instance, for the dome collapse accident (App. I), the maximum drop height that corresponds to a tank that is less than half full is chosen. Likewise, the "super tank" source term that bounds all the single-shell tanks (SSTs) in the tank farm is used in quantifying the radiological consequences (App. R). The major accident scenario that leads to dome collapse is a deflagration in the dome space. In computing the accident frequency, large gas-release volumes that would normally be observed in full tanks (App. L) are used. Likewise, the minimum dome space volume is used in computing the dome concentrations (App. L), assuming a worse-case gas compositions (App. C). The bounding accident consequences are compared with the risk guidelines (RGs) (see Section 5) using the frequencies computed per year per tank basis.

However, it has been suggested that the frequency should be multiplied by the number of tanks that would be sampled during the year. There are reasons to question the validity of this approach. Simply multiplying "super tank" worse case accident frequencies by the number of sampling operations in the farm does not provide a reasonable estimate of the RMCS risk. At best, it provides a bound on the risk. The usefulness of this bound depends on its intended use.

The first reason to question whether this multiplication yields a reasonable estimate is the conservative nature of the assumptions used in deriving the bounding consequences computed in this SA. There is not a one tank that is represented by the super tank, hence there is no idea of how far removed the super tank is from a representative tank in accident frequencies and consequences. Because of the conservative nature of the SA results, no estimate of tank specific accidents frequencies has been made. Without further analysis, it is unknown, how representative the frequencies are to realistic tank conditions. In a similar vein, consequences based on a super tank are only meant to provide an upper bound. Again, it is unclear how far removed tank specific realistic consequences are from the bounding super tank consequences.

The second reason to question whether simple frequency multiplication is reasonable has to do with risk guidelines (RGs) in general, and WHC RGs in particular. Generally speaking, RG arose in the context of Probabilistic Risk

Assessment (PRA). The RGs are intended to be used with PRA results, which include conservative assumptions when warranted. However, the PRA results are not considered worse-case or bounding. Hence, RG would not normally be used with bounding results. The fact that bounding analyses yields results below the RGs means only that the realistic case is bounded. It does not provide information what the actual risk really is. More specifically, WHC RGs are not cumulative in nature. In other words, following the WHC RGs, all frequency/consequence point representing accident sequences are compared individually to the RG. It can be seen that any differences between a real tank and the super tank will manifest themselves as different points in frequency/consequence space.

Based on these discussions, we do not believe that the proposed approach of multiplying the frequencies by the number of tanks may not be adequate in obtaining a realistic risk for the RMCS operations. Such an approach may grossly overestimate the risk and result in slowing down progress in the characterization program.

In this appendix, an example problem is provided. In this sample problem, bounding SA consequences acquired using SA methodology are compared with the risk of performing the same activity in a collection of tanks. The 19 single-shell tanks (SSTs) that are on the original Flammable Gas Watch List (FGWL) are chosen as the collection of tanks in this example.

Before the quantitative evaluation of the sample problem is started, the reader must be warned that the objective is not to provide a total realistic site-wide risk for the RMCS operations. The sole objective is to demonstrate that multiplying the risk of a bounding accident obtained using the SA methodology by the number of tanks may grossly overestimate the risk. In the process, an attempt was made to use realistic assumptions and input parameters while linearizing many of the mechanistic models for simplicity.

## 2.0. DESCRIPTION OF SAMPLE PROBLEM

For the sample problem, the dome collapse accident is considered. In the following subsections, the mechanistic models used for consequence and frequency analysis are discussed.

### 2.1. Consequence Model

The model used in Appendix I shows that the respirable solid waste material (M) that becomes aerosol as a result of dome collapse is directly proportional to the impact energy of collapsing concrete and soil. Assuming a constant concrete and soil weight on each tank, the impact energy is proportional to the drop height (D). The radiological consequences (C) of the release is proportional to the amount of respirable material (M), the atmospheric dispersion coefficient ($\chi/Q$), and the unit dose associated with the waste material(S). Thus,

$$C \propto M \times S \times \left(\frac{\chi}{Q}\right) \propto D \times S \times \left(\frac{\chi}{Q}\right) \quad . \tag{Q-1}$$

For simplicity, the off-site consequences are considered using the approximation that the offsite receptor is at a constant distance and direction from each tank. Thus, the $\chi/Q$ for each tank is constant. However, for the bounding consequence analysis, 95% weather conditions are used. But, the tanks will be sampled at different times during the year, and the assumption that 5% weather conditions exist each time is overly conservative in assessing the risk. Assuming that the sampling activities are randomly spread over the year, the use of 50% meteorology is more appropriate for risk assessment. Thus, the ratio of individual tank consequence and the bounding consequence may be computed as

$$\frac{C_i}{C_{max}} = \frac{D_i}{D_{max}} \times \frac{S_i}{S_{max}} \times \frac{(\chi/Q)_{50\%}}{(\chi/Q)_{95\%}} \quad . \tag{Q-2}$$

## 2.2. Frequency Model

For this sample problem, it is assumed that the dome collapse scenario is a dome space deflagration caused by a lightning strike when flammable gases exist in the dome space. Each tank has the same cross-sectional area. Assuming that each tank has equal lightning protection, the lightning strike frequency per tank per year is constant. Thus, the frequency of dome deflagration caused by lightning is directly proportional to time-at-risk (T), which is defined as the time period during which the dome concentration is above flammable conditions. Thus,

$$F \propto T$$

Note that, for the purpose of this sample problem, lightning may be replaced with any other spark source which randomly occurs in time. To further simplify the problem, the following assumptions are introduced:

- Intrusion by the RMCS device causes a gas-release event (GRE) in each tank; and

- The volume of gas released is directly proportional to the volume of waste in the tank:

  $$Q \propto V_W = a \times V_W . \tag{Q-3}$$

  where Q is the gas-release volume, a is the proportionality constant and $W_W$ is the waste volume. This assumption may be challenged as not being applicable to all tanks depending upon the waste properties in each tank. On

the other hand, it can be argued that (based on the current knowledge of the overall SST waste properties and gas release mechanisms discussed in App. L), releasing a gas volume of 5 volume percent of the waste volume in each RMCS operations conservatively bounds all the tanks.

Assuming homogeneous mixing in the dome, the dome space concentration (X) as a result of the GRE is given by

$$X(t)=\begin{cases}1-\exp\left(-\frac{q}{V}t_o\right) & \text{if } 0\le t\le t_o\\ \left[1-\exp\left(-\frac{q}{V}t_o\right)\right]\exp\left[-\frac{w}{V}(t-t_o)\right] & \text{if } t>t_o\end{cases} \qquad \text{(Q-4)}$$

where q is the gas-release rate, V is the dome volume, t is the time after the GRE, $t_o$ is the release period, and w is the ventilation flow rate. Assuming an instantaneous release and linearizing the concentration decay curve, Equation (Q-4) yields:

$$X(t)=\frac{Q}{V}\left(1-\frac{w}{V}t\right) \quad wt<V \quad . \qquad \text{(Q-5)}$$

Defining the lean flammability of the gas mixture as the Low Flammability Limit (LFL), the time-at-risk (T) may be obtained as

$$T=\begin{cases}0, & \text{if } a\times V_w/V\le LFL\\ \frac{V}{w}\left(1-\frac{LFL\times V}{a\times V_w}\right), & \text{if } a\times V_w/V>LFL\end{cases} \qquad \text{(Q-6)}$$

Thus, the ratio of accident frequency for individual tanks to the bounding accident frequency can be computed as

$$\frac{T_i}{T_{max}}=\frac{V_i}{V_{max}}\frac{\left(1-\frac{LFL\times V,i}{a\times V_{w,i}}\right)}{\left(1-\frac{LFL\times V_{max}}{a\times V_{w,max}}\right)} \quad . \qquad \text{(Q-7)}$$

Two additional assumptions were introduced in deriving Eq. (Q-7):

- The same ventilation flow rate is used in all the tanks; and
- LFL is the same for all tanks and is equal to 0.04. One could introduce more details into this problem by using individual gas compositions and

corresponding LFL values as discussed in Appendix C. However, such an exercise would be academic at best for the purpose of this calculation.

## 3.0. RESULTS

For the bounding accident, we use the following parameters,

$V_{max}$ = 50000 $ft^3$ (App. C),
$D_{max}$ = 30 ft (App. I),
$S_{max}$ = 2.4 x $10^5$ Sv/L (App. R),
$(\chi/Q)_{95\%}$ = 1.9 x $10^{-5}$ $s/m^3$ (App. R),
$V_{w,max}$ = 130,000 $ft^3$ (App. C), and
a = 0.05 (conservative estimate based on discussions in App. L).

The 50% atmospheric dispersion coefficient is obtained from Reference 1 as approximately 10% of $(\chi/Q)_{95\%}$. The individual tank data are obtained from Appendix C and listed in Table Q-1. Also shown in Table Q-1 are the individual tank source terms [denoted as ($S_a$) obtained from Agnew's database].[2] This database includes only the $^{137}Sr$, $^{137}Cs$, and Pu. These nuclides make up ~70% of the bounding source term given in Appendix R. Thus, when using Agnew's data the comparable bounding source term would be $S_{max}$ = 1.6 x $10^5$ Sv/L (Ref. 2). The estimates by Agnew are based on historical fill records and a set of defined waste types that are based on many factors. Agnew defines a tank layer model (TLM), supernate mixing model (SMM) and total inventory (TI). In this sample problem, we use the TLM values because they are more representative of the total tank waste, and we used the bounding value where the maximum dose for each nuclide is chosen among the TLM, SMM and TI values. This is similar to the "super tank" approach used for the source terms in Appendix R. Instead of choosing the maximum nuclide for the entire tank farm, the maximum nuclide for a given tank is used. This source term is denoted as $S_{a,max}$ in Table Q-1.

Another alternative to using Agnew's data would be to use the SST flammable gas subset source term developed in Reference 3 for all the tanks. It can be argued that, because the database is small, this subset does not necessarily bound all the flammable-gas tanks. However, for the purpose of this sample problem, a realistic source term for each tank rather than a bounding source term for all the tanks is of interest. The SST flammable-gas subset given in Reference 3 is possibly still conservative for these purposes. The bounding SST flammable-gas source term is given as 6.1 x $10^3$ Sv/L (Ref. 3).

Details of the calculations are given in Reference 4. The results are summarized in Table Q-2.

**TABLE Q-1**
**INDIVIDUAL TANK DATA**

| TANK | V ($ft^3$) | $V_w$ ($ft^3$) | D (ft) | $S_a$ (Sv/L) | $S_{a,max}$ (Sv/L) |
|---|---|---|---|---|---|
| A-101 | 51,900 | 127,000 | 16 | 800 | 20,910 |
| AX-101 | 76,600 | 102,400 | 21 | 1460 | 38,500 |
| AX-103 | 163,500 | 15,600 | 41 | 5260 | 39,350 |
| S-102 | 65,200 | 75,500 | 20 | 400 | 2740 |
| S-111 | 65,200 | 75,500 | 20 | 1360 | 3950 |
| S-112 | 68,100 | 72,500 | 20 | 1170 | 6900 |
| SX-101 | 115,600 | 63,300 | 30 | 1580 | 2040 |
| SX-102 | 103,500 | 75,500 | 27 | 730 | 2820 |
| SX-103 | 88,700 | 90,200 | 24 | 1110 | 1510 |
| SX-104 | 91,600 | 87,300 | 25 | 1110 | 2200 |
| SX-105 | 84,300 | 94,600 | 23 | 1300 | 4750 |
| SX-106 | 102,700 | 76,200 | 27 | 660 | 1370 |
| SX-109 | 144,000 | 35,000 | 37 | 2710 | 2710 |
| T-110 | 57,600 | 54,500 | 16 | 60 | 60 |
| U-103 | 50,600 | 61,500 | 15 | 710 | 820 |
| U-105 | 56,900 | 55,200 | 16 | 920 | 960 |
| U-107 | 50,200 | 61,900 | 15 | 2690 | 11,270 |
| U-108 | 51,300 | 60,780 | 15 | 1570 | 17,500 |
| U-109 | 58,700 | 53,400 | 17 | 1780 | 6080 |

In Table Q-2, c represent the consequence from individual tanks as a percent of the bounding consequence ($C_{max}$). Thus,

$$c = 100\frac{C_i}{C_{max}} \quad . \tag{Q-8}$$

The individual accident frequencies (f) for the tanks are expressed as percent of the accident frequency for the bounding case ($F_{max}$). Thus,

$$f = 100\frac{F_i}{F_{max}} \quad . \tag{Q-9}$$

We define the risk as the product of frequency and consequences. The term r in Table Q-2 is defined as the percent fraction of the bounding risk. Thus,

$$r = 100\frac{R_i}{R_{max}} = 100\frac{F_i C_i}{F_{max} C_{max}} \quad . \tag{Q-10}$$

**TABLE Q-2**
**SAMPLE PROBLEM RESULTS**

| TANK | $c_1$ (%) | $c_2$ (%) | $c_3$ (%) | f (%) | $r_1$ (%) | $r_2$ (%) | $r_3$ (%) |
|---|---|---|---|---|---|---|---|
| A-101 | 0.14 | 0.03 | 0.69 | 100 | 0.14 | 0.03 | 0.70 |
| AX-101 | 0.18 | 0.06 | 1.66 | 89 | 0.16 | 0.06 | 1.48 |
| AX-103 | 0.35 | 0.44 | 3.32 | 0 | 0.00 | 0.00 | 0.00 |
| S-102 | 0.17 | 0.02 | 0.11 | 58 | 0.10 | 0.01 | 0.07 |
| S-111 | 0.17 | 0.06 | 0.16 | 58 | 0.10 | 0.03 | 0.10 |
| S-112 | 0.17 | 0.05 | 0.28 | 49 | 0.08 | 0.02 | 0.14 |
| SX-101 | 0.25 | 0.10 | 0.13 | 0 | 0.00 | 0.00 | 0.00 |
| SX-102 | 0.24 | 0.04 | 0.16 | 0 | 0.00 | 0.00 | 0.00 |
| SX-103 | 0.20 | 0.05 | 0.07 | 55 | 0.11 | 0.03 | 0.04 |
| SX-104 | 0.21 | 0.06 | 0.11 | 43 | 0.09 | 0.02 | 0.05 |
| SX-105 | 0.20 | 0.06 | 0.22 | 70 | 0.14 | 0.04 | 0.16 |
| SX-106 | 0.23 | 0.04 | 0.08 | 0 | 0.00 | 0.00 | 0.00 |
| SX-109 | 0.31 | 0.21 | 0.21 | 0 | 0.00 | 0.00 | 0.00 |
| T-110 | 0.14 | 0.00 | 0.00 | 26 | 0.04 | 0.00 | 0.00 |
| U-103 | 0.13 | 0.02 | 0.03 | 50 | 0.06 | 0.01 | 0.01 |
| U-105 | 0.14 | 0.03 | 0.03 | 29 | 0.04 | 0.01 | 0.01 |
| U-107 | 0.13 | 0.08 | 0.35 | 51 | 0.07 | 0.04 | 0.18 |
| U-108 | 0.13 | 0.05 | 0.54 | 48 | 0.06 | 0.02 | 0.26 |
| U-109 | 0.14 | 0.06 | 0.21 | 21 | 0.03 | 0.01 | 0.04 |
| TOTAL | 3.6% | 1.5% | 8.4% | 746% | 1.2% | 0.3% | 3.2% |

Subscripts (1) Flammable Gas Source Term (Ref. 3)
(2) Agnew's Best-estimate Source Term $S_a$(Ref. 2)
(3) Agnew's Bounding Source Term $S_{a,max}$ (Ref. 2)

As shown in Table Q-2, the total consequences range between 1.4 and 8.4% of the bounding consequences using different source terms. The lowest cumulative consequence is obtained using Agnew's best-estimate source term. The highest consequence results from Agnew's bounding source term. These results suggest that, using conservative tank specific models, the offsite consequences of 19 consecutive dome collapses in a year is less than 10% of the bounding dome collapse consequences computed in this SA.

The major contribution to the overall consequences (>30%) is from Tank AX-103 which has a very small waste volume and a large dome volume. Thus, the deflagration frequency for this tank is 0 resulting in a 0% contribution to the overall risk.

The total relative frequency may be obtained as 7.5 (750% of the bounding tank frequency). The major contributors are tanks A-101 (100%) and AX-101 (~90%) because they have a large waste volume to dome volume ratio compared to other

tanks. Thus, for this sample problem, doing RMCS activities in 19 tanks increases the frequency by a factor of 7.5 instead of a factor of 19 that the conservative approach would require.

Finally, this sample problem shows that, using conservative tank-specific parameters, RMCS operations in 19 FGWL tanks would result in a total risk to an off-site individual, which is only 1.2% of the bounding risk computed in this SA (using the flammable-gas source term). Using Agnew's upper-bound source terms for each tank, the total risk becomes 3.2% of the risk obtained from bounding analysis. For the conservative case, nearly 70% of the total risk is from Tanks A-101 and AX-101 whereas the remaining 17 tanks only contribute 30% of the total risk. The maximum risk from an individual tank is from Tank AX-101, which is only 1.5% of the bounding risk.

## 4.0. SUMMARY AND CONCLUSIONS

The sample problem discussed in this appendix clearly illustrates that in obtaining the total risk associated with the RMCS operations in multiple tanks over a year, we should not take either the consequences or frequencies obtained for one tank and multiply it by the number of tanks. This approach would be overly conservative. The above sample problem demonstrates that using tank-specific yet conservative estimates, the total risk of dome collapse risk in running the RMCS device in 19 FGWL SSTs is ~3.2% of the bounding risk calculated in this SA per tank. Three big factors that reduce the total risk are as follow:

- The use of tank-specific source terms,
- The use of 50% meteorology in computing the atmospheric dispersion factors, and
- The use of tank-specific gas-release volume and time-at-risk magnitudes derived from a simple scale model.

Based on the analysis provided in Section 5 of this SA, the radiological offsite consequences of a dome collapse accident is < 10 rem. The mitigated frequency of the dome collapse accident for a bounding tank is shown to be < 1.0E-6/yr in this SA. Assuming a frequency of 1.0E-06/yr, the risk is equal to 1.0E-5 rem/yr.

As shown in this sample problem, the worse case consequence among the 19 FGWL tanks analyzed is 0.3 rem. In order to exceed the radiological offsite RGs, the accident frequency must be > 1.0E-2/yr.

In a typical risk assessment, one would complement the above calculations with an uncertainty analysis. The purpose in this appendix is not to provide a full risk assessment. First, a conservative source term is used even for tank specific conditions. Further, the orders of magnitude differences between the proposed

approaches demonstrate the point, and further analysis using these linearized simple models will be at most academic at this stage.

If one were interested in obtaining the site-wide risk associated with running the RMCS in all the flammable-gas tanks, an approach similar to the one shown here can be used. The use of the bounding accident consequences and frequencies as being applicable to each tank to estimate the site-wide risk will greatly overestimate the risk and unnecessarily slow down the progress in the tank characterization program.

## 5.0. REFERENCES

1. C. Unal, "Evaluation of Atmospheric Dispersion Coefficients at Elevated Discharge Temperatures, Velocities, Diameters and Release Heights by Using AI-RISK Computer Program," Los Alamos National Laboratory Calc-Note TSA10-CN-WT-SA-TH-078 (August 1995).

2. R. T. Perry, "Bounding Radioactive Source Term for Hanford Tanks," Los Alamos National Laboratory Calc-Note TSA10-CN-WT-SA-RAD-009 (November 1995).

3. R. J. Van Vleet, "Radionuclide and Chemical Inventories for the Single-Shell Tanks," Westinghouse Hanford Company report WHC-SD-WM-TI-543 (1993).

4. K. P. Pasamehmetoglu, "Computation of the Site-Wide Risk," Los Alamos National Laboratory Calc-Note TSA10-CN-WT-SA-TH-113 (February 1996).

# APPENDIX R

# SOURCE TERM, CRITICALITY, RADIATION EXPOSURES AND CONSEQUENCE CALCULATION METHODOLOGY

## 1.0. INTRODUCTION

In this appendix, the following issues are addressed:

Section 2.0: Bounding source terms applicable to single-shell tank (SST) waste are summarized. The inhalation doses resulting from the bounding source term also are included in this section.

Section 3.0: The criticality issues associated with the rotary-mode core sampling (RMCS) operations are discussed.

Section 4.0: The high-efficiency particulate air (HEPA) filter loading and resulting radiation exposure doses are estimated. Radiation doses from the shielded receiver and the drill unit also are discussed in this section.

Section 5.0: This section summarizes the methodology used for estimating the receptor doses from material releases.

## 2.0. SST SOURCE TERM

The radionuclides used in this safety assessment (SA) for the source term are based on an evaluation of the data characterizing the tank waste made by Westinghouse Hanford Corporation (WHC) engineers. The results are based upon the information contained in References 1 through 6. In addition, files of sample data collected by the Tank Characterization Program, Tank Characterization Report, and the Tank Contents Database maintained by Pacific Northwest Laboratories for WHC were also used. Scatter plots of activities versus tank and tables containing very high and very low activities were prepared from the reports and data noted. The results are given in Reference 7.

Eleven radionuclides that account for 99.9% of the total dose based on the data from References 1 and 2 were plotted. On each plot, a line was drawn that represented the maximum activity concentrations obtained. When an experimental sample point higher than the line was found, it was reviewed by a panel. If the panel could not technically justify eliminating the point, it was used. Conversely, the panel would lower a point on the line if it could be justified.

After the maximum sample activity concentrations were established, a maximum sample activity composite was developed for nine tank groupings based on the recommended maximum activity concentrations for each of the nuclides. A

nuclide is listed if it contributes to 0.1% or more of the activity. These source terms for SST solids and SST liquids are listed in Table R-1. These activities would be used for external exposure calculations.

The unit-liter-dose values that are used to calculate exposure from inhalation are based on the source terms described above and dose conversion factors. The dose conversions factors are those found in Reference 8. Multiplying the dose conversion factors for each nuclide by the source term for each nuclide results in a committed effective dose equivalent (CEDE). These CEDEs are summed for each composite for a total CEDE. The CEDEs summed with effective dose equivalent (EDE) caused by external dose radiation result in a total effective dose equivalent (TEDE). Here, however, the EDEs are negligible for all accident scenarios except for those involving a liquid pool. The results here assume that the TEDE is equal to the CEDE. The CEDE for SST liquids and SST solids based on the maximum activities per liter for SST tanks are also given in Table R-1.

## 3.0. CRITICALITY CAUSED BY RMCS OPERATIONS

The purpose of this section is to address the criticality issues associated with the RMCS operations. It presents calculations and the reasoning made to determine if the single-shell Flammable Gas Watch List tanks are criticality safe under all conditions for the proposed rotary-core drilling.

The maximum plutonium content found in any experimental sample in SST analysis forms the basis for the $^{239}Pu$ content. This value is given in Table R-1, which has the maximum value of plutonium found in any sample for SSTs.

For solids in single-shell tanks, the plutonium concentration is given as 4.4e+08 Bq/L. This value contains both the contribution from $^{239}Pu$ and $^{240}Pu$. Plutonium-240 is not fissionable. However, assuming all activity is caused by the fissionable $^{239}Pu$, this translates to 0.191 g/L, a bounding value for $^{239}Pu$ in single-shell tanks. The plutonium concentration demonstrated to be criticality safe has been calculated and reported in References 9 and 10.

The minimum critical plutonium concentration calculated by Rogers[9] was 2.6 g/L with a 95% confidence level. He used a reasonably conservative mixture of high-level tank waste, which did not include some significant neutron absorbers known to be in the waste. This analysis is discussed and accepted in Reference 11.

The minimum critical plutonium concentration calculated by Carter[10] was 3 g/L. He states that as long as the concentration in waste remains under this value, criticality will not occur for any conditions of moderation or reflection. This analysis is discussed and accepted in Reference 12.

## TABLE R-1
## ACCIDENT SOURCE TERM ACTIVITY CONCENTRATIONS AND UNIT-LITER-DOSE VALUES FOR ACCIDENTS INVOLVING RELEASE OF SOLID OR LIQUID TANK WASTE

| Nuclide | SST Liquid Source-Bq/L | SST Solid Source-Bq/L | Conversion Factor | SST Liquid CEDE-Sv/L | SST Solid CEDE-Sv/L |
|---|---|---|---|---|---|
| $^{14}C$ | 1.0e+05 | 1.2e+05 | 5.64e-10 | 5.9e-05 | 7.0e-05 |
| $^{60}Co$ | 1.2e+07 | 5.3e+08 | 5.91e-08 | 7.1e-01 | 3.1e+01 |
| $^{79}Se$ | * | 1.7e+04 | 2.66e-09 | * | 4.5e-05 |
| $^{90}Sr$ | 1.1e+10 | 1.7e+12 | 6.47e-08 | 7.2e+02 | 1.1e+05 |
| $^{90}Y$ | 1.1e+10 | 1.7e+12 | 2.28e-09 | 2.5e+01 | 3.9e+03 |
| $^{99}Tc$ | 1.7e+07 | 1.2e+10 | 2.77e-10 | 4.7e-03 | 3.4e+00 |
| $^{106}Ru$ | 3.3e+03 | 2.4e+05 | 1.29e-07 | 4.3e-04 | 3.1e-02 |
| $^{125}Sb$ | 5.3e+04 | 2.8e+08 | 3.30e-09 | 1.8e-04 | 9.2e-01 |
| $^{129}I$ | 1.0e+04 | 6.4e+08 | 4.69e-08 | 4.7e-04 | 3.0e-01 |
| $^{134}Cs$ | 2.1e+05 | 2.6e+06 | 1.25e-08 | 2.6e-03 | 3.2e-02 |
| $^{137}Cs$ | 2.3e+10 | 7.5e+10 | 8.63e-09 | 2.0e+02 | 6.5e+02 |
| $^{144}Ce$ | 4.3e+01 | 1.6e+03 | 1.01e-07 | 4.3e-06 | 1.6e-04 |
| $^{154}Eu$ | 2.7e+09 | 6.6e+09 | 7.73e-08 | 2.1e+02 | 5.1e+02 |
| $^{155}Eu$ | 7.5e+07 | 6.4e+06 | 1.12e-08 | 8.4e-01 | 7.1e-02 |
| $^{237}Np$ | * | 3.0e+07 | 1.46e-04 | * | 4.7e+03 |
| $^{238}Pu$ | 9.3e+04 | 1.9e+08 | 1.06e-04 | 9.8e+00 | 2.0e+04 |
| $^{239}Pu$** | 3.6e+07 | 4.4e+08 | 1.16e-04 | 4.2e+03 | 5.2e+04 |
| $^{241}Pu$ | 2.8e+08 | 3.5e+09 | 2.23e-06 | 6.3e+02 | 7.8e+03 |
| $^{241}Am$ | 3.7e+07 | 3.6e+08 | 1.20e-04 | 4.4e+03 | 4.4e+04 |
| | | | | | |
| ULD | | | | 1.0e+04 | 2.4e+05 |

*No Data Available. These radionuclides have a negligible impact on the radiological dose evaluations because of their low activity concentrations.

**The $^{239}Pu$ nuclide dose contribution also includes $^{240}Pu$.

ULD - unit-liter dose. ULD values are given for each composite in terms of committed effective dose equivalent (Sv) per unit-liter of waste inhaled at the location of the maximum on-site/off-site individual.

Because the bounding value of $^{239}Pu$ concentration in the tanks is 0.191 g/L, the tanks are currently criticality safe because this value is at least an order of magnitude less than the minimum critical plutonium concentration. The question then is whether there is a possible mechanism resulting from the rotary-core drilling that could concentrate the plutonium into a critical configuration.

The rotary-core drilling will not add any fissionable material to the tank, and in fact, will be removing some material during the process as the drill penetrates the salt cake. Pockets of possible high concentration would not be forced into smaller volumes; they would be removed as the drill passes through. The process should actually decrease the multiplication factor by removing material.

If the drill enters a liquid layer, the material would be displaced without concentration. The plutonium concentration in liquid is less than that found in solids by an order of magnitude or more, according to Table R-1. If the liquid were forced into the salt or sludge, it would serve as a diluent, resulting again in a decrease in the multiplication factor.

If the drill enters the sludge in the bottom of the tank, the sludge would be mixed if the sampling is assumed to cause a local rollover or tank rollover through a gas-release mechanism, resulting in a mixture with a layer with less concentration of Pu, again acting as a diluent.

The above analysis and facts provide assurance that nuclear criticality within the single-shell Flammable Gas Watch List tanks will not occur as a result of RMCS.

## 4.0. RADIATION EXPOSURE CALCULATIONS

In this section we estimate the radiation exposure from the HEPA filters, shielded receiver, and the drill string. Only gamma exposure is calculated. The gamma source strength in the solid is from the column labeled "SST Solid" in Table R-1. The only gamma emitter of importance is $^{137m}Ba$, a daughter of the decay of $^{137}Cs$. The source strength of $^{137}Cs$ from the column "SST Solid" is 7.5e10 Bq/L. The $^{137}Cs$ is in secular equilibrium with $^{137m}Ba$, and 94.6% of the decay from $^{137}Cs$ produces $^{13m}Ba$. Using a salt density of 2.2 grams/$cm^3$, the $^{137m}Ba$ source strength is 8.71e-04 Ci/g.

### 4.1. HEPA Filter Loading and Radiation Exposure

The HEPA filter is designed to trap the particle escaping the tank during the drilling operations. This note gives an estimate of the exposure from the filter caused by the capture of the radioactive particles during drilling operations.

In Table 2 of Ref. 13, the total mass out of the riser and to the HEPA filter is 901 g, a value based on continuous operation of the exhauster, a total drilling depth of 266 inches, and a schedule of 40 minutes of drilling (19 inches) followed by a 60-minute delay before starting the next drilling period. Only particles greater than 5.5 μm were assumed to have been carried up the stack. The total exhaust flow for the case used here is 250 $ft^3$/min. These results were calculated using the TRAC-TE code. This code and the results are discussed in Reference 13. The results take into account the settling of the aerosol created. The time required to reach an equilibrium concentration was not given; however, the time required to reach an equilibrium condition for a 700 scfm with continuous exhauster flow case was given as 400 minutes. For this 700-$ft^3$/min case, the mass flow rate out the stack for the first 100 minutes was 90% of the average mass flow rate. Thus, for the calculations in this note, it is not unreasonable to use an average exhaust rate of 901g/1400 minutes, i.e., 64.4 grams captured in the filter in 100 minutes of operation. This would be one drilling period and one hour's wait. The filter would have 64.4 grams x 8.71 Ci/g loading.

Using the code MicroShield,[14] a filter geometry of 24 in. x 24 in. x 11.5 in. containing $SiO_2$ at a density of 0.1 g/$cm^3$, we find the exposure at 1 cm from the surface is 317 mR/h at the end of 100 minutes of operation. This exposure may be scaled with units of 100 minutes of time because it is based on an average mass flow rate.

The maximum allowable dose for a worker is 300 mrem/week. These calculations indicate that there may be cases in which this limit could be exceeded. It is necessary then that health and safety personnel monitor the filter during operation. Also, the size of the exposure seems to require a prefilter in the limiting cases when the source term is of this size.

### 4.2. Radiation Exposure From Shielded Receiver and Drill Unit

**Shielded Receiver.** The receiver is modeled as a series of concentric cylinders 19 inches long. The dimensions and materials are given in Table R-2.

**TABLE R-2**
**MATERIALS, DIMENSIONS, AND DENSITY OF THE SAMPLE RECEIVER**

| Material | Density, (g/$cm^3$) | Maximum Radius (in.) |
|---|---|---|
| | | |
| $NaNO_3$ | 2.2 | 0.564 |
| Steel | 7.93 | 0.75 |
| Air | 0.00122 | 1.0335 |
| Steel | 7.93 | 1.1875 |
| Lead | 11.34 | 2.013 |
| Steel | 7.93 | 2.25 |

The source-containing material is modeled as $NaNO_3$. The $^{137m}Ba$ source contained in the $NaNO_3$ is 0.596 curies (7.0874e+07 $Bq/cm^3$). Using the code MicroShield,[14] we find the exposure at 1 cm from the surface is 211 mR/h. The bounding value of exposure calculated is 211 mR/h at 1 cm from the surface of the receiver. It would be expected that there would be no samples that would actually produce this value because the samples would contain liquid that have a lower source strength. In addition, the source strength used here is the maximum found in any sample. However, this value could cause a worker to exceed the limit of 300 mrem/week. It is necessary then that health and safety personnel monitor the receiver during operation.

**Contaminated Pintle Rod.** In this section, the exposure rate from a contaminated pintle rod is determined. The exposures determined are results from the MicroShield code. In these calculations, the equivalent volume of waste that would be found on a contaminated pintle rod is modeled in the center of the quill rod. These approximations are conservative.

The volumes of waste placed in the center of the quill rod are based on a 1-mm and a 3-mm-thick contamination on the pintle rod. The pintle rod is 92.48 cm long with a radius of 0.237 cm. A 1-mm contamination gives an equivalent radius of 0.24 cm of contamination in the center of the quill rod and a 3-mm contamination gives an equivalent radius of 0.482 cm. Using the bounding value of $^{137}Cs$ found in solid waste, the two source strengths are 0.137 and .0338 Ci, respectively.

The steel quill rod has an inside radius of 2.42 cm and an outside radius of 2.875 cm. The exposure as determined using MicroShield at 1 cm from the surface of the quill rod for the 1-mm contamination is 0.72 R/h, and for the 3-mm contamination, the exposure at 1 cm for the surface of the quill rod is 2.84 R/h. At 1 meter from the surface of the quill rod, the exposure is 8.6 mR/h for the 1-mm contamination and 35 mR/h for the 3-mm contamination.

The magnitude of these exposures indicates that radiation monitoring of the quill rod is necessary to prevent unnecessary exposure to personnel in the event that the rod becomes contaminated.

## 5.0. RECEPTOR DOSE CALCULATIONS

In this section, the radiological dose calculation methodology is discussed. The methodology is adopted from Reference 15 for consistency with other safety basis documents employed at the Hanford Site. In Reference 16, this methodology is compared with the AI-RISK methodology[17] previously used in the Tank 101-SY Mixer Pump SA.[18] The receptor dose is calculated as

$$D = Q \times \frac{\chi}{Q'} \times R \times ULD \qquad \text{(R-1)}$$

where

D is the dose in Sv,
Q is the material release volume (L),
$\chi/Q'$ is the atmospheric dispersion coefficient (see Tables R-3 and R-4),
R is the breathing rate
= $3.3 \times 10^{-4}$ $m^3/s$ typical acute breathing rate (light activity)
= $2.7 \times 10^{-4}$ $m^3/s$ typical chronic breathing rate (24 h average), and
ULD is the unit liter dose in Sv/L obtained from Table R-1.

The atmospheric dispersion coefficients are obtained using the computer code GXQ, which uses the methods in the Nuclear Regulatory Commission (NRC) Regulatory Guide 1.145 (Ref. 19). The atmospheric dispersion coefficient is the time-integrated normalized air concentration at the receptor for radiological releases and continuous chemical releases. For puff chemical releases the atmospheric dispersion coefficient is the instantaneous maximum concentration at the receptor. Only the plume meander correction was used in the calculations. The coefficients used to calculate dose or concentration are presented in Tables R-3 through Table R-4. The acute release values were developed for weather conditions that result in downwind concentrations exceeded only 0.5% of the time in the maximum sector (16 sectors) or 5% of the time for the overall site. The larger of the two values was used as the integrated bounding value for the on-site and off-site individuals. The chronic annual average $\chi/Q'$ values were obtained by calculating chronic annual average values for each sector and using the highest value for calculation purposes. This value is suitable for long-term releases but not for accidents.

**TABLE R-3**
**DISPERSION COEFFICIENTS**

| RECEPTOR | $\chi/Q'$ ($s/m^3$) | $\chi/Q'$ with PM* ($s/m^3$) | CAA** $\chi/Q'$ ($s/m^3$) |
|---|---|---|---|
| Onsite | 3.44 E-02 | 1.13 E-02 | 4.03 E-04 |
| Offsite | 1.88 E-05 | 1.49 E-05 | 9.16 E-08 |

*PM: plume meander correction applied
** CAA: chronic annual average

For a release duration of less than 1 h, the $\chi/Q'$ (first column) is used. For a release duration between 1 and 2 h, the plume meander correction is applied, and the $\chi/Q'$ with PM (second column) is used. For a release duration greater than 8760 h (1 yr), the CCA $\chi/Q'$ (third column) is used. For a release duration between 2 h and 8760 h, a logarithmic interpolation between values in column 2 and column 3 is used. The

offsite receptor distances for the 200-Area tank farms obtained from Reference 15 are shown in Table R-4.

**TABLE R-4**
**SITE BOUNDARY DISTANCES FOR THE TANK FARMS[15]**

| Direction | Distance (km) |
|---|---|
| S | 16.650 |
| SSW | 16.650 |
| SW | 13.875 |
| WSW | 11.100 |
| W | 11.100 |
| WNW | 11.100 |
| NW | 14.800 |
| NNW | 14.800 |
| N | 16.650 |
| NNE | 23.125 |
| NE | 19.425 |
| ENE | 15.725 |
| E | 15.725 |
| ESE | 21.275 |
| SE | 24.975 |
| SSE | 21.275 |

One case referred to in this SA requires the evaluation of the dispersion coefficient for a 1-wk (168-hr) duration release. Applying the logarithmic interpolation, the on-site and off-site dispersion coefficients may be obtained as

$$\frac{\log(1.13\times10^{-2})-\log\left(\frac{\chi}{Q'}\right)}{\log(1.13\times10^{-2})-\log(4.03\times10^{-4})}=\frac{\log(2h)-\log(168h)}{\log(2h)-\log(8760h)}=\frac{\chi}{Q'}=1.94\times10^{-3}$$

and

$$\frac{\log(1.49\times10^{-5})-\log\left(\frac{\chi}{Q'}\right)}{\log(1.49\times10^{-5})-\log(9.16\times10^{-8})}=\frac{\log(2h)-\log(168h)}{\log(2h)-\log(8760h)}=\frac{\chi}{Q'}=1.01\times10^{-6}$$

respectively.

Table R-5 provides the receptor doses for a 1-L release.

TABLE R-5
RECEPTOR DOSES FOR A 1-LITER RELEASE

| | ONSITE | | OFFSITE | |
|---|---|---|---|---|
| | SST Solid | SST Liquid | SST Solid | SST Liquid |
| Prompt (< 1h) | 2.76E+00 Sv<br>2.76E+02 rem | 1.15E-01 Sv<br>1.15E+01 rem | 1.49E-03 Sv<br>1.49E-01 rem | 6.20E-05<br>6.20E-03 rem |
| 1 week | 1.54E-01 Sv<br>1.54E+01 rem | 6.40E-03 Sv<br>6.40E-01 rem | 8.00E-05 Sv<br>8.00E-03 rem | 3.33E-06 Sv<br>3.33E-04 rem |
| 1 month | 8.65E-03 Sv<br>8.65E-01 rem | 3.60e-05 Sv<br>3.60E-02 rem | 3.31E-05 Sv<br>3.31E-03 rem | 1.38E-06 Sv<br>1.38E-04 rem |
| 1 year | 3.20E-03 Sv<br>3.20E-01 rem | 1.33E-05 Sv<br>1.33E-02 rem | 7.26E-06 Sv<br>7.26E-04 rem | 3.02E-07 Sv<br>3.02E-05 rem |

## 6.0. REFERENCES


1. R. J. Van Vleet, "Radionuclide and Chemical Inventories for the Double Shell Tanks," Westinghouse Hanford Company report WHC-SD-WM-TI-543 (1993).

2. R. J. Van Vleet, "Radionuclide and Chemical Inventories for the Single Shell Tanks," Westinghouse Hanford Company report WHC-SD-WM-TI-565 (1993).

3. D. J. Braun, et al., "High-Level Waste Tank Subcriticality Safety Assessment," Westinghouse Hanford Company report WHC-SC-WM-SARR-003 (1994).

4. F. M. Jungfleisch, "TRAC: Preliminary Estimation of the Waste Inventories in Hanford Tanks Through 1980," Westinghouse Hanford Company report WHC-SD-WM-TI-057 (1984).

5. S. R. Agnew, "Estimated Chemical and Radiochemical Inventories Spreadsheet: NE Quadrant, A, AX, B, BX, BY, C Farms," Westinghouse Hanford Company report WHC-SD-WM-TI-628, Rev. 0, (1994).

6. S. R. Agnew, "Estimated Chemical and Radiochemical Inventories Spreadsheet: SW Quadrant, S, SX, U Farms," Westinghouse Hanford Company report WHC-SD-WM-TI-631, Rev. 0 (1994).

7. W. L. Cowley, "Tank Waste Source Term Inventory Validation," Westinghouse Hanford Company report WHC-SD-WM-ER-400, Rev. 0 (1995).

8. K. F. Eckerman, et al., "Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion," Federal Guidance Report No. 11 (DE89-011065) Office of Radiation Programs, US Environmental Protection Agency (1988).

9. C. A. Rogers, "An Analytical Model for Evaluating Subcritical Limits for Waste in Hanford Site Storage Tanks," Westinghouse Hanford Company report WHC-SD-SQA-CSA-20356 (1993).

10. R. D. Carter, "CSAR 79-007 Underground Waste Storage Tanks and Associated Equipment," Westinghouse Hanford Company report SD-SQA-CSA-20108 (1979).

11. D. J. Braun et al., "High-Level Waste Tank Subcriticality Safety Assessment," Westinghouse Hanford Company report WHC-SD-WM-SARR-003 (1994).

12. T. S. Vail, "Justification for Continued Operation of Hanford High-level Waste Tanks Resulting from the Criticality" Westinghouse Hanford Company report USQ, 492-CRITSAF, WHC-SD-WM-JCO-001 Rev. 3 (1993).

13. P. M. Francis, "Aerosol Study for the Rotary Mode Exhauster," Westinghouse Hanford Company report WHC-SD-WM-ES-225 REV 0 (1993).

14. C. A. Engine and G. Work, Micro Shield Version 4, (Grove Engineering, Inc., Rockville, Maryland, 1992).

15. "Tank Waste Composition and Atmospheric Dispersion Coefficients for Use in Accelerated Safety Analysis Consequence Assessment," Westinghouse Hanford Company report WHC-SD-WM-SARR-016, Rev. 1 (October 1995).

16. K. O. Pasamehmetoglu, "Comparison of the Radiological Consequence Analysis Used in the Mixer Pump SA with the ASA Analysis," Los Alamos National Laboratory Calc-Note TSA10-CN-WT-SA-TH-073 (October 1995).

17. Y. Y. Chien, and D. MacFarlane, "AI-RISK: A Computer Program for Calculating Doses and Health Risk from Accidental Release of Radioactive Materials," Los Alamos National Laboratory report LA-UR-92-2636, (July 1992).

18. L. H. Sullivan et al., "A Safety Assessment for the Proposed Pump Mixing Operations to Mitigate Episodic Gas Releases in Tank 241-SY-101: Hanford Site, Richland, Washington," Los Alamos National Laboratory report, LA-UR-92-3196, Rev. 14 (March 31, 1995).

19. "Atmospheric Dispersion Models for Potential Accident Consequence Assessments at Nuclear Power Plants," Regulatory Guide 1.145, US Nuclear Regulatory Commission, (1982)

# APPENDIX S

# SPILL RELEASE FRACTIONS

## 1.0. INTRODUCTION

Several spill scenarios are identified in the hazards evaluation. One of the most important scenarios is a spill from the core barrel when the core barrel is flooded. The other one is a spill from the core sampler.

If waste collects inside the core barrel or the drill rods, handling could cause a release. Even though accumulated waste may be discovered by radiological monitoring, this would only aid workers in preparing to catch the spill that could follow removal.

The length of the core barrel is 1.1 m (40 in.), and the inside diameter is 5.08 cm (2 in.). Thus, the core barrel could contain 2.2 L (0.07 $ft^3$) of waste. Using a waste density of 1.6 kg/L (100 $lb/ft^3$), the corresponding mass is obtained as 3.5 kg (7.8 lb).

The sampler is 48 cm (19 in.) long and has a 1-in. (2.54-cm) diameter. The volume of the sampler is 0.25 L (15 $in.^3$) and would contain 0.4 kg (0.9 lb) of waste.

## 2.0. ANALYSIS

In order to estimate the aerosol fraction during a spill, the waste may be modeled as liquid or solid.

The airborne material (source term) released from a liquid spill can be evaluated from the following equation, as suggested in the Department of Energy (DOE) Handbook:[1]

$$\text{source term} = MAR \times DR \times F \times RF \times LPF, \quad \text{(S-1)}$$

where

MAR = material at risk,
DR = damage ratio = 1,
F = airborne release fraction,
RF = respirable fraction, and
LPF = leak path factor = 1.

The LPF and DR are assumed as 1.

## 2.1. Respirable Aerosol Fraction for Liquid Spills

Reference 2 (Sec. 4.4.2.2, p. 4.74) summarizes the experimental release fraction from liquid spills. Most of the experimental data are obtained at Pacific Northwest Laboratory (PNL)[3] and are for viscous liquids and slurries. The spill height was 3 m (10 ft) in PNL's experiments. Other parameters such as the diameter of particles, densities of liquids and solids, and the viscosity of slurry and liquids were varied. Also included in the database was a slurry containing important species of 101-SY waste. The resulting correlation is given as

$$F = 6.31 \times 10^{-6} Ar^{0.45} \left( \frac{\rho_{air}}{\rho_{liq}} \right)^{2.2} Fr^{0.35} \quad , \tag{S-2}$$

where

$F$ = fraction airborne,
$\rho_{air}$ = air density,
$\rho_{liq}$ = solution density,
$Fr$ = Froud number, and
$Ar$ = Archimedes number.

Froud and Archimedes numbers are defined as

$$Fr = \frac{V^2}{gR} \quad \text{and} \quad Ar = \frac{\rho_{liq}^2 h^3 g}{\mu^2} \quad , \tag{S-3}$$

where

$h$ = spill height,
$g$ = gravitational constant,
$\mu$ = viscosity of solution,
$V$ = impact velocity, $(2gh)^{1/2}$,
$R$ = radius of liquid drop, $(3/4\ Vol/\pi)^{1/3}$, and
$Vol$ = volume of solution.

Equation (S-2) shows that the respirable fraction is proportional to the drop height and drop velocity and inversely proportional to the volume of the material and viscosity. Using a bounding drop height of 5 m (15 ft), a minimum liquid volume of 0.25 L ($7.1 \times 10^{-6}$ ft$^3$), a liquid density of 1000 kg/m$^3$ (62.4 lb/ft$^3$), and a liquid viscosity of 1 cP, the respirable fraction (F) is obtained as $1.0 \times 10^{-4}$. Note that the liquid density and viscosity used in this calculation correspond to water density and viscosity, which is very conservative for the waste supernate.

### 2.2. Respirable Aerosol Fraction for Solid Waste Spills

To estimate the respirable aerosol fraction of a solid waste spill, we use the formula provided by MacDougall et al.[4] given by the following simple relationship:

$$F = 2 \times 10^{-10} \frac{E}{Vol} \quad , \tag{S-4}$$

where E is the impact energy in joules and Vol is the material volume in $m^3$.

Equation (S-4) was derived from Argonne National Laboratory experiments (Refs. 5, 6, and 7) involving the brittle fracture of small samples of glass, ceramics, uranium dioxide pellets, and concrete. A test consisted of placing a single cylindrical specimen on its side between two hardened tool steel plates inside a sealed chamber. Each specimen received a dynamic diametrical impact by a weight dropped from a preselected height onto the upper plate. The impact energy is dissipated by disintegration, and some aerosol particulate is formed. The net respirable fraction of the brittle material (particulates with a diameter of less than 10 μm) is given by F, which is found to be linearly proportional to the impact energy. If the energy is set equal to the impact energy of the material being spilled, Eq. (S-4) reduces to

$$F = 2 \times 10^{-10} (\rho g h) \quad , \tag{S-5}$$

where ρ is the waste density taken as 1600 $kg/m^3$ (100 $lb/ft^3$) and h is the drop height bounded by 5 m (15 ft). Thus, the respirable fraction becomes $1.6 \times 10^{-5}$.

## 3.0. CONCLUSIONS

In this safety assessment, a conservative value of $2 \times 10^{-4}$ (Ref. 8) is used for the respirable fraction during a spill accident. The analysis provided in Section 2 of this appendix shows that a release fraction of $2 \times 10^{-4}$ is bounding for liquid and solid waste spills of interest.

## 4.0. REFERENCES

1. "Airborne Release Fractions/Rates and Respirable Fractions For Nonreactor Nuclear Facilities" DOE Handbook 3010-94 (October 1994).

2. J. E. Ayer et al. "Nuclear Fuel Cycle Facility Accident Analysis Handbook," NUREG-1320, Nuclear Regulatory Commission (April 1988).

3. M. Y. Ballinger and W. H. Hodgson, "Aerosols Generated By Spills of Viscous Solutions and Slurries," PNL-5910, NUREG/CR-4658, Nuclear Regulatory Commission (November 1986).

4. H. R. MacDougall, L. W. Scully, and J. R. Tillerson, "Preliminary Preclosure Radiological Safety Analysis," Appendix F in "Site Characterization Plan Conceptual Design Report," Sandia National Laboratory report SAND84-2641 (1987).

5. W. J. Mecham, L. J. Jardine, R. H. Pelto, G. T. Reedy, and M. J. Steindler, "Interim Report of Brittle-Fracture Impact Studies: Development of Methodology," Argonne National Laboratory report ANL-81-27 (October 1981).

6. L. J. Jardine, W. J. Mecham, G. T. Reedy, and M. J. Steindler, "Final Report of Experimental Laboratory-Scale Brittle Fracture Studies of Glasses and Ceramics," Argonne National Laboratory report ANL-82-39 (October 1982).

7. W. J. Mecham, L. J. Jardine, G. T. Reedy, and M. J. Steindler, "General Statistical Description of the Fracture Particulates Formed by Mechanical Impacts of Brittle Materials," *Ind. Eng. Chem. Fundam.*, **22**, 384-391 (1983).

8. R. M. Marusich, "Safety Assessment for Push Mode Core Sampling in Tank 101-SY," Westinghouse Hanford Company report WHC-SD-WM-SAD-008, Rev. 0-A (May 10, 1991).

# APPENDIX T

# BUREAU OF MINES IGNITION TEST PROGRAM FUNCTIONAL REQUIREMENTS AND ACCEPTANCE CRITERIA

## 1.0. INTRODUCTION

The hazard identification process presented in Section 3 of this safety assessment (SA) resulted in numerous burn initiators in the dome, in the drill string, in the waste and aboveground. Section 4 discusses these accidents and their possible initiators. Some of these burn accidents are postulated to occur as a result of mechanical sparks during rotary-mode core sampling (RMCS) normal operations or accidental conditions. The frequencies of these accidents are determined in Appendix E and summarized in Section 4. The discussion in Section 4 shows that, without additional experimental studies, the consequences and frequencies of the burn accidents caused by mechanical sparks are not acceptable.

The key reason to do experiments with prototypical atmospheres is the need for a database to support safety and engineering decisions on a technical basis. Unless there is a reliable and experimentally tested theoretical basis for predicting behavior, one will be reduced to making ad hoc decisions in the absence of experimental data. There is no general and reliable theory of frictional ignition that will enable test results with one mixture and frictional ignition situation to be extrapolated to a very different mixture or frictional stimulus. In the multicomponent mixtures characteristic of the flammable gases in the Hanford tanks, the interactions of the various components are a key aspect of behavior that can only be conclusively resolved in experimental studies.

Table T-1 summarizes the accident scenarios in which the mechanical sparks are initiators for a burn accident and the experimental results are necessary to conclude that the risk is bounded by the guidelines. Also included in Table T-1 is the section number where the bounding tests for each accident is discussed. Note that a separate series of tests for each accident is not needed, and a number of accidents (mainly the drop accidents) in Table T-1 may be bounded by one set of tests.

As a requirement of this SA, an experimental test program is implemented to demonstrate that no sparks capable of igniting a bounding flammable-gas mixture under bounding operating conditions can be generated as a result of the accidents listed above. These experiments are being performed at the U.S. Bureau of Mines (BOM) In some cases, a bounding set of tests are used to cover more than one accident scenario shown in Table T-1. Unfortunately, at the time of submittal of this SA, BOM ignition experiments are still being performed. In this appendix, the necessary BOM ignition tests required by this SA and their functional design requirements are listed. The acceptance criteria also are described for each test.

TABLE T-1
SUMMARY OF ACCIDENT CASES FOR WHICH TEST RESULTS ARE NEEDED

| Ignition Scenario | Description | Section |
|---|---|---|
| Ignition caused by frictional sparks as a result of the drill bit penetration | During the drill-bit penetration through the crust or waste sludge, a frictional spark can ignite the flammable gas in the vicinity of drill bit. | 2.0 |
| Ignition under the waste surface caused by frictional sparks by the drill bit | The ignition of the flammable gas in the waste by the frictional sparks created by the drill bit is of concern if the drill bit strikes hard materials such as rocks, metals, or hard waste layers. | 2.0 |
| Ignition in the riser caused by a frictional spark | If the conductive sleeve-nitrogen purge system fails, ignition of flammable gases is possible. Another case considered is the ignition of hydrogen in the riser (between the conductive sleeve and riser). | 3.0 |
| Ignition in the drill string caused by assembly/disassembly of drill strings or drill rod-quill rod adopter impact | The ignition of the flammable gas in the drill string caused by impacts that could be created during drill string or drill string quill rod assembly or disassembly are possible. | 4.0 |
| Ignition in the riser caused by the drill string, equipment, or tool drop | The flammable gas in the riser/dome can be ignited if equipment, drill string, or tools are dropped into or onto the riser during the installation or removal phase. | 4.0 and 6.0 |
| Ignition caused by the drill string or tool drop on crust | Dropping the drill string or other tools on the crust may ignite the flammable gas in the vicinity of the crust. | 4.0, 5.0, and 6.0 |
| Ignition in the drill string caused by drops | Ignition in the drill string as a result of frictional sparks, dropping the grapple, remote latch unit, and core sampler are possible. | 4.0, 5.0, and 6.0 |
| Ignition in X-ray or cask | The ignition source is the drop of the sampler into the X-ray container or the cask. Low-impact energies and velocities are involved. | 6.0 |
| Ignition in the shielded receiver | The drop of the remote latch unit (RLU) or core sampler in the shielded receiver could cause spark. RLU may be dropped on the core sampler because of a mechanical failure to grab the core sampler or the failure of the cable pin on the drum. Low-impact energies and velocities are involved. | 6.0 |

## 2.0. DRILL BIT FRICTIONAL IGNITION TESTS

One of the safety concerns of sampling with rotary mode in single-shell flammable-gas tanks is the ignition of the flammable gases retained in the waste. The ignition of flammable gas may occur in several different ways:

- The waste may be hard enough to create a frictional spark as the drill bit penetrates the salt cake or any other hard layer in the waste;
- The drill bit may also strike metal debris and cause a metal-to-metal friction resulting in a spark; and

- Friction on hard debris may cause local hot spot generation during which the temperature exceeds the autoignition temperature of the gas mixture.

The objective of drill bit frictional ignition tests is to demonstrate that the operation of rotary core drilling in a bounding frictional environment and bounding gas composition does not cause an ignition. The following are the sections in which the test parameters for the ignition tests are discussed:

- Downforce (Section 2.1.)
- Rotational Speed (Section 2.2.)
- Nitrogen flow rate (Section 2.3.)
- Gas Temperature (Section 2.4.)
- Gas Composition (Section 2.5.)
- Debris Material and Configuration (Section 2.6.)
- Drill-Bit Type (Section 2.7.)
- Number and Duration of Tests (Section 2.8.)
- Autoignition Temperatures (Section 2.9.)

## 2.1. Downforce

The downforce used during tests must be at least 120% of the nominal downforce that will be used during drilling in the actual waste. Currently, the analysis provided in Appendixes F and N determine the maximum allowable downforce. In ignition testing, the downward force must be ≥120% of the limiting value defined by the envelope tests or structural analysis.

## 2.2. Rotational Speed

Like the downforce, the rotational speed (rpm) must be set higher than the nominal rotational speed that will be used during actual sampling operations, which is 55 rpm. For the tests, the rotational speed must be ≥120% of the limiting value defined by the envelope tests or structural analysis (approximately 65 rpm). This margin is believed to be sufficient for protection against accidentally exceeding the nominal speed, considering the other conservative features of the test.

### 2.3. Nitrogen Purge Flow Rate

During ignition tests, the nitrogen purge system will not be used.

### 2.4. Gas Temperature

To bound the maximum waste temperatures in all the flammable-gas tanks (including the measurement uncertainties), the gas mixture must be ≥100°C.

### 2.5. Gas Composition

The initial analyses of the limited data show that the gas composition varies in each tank (App. C). Thus, the frictional ignition testing using actual drill bits must be performed in a bounding gas composition and bounding contact configuration.

It is very difficult to determine a realistic gas composition that bounds all possible combination of species mentioned above for all single-shell tanks. Using the current database, one can only determine major flammable-gas species that may be assumed to exist in all of the single-shell tanks. Based on the analysis provided in Appendix C, the major flammable-gas species are hydrogen ($H_2$), nitrous oxide ($N_2O$) which is an energetic oxidizer and $NH_3$. Based on observation of waste simulants, free oxygen ($O_2$) is not expected in the waste gas. However, air addition to the waste is possible during the RMCS operation.

In summary, the important gas species to consider are $H_2$, $NH_3$, $N_2O$, $O_2$, (used to conservatively bound the effect of entrained air). Instead of trying to determine a realistic gas composition that may bound all tanks, the stoichiometric mixtures are chosen. In determining the stoichiometric mixtures, the findings of the previous studies are used.

Kork and Shepherd[1] were unable to ignite a typical Tank 101-SY gas mixture (without ammonia and air) by striking two bars together or creating sparks by grinding. They were able to ignite the 101-SY gas mixture with a grinder striking on a metal piece when it is mixed with air fractions between 75% and 90%. It is concluded that, in the gas mixtures tested, $N_2O$ acts as an ignition inhibitor. References 2 and 3 also confirm that a typical 101-SY gas mixture cannot be ignited with the frictional operation of the drill bit in a simulated waste crust or on a steel plate. Based on these findings, it appears that a stoichiometric $H_2$-$O_2$ mixture would be bounding for mechanical sparks.

The evidence about the ability of bronze and brass strikers to cause frictional ignition is controversial. Powell[4] cites evidence for ignition with hydrogen and methane but not with gasoline fumes in an enriched oxygen atmosphere. The phenomena of frictional ignition is sensitive to surface phenomena such as the oxidation state of the metal and contaminants such as aluminum. Very small

amounts of aluminum or an aluminum-containing compound on a surface can produce frictional ignition in situations that otherwise would be considered absolutely safe. Ammonia is known to be chemically reactive with copper and other base-metal containing compounds and will alter the state of the surface. This clearly raises the issue that the frictional ignition characteristics of a surface may be affected by ammonia. There have been no studies on frictional ignition in the presence of ammonia. Although one may suspect that frictional ignition of ammonia will be difficult because of the low flame speed of ammonia-air mixtures, that is really not a valid reason to rule out ammonia as playing a role in frictional ignition in multi-component mixtures. There is a need for experimental data to determine the effect of ammonia on the bronze or brass cutting tools and how this affects the frictional ignition characteristics in order to make sound technical decisions about the safety of drilling in mixtures containing ammonia. Thus, a stoichiometric mixture is introduced (keeping the hydrogen to ammonia ratio as 1) of $H_2$ - $NH_3$ and $O_2$ in the test matrix.

Finally, although the earlier studies[1-3] show that mechanical sparks are not expected to ignite $H_2$-$N_2O$ mixtures, the addition of ammonia to this mixture has not been tested. References 5 and 6 indicate that ammonia may be very explosive in a nitrous oxide atmosphere. The studies documented in References 5 and 6 do not include mechanical sparks. However, because of the high explosiveness of this mixture, a stoichiometric mixture of $H_2$-$NH_3$ and $N_2O$ also must be tested.

Thus, as part of the acceptance criteria, three gas mixtures must be tested. These mixtures are summarized in Table T-2.

**TABLE T-2**
**GAS MIXTURES**

| Species | Mixture #1 | Mixture #2 | Mixture #3 |
|---|---|---|---|
| Hydrogen | 66% | 30% | 0.20 |
| Oxygen | 34% | 40% | - |
| Ammonia | - | 30% | 0.20 |
| Nitrous Oxide | - | - | 0.60 |

## 2.6. Debris Material and Configuration

The condition of waste in terms of hardness is not known before operation. There exists a possibility of penetrating a very hard waste layer in a tank. In addition, there may exist some metal debris lost or dropped from the riser in the past. Hard materials such as rocks also may exist in the waste. Thus, it is likely that the drill bit may strike against metal and other hard objects during the operation.

The possibility of ignition is higher if the drill bit strikes on harder materials such as carbon or stainless steel rather than hard salt cake or crust. Because of this, the use

of a simulant to model the frictional sparks during the waste penetration in the proposed testing is not necessary. Instead, the bounding spark initiating contact condition, i.e., striking metal objects or rocks are considered.

The conditions of the metal or hard object and geometry of the contact is another key parameter for ignition testing. The metal objects may already be corroded and may have a rough surface. The drill bit may strike wedge-shaped objects, a flat metal surface, or the edge of an inclined metal sheet or pipe. The configuration of drill bit-to-metal contact may play a role in generating a frictional spark that is capable of igniting the flammable-gas mixture. The metal object may be made of soft carbon steel as well as hard carbon steel. Thus, the selection of a bounding drill bit contact configuration and material needs to be addressed by testing.

Two bounding materials are selected for the frictional ignition tests;

1. 4140 hardened tool steel shapes, and

2. rocks found in the area of the Hanford Tank Farms.

The basis for the selection of 4140 hardened alloy steel is because of its relative incendivity and radiance properties. The relative radiance indicates the ability to create a spark (Ref. 7). Relative incendivity is the parameter to describe the ability to ignite hydrogen-air mixture in an ignition test. Both parameters are defined relative to the properties of pure iron.

Relative incendivity is defined as the inverse of the time to ignition in a given ignition test as described in Reference 7. This parameter is found to be a function of the applied loading pressure and surface speed. The relative incendivity of the hardened 4140 steel was found to be much higher than mild steel, structural steel, and stainless steel.

Relative radiance (as quantified by the measured radiant flux) for 4140 hardened tool also is much higher than the carbon steel (1018, 1096, 1030, 1080, 1040, 1060, etc.).

Figure T-1 shows the three sharp-edge shape made of 4140 hardened-steel piece before the ignition test. This contact geometry is believed to be bounding to cause frictional spark. Figure T-2 illustrates the drilling process onto these sharp-edged steel pieces. Figure T-3 is the photograph of these pieces after drilling. As shown, the drill bit surface is quite damaged.

### 2.7. Duration and Number of Tests

For each gas mixture #1 (stoichiometric $H_2$-$O_2$) shown in Table T-2 and for each material (metal and rocks as described previously), a minimum of five tests must be conducted. If there are uncertainties in the bounding configurations, multiple configurations may be tried as part of the minimum number of tests required.

The number of tests for the other two gas mixtures shown in Table T-2 must be ≥ 3 for each material and each gas mixture tested. Different configurations may be used to count towards the requirement of the minimum number of tests for each material.

In the accident analysis, the operators are credited for a few minutes response time in case the penetration rate control is violated. For consistency with that credited control, each test must be run for a duration ≥ 3 minutes.

Tests must be conducted in well-mixed mixtures at elevated temperatures. The test chamber must be purged sufficiently before the flammable gas is introduced into the chamber. The flammable gas must be introduced into the chamber with a sufficient period. The gas composition in the chamber must be verified. To verify that well-mixed flammable gases existed during the test, the gases must be ignited with an alternate ignitor at the end of each test if a frictional ignition does not occur during the test.

### 2.8. Drill Bit Type

The drill bit cutting teeth are made of a proprietary sintered bronze with carbide chips in the bronze matrix. This material can wear down easily when the drill strikes metal objects or hard materials. The core sample drill bits used in RMCS are Longyear (trademark of Longyear Incorporated) Parts Numbers 1001VD/5 (currently used) and 9505-15B (new prototype bit). BOM ignition testing also considers a new drill bit (Longyear part number 9505-15B).[5] This new drill bit is not used during testing to determine the safe operating parameters to prevent waste ignition (Appendix F); therefore, it is not considered in this SA. The purpose of specifying the drill bit is not exactly to indicate that no other drill bit can be used in an RMCS operation. This appendix summarizes the requirements of tests. However, any drill bit that is to be used in RMCS operations must pass both ignition and envelope testing requirements. The safe operating parameters (envelope tests) are obtained from experiments performed with the current drill bit. Therefore, the drill bit model number is specified to indicate that this type is the only one tested in ignition and envelope tests. When the drill bit model is changed or a new one is developed, it must pass the requirements of ignition and safe envelope testing, before it can be used in RMCS operations.

The current and new drill bits, current and new one, include carbon steel pins in the base of the drill teeth. Westinghouse Hanford Company (WHC)[5] currently is performing ignition tests for both bits to demonstrate that both drill bits do not ignite a flammable-gas mixture that may bound all possible combinations of flammable gases in single-shell Flammable Gas Watch List tanks (SSFGWLT). Tests are designed to simulate the action of a drill bit striking a hard object in the waste, such as a piece of structural steel or a rock, and determine what, if any, core drilling conditions exist that could ignite the flammable-gas mixtures. Tests were conducted

in a bounding stoichiometric hydrogen oxygen and ammonia nitrous oxide mixture as required by this SA.

Tests to date with different structurally sharp carbon-steel objects consistently showed no ignition in the $H_2$-$O_2$ mixture. However, drilling on a hard rock resulted in ignition of the hydrogen oxygen mixture when the new bit was used. Examination of the new drill bit after the ignition indicated that the teeth were worn and carbon-steel pins were exposed to the rock.

The conclusion of testing is that the ignition of bounding mixtures of hydrogen and oxygen is likely if carbon-steel pins contact steel or rock targets. Because ignition is observed and the reason was proven to be the carbon-steel pins, this SA requires that the carbon steel pins or carbon steel components must be removed from the tooth region of the bit before using them in the tanks. A control also is implemented to replace the drill bit if a trip signal is received on the penetration rate four times with a cumulative penetration of 0.3 in. This control and the requirement to pass the tests listed in this appendix control the spark sources in the drill bit.

When the drill bit is redesigned to include pins with different materials such as stainless steel or brass, a series of ignition testing could be set up. In these tests, ignition tests with 3-min. drilling periods should be performed until the hydrogen-oxygen mixture is ignited. After each 3-min period, a waiting period must be implemented to make sure starting temperatures are same. The number of tests that give the ignition should be higher than three; otherwise, control must be changed to half of this new number. If ignition occurs in the first or second test, the material must be re-evaluated.

## 2.9. Autoignition Temperatures

During one of the rock-drilling tests that was run for more than 5 minutes, the hydrogen oxygen mixture was ignited after 6 minutes of testing. It was postulated that the ignition occurred because the autoignition temperature at the teeth surface was reached. The test was repeated, and the ignition was observed at almost the same time. The bit teeth were not worn sufficiently to cause the carbon steel pins to be exposed. Additional tests without flammable gas were performed to determine the interface temperature. In one of the tests, a thermocouple is placed 1/8 in. beneath the assorted rock. The rock was not worn significantly; therefore, the temperature just beneath the rock could be measured. The rock temperature 1/8 in. beneath the surface was 236°C after 6 minutes of testing. An infrared temperature probe was also used to determine the surface temperature of the teeth. After 4 minutes of testing, temperatures up to 400°C were observed. All of this evidence indicates that the autoignition temperature can be reached if the drilling lasts more than 5 minutes.

To ensure that, during drilling into the rock without purge gas and minimal insertion rate, the temperatures will not reach autoignition temperatures, the following tests must be performed. Ten runs shall be performed while drilling into a rock with gas mixture #1, and with the downforce and rotational speed specified above. The run period shall be 3 minutes. After each 3-minute run, the bit and the rock shall be allowed to cool to approximately ambient temperature. The pit face and the rock surface shall be photographed after each run. Ignition during any of the runs shall be sufficient cause to disqualify the tested bit design from FG/RMCS.

**Envelope Testing**

Because the drill bit material and configuration is not known, there exists a possibility that the ignition could be caused by the drill bit-material interface temperature exceeding 160°C. To eliminate this possibility, envelope testing, as described in Appendix F shall be performed using both pumice stone and the rock material specified in this appendix.

## 3.0. CONTACT BETWEEN DRILL STRING AND TANK RISER MATERIAL

Upon loss of nitrogen purge flow to the riser (annulus between the drill string and conductive sleeve), frictional sparks can be generated through the drill string and conductive sleeve contact. In order to demonstrate that sparks cannot be generated from drill string and sleeve contact, ignition tests must performed by the BOM. Four different sets of tests must be conducted in a stoichiometric hydrogen-oxygen mixture. A prototype drill rod was rotated within a test chamber with a side load, 200 lbf, pressed against it. The side load acts against the drill string itself and not against the drill bit. The following materials must be used for the drill string:

1. A standard uncoated steel drill string rubbing against carbon steel;

2. A standard steel drill string with a pipe joint compound on it rubbing against a carbon steel

3. A nickel plated and fluted drill string rubbing against carbon steel;

4. A fluted drill string with the nickel coating ground off rubbing against carbon steel.

Note that these test parameters are conservative because the conductive sleeve is made of a stainless-steel pipe and if flammable gas exists in the riser, it is a hydrogen-air mixture. The rotational speed is 65 revolutions per minute (rpm). A total number of 12 tests are conducted (three repeat tests for each material discussed above).

The steel selected was 4140 carbon-steel. The 4140 carbon-steel is bounding as discussed previously. Figure T-5 shows the 4140 steel piece after one the tests. If

tests are performed with actual configuration (drill string is inside of the sleeve), the annulus must be purged with the well mixed gas mixture. If the drill string is rubbing on the outside surface of a pipe or a flat steel surface, only adequate mixing in the vicinity of the contact point must be provided. The temperature of the well mixed hydrogen-oxygen should be ~100°C. The purge flow rate should be minimized to provide well-mixed flammable-gas mixture.

The test period must be longer for these tests. The maximum period must be 26 minutes. This number is obtained by dividing the average drill rod length, 19 in., with the minimum penetration rate of 0.75 in./min.

These tests must show that the rotational motion of a carbon-steel drill string or a nickel-plated fluted drill string cannot create the ignition of a stoichiometric hydrogen oxygen mixture when the rotational speed and normal force are controlled.

## 4.0. DROP OF A NINETEEN-INCH DRILL STRING SECTION

A spark during disconnecting the quill rod from the drill string has been observed in the field. The quill rod adapter and the drill string were made of carbon steel. Any misalignment between the drill string and the quill rod caused by undesired platform movement or operator errors could create a relatively fast impact between the quill rod and the drill string when the drill string is disconnected. There is no instrument to detect the misalignment or any stress level on the drill string or quill rod adapter. Therefore, it is very difficult to evaluate the condition of drill string-quill rod adapter before disconnecting the drill string. Because a spark is observed in the field operation, this event must be assumed to have a high likelihood.

The drill string is assembled by adding the drill rods. The addition of a drill rod could be performed as follows:

1. Manual installation by an operator; or

2. Manual installation using the lifting bail.

During both modes, drill-string-to-drill-string impact also is possible. Impact can be caused by a drop of the drill string or by an operator error. This accident is likely because the drill rods are made of carbon steel and assembling/disassembling is performed for each sample. The change-out assembly is installed after the drill string is disconnected from the quill rod adapter. If dropped on the drill string, the change-out assembly also may cause a spark.

Ignition tests are designed to simulate the impact of prototypically dropping a 19-in. drill rod on a vertically oriented drill string from a height of 3 feet. A height of 3 feet corresponds to an impact velocity of 14 ft/s. These tests must be performed 30 times because the expectation is that carbon-steel pieces could create sparks when

impacted. Provided that these tests conducted with realistic prototypical conditions result in no ignition of stoichiometric hydrogen-air mixture, the probability of ignition may be estimated using binomial theorem. For 30 tests with no ignition, the probability of ignition is ~$2.0 \times 10^{-2}$. Considering this probability, the accident frequency becomes on the order of ~$10^{-7}$.

A well-mixed gas mixture must be provided to the impact point. This is a key issue in these drop tests. To achieve mixing, the gas mixture must be provided with a minimum flow rate so as not to cause significant convective effects inside the stationary drill string. The purge time and flow rate must account for the volume of the test chamber as well as the drill string volume. Appropriate mixing in the test chamber also must be provided. The gas temperature must be $\geq 100^{\circ}C$, and the gas mixture must be a stoichiometric mixture of hydrogen-air for these tests.

Tests must not induce ignition the of the stoichiometric hydrogen-air mixture.

## 5.0. DROP TEST OF A ROTARY MODE SAMPLER ON TO A ROTARY BIT

Drop tests simulating the drop of the core sampler on the drill bit is being performed in the following fashion. A prototype core sampler must be dropped from a height of 60 feet through a prototype drill string on the drill bit attached to the lower end of the drill string. The test chamber and drill string must be filled with a stoichiometric hydrogen-air mixture. Ignition is not expected because the bottom of the core sampler is made of stainless steel. Tests must be repeated ten times to confirm this expectation.

A well-mixed gas mixture to the impact point must be provided. Note that the 60-foot drill string may require significantly larger purge periods. The gas mixture must be purged with a minimum flow inside of the stationary drill string in all tests. The purge time and flow rate must account for the volume of the test chamber as well as the long drill string volume. Mixing in the test chamber should also be provided. The gas temperature must be $\geq 100^{\circ}C$.

There are pins inside the current drill bit. If these are made of carbon steel, they need to be scratched so that the core sampler can impact on carbon steel pins. For this experiment, you must use the current drill bit (Longyear, trademark of Longyear Incorporated) Parts Numbers 1001VD/5). The number of tests must not be less than 10.

These tests must conclude that no ignition of stoichiometric hydrogen-air mixtures is observed in ten core sampler drop tests performed with prototypical conditions.

## 6.0. DROP TEST OF REMOTE LATCHING UNIT ONTO THE SAMPLER

Drop tests must also be performed for RLU-quadralatch impact-related accidents. For these tests, a prototype RLU (stainless steel) must be dropped onto a carbon-steel quadralatch (old design material) from a height of 60 feet at least 10 times. If a stainless steel quadralatch is used, 10 additional drop tests of RLU on carbon steel (drill rod material) must be performed to simulate drill string-to-quill rod adapter impact. A long drill string with an open lower end must be used to achieve the drops. A prototype RLU must be dropped through the open drill string onto the stationary quadralatch placed in a test chamber filled with a stoichiometric hydrogen-air mixture. The drill bit must not be placed at the end of the drill string in these tests.

A well-mixed gas mixture with a minimum flow rate must be provided to the impact point. The purge time and flow rate must account for the volume of the test chamber as well as the long drill string volume. The gas temperature must be $\geq 100^{\circ}C$.

Tests in this section also addresses the spark issues as a result of quill rod adapter and drill string impact. The impact velocity in these tests is high and bound the impact between the quill rod and the drill rod.

These tests must be repeated 10 times and must show no ignition.

## 7.0. SUMMARY AND CONCLUSIONS

If any of the tests described above show ignition, the safety basis for the RMCS operations must be evaluated.

If none of the tests result in ignition, all the test procedures and results must be documented in a report that can be referenced. The report must be reviewed and approved by the PRC before this SA may be used as a safety basis document for the RMCS operations in flammable-gas tanks.

## 8.0. REFERENCES


1. J. C. Kork and J. E. Shepherd, "Electrical and Frictional Spark Ignition of $N_2O$-$H_2$-$N_2$-air Mixtures," (June 1993).

2. L. C. Kenneth, K. S. Witwer, A. Furno, G. M. Green, R. A. Thomas, "Ignitability Testing for Core Drilling Systems," Westinghouse Hanford Company report WHC-SD-WM-TRP-224 (March 1995).

3. L. C. Kenneth, M. Herzberg, I. A. Zlochower, C. E. Lucci, G. M. Green, and R. A. Thomas, "Laboratory Flammability Studies of Mixtures of Hydrogen, Nitrous Oxide, and Air, " Westinghouse Hanford Company report WHC-SD-WM-ES-219, Rev. 0 (August 1992).

4. M. Hertzberg and I. A. Zlochower, "Explosibility of Nitrous Oxide: The Effect of H-Atom Bearing Impurities," Twenty-Fifth International Symposium on Combustion, University of California, Irvine (July 31–August 5, 1994).

5. E. Jones and J. C. Kerr, "Inflammability Limits of Ammonia, Nitrous Oxide and Air," *J.S.C.I.*, Vol. 68 (January 1949), pp. 31–34.

6. F. Powell "Ignition of Gases and Vapors," *Industrial and Engineering Chemistry*, Vol. 61, No. 12, p. 29 (1969).

7. R. Blickensderfer, J.E. Kelley, D.K. Deardorff, and M.I. Copeland, "Testing of Coal-Cutter Materials for Incendivity and Radiance of Sparks," Bureau of Mines Report of Investigation, RI-7715 (1972).

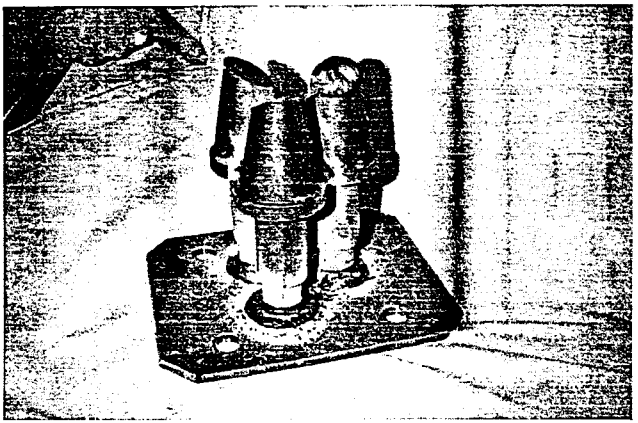

**Figure T-1. The photograph of three sharp hardened 4140-steel shape before drilling.**

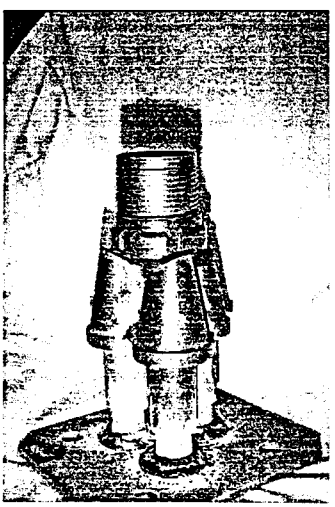

**Figure T-2. The photograph of illustration of the three sharp hardened 4140-steel shape during drilling.**

**Figure T-3.** The photograph of three sharp hardened 4140-steel shape after drilling.

# APPENDIX U

# FUNCTIONAL REQUIREMENTS FOR FLAMMABLE AND TOXIC GAS SENSORS

## 1.0 INTRODUCTION

The purpose of the sensors is to provide signals that can be used as safety shut-down indicators for both flammability and toxic hazards during rotary-mode core sampling (RMCS) operations. The primary flammability hazard is the release of hydrogen gas, and the primary toxicity hazard is the release of ammonia gas (which is also flammable). The signal will be used to shut down the drill truck and to alert personnel to evacuate the tank farm as a protection against toxic-gas exposure. The objective of this appendix is to specify the functional requirements of the chosen sensors for this applications.

## 2.0 EVALUATION OF THE SENSOR

At the time of the submittal of this safety assessment (SA), two sensors have been identified and are being designed as part of the ventilation system. The first is a Wittaker Cell hydrogen detection system and the second is an SMC combustible gas sensor.

The Wittaker Cell is an electrochemical cell with a membrane placed between the sample gas and the active element. It is very selective for hydrogen and responds directly to the partial pressure of hydrogen on the other side of the membrane. It is configured with a calibration port that can be used to flood the sensor region with a calibration or zero gas during operation conditions. For the sensor to read out concentration it is essential that the pressure in the sensor region be identical during the calibration as it is during actual operations.

The SMC combustible gas sensor uses a catalyst to "burn" the gas and detects the resulting heat release. To increase sensitivity and decrease drift, the heat detection is done by comparing the temperature of a reference (uncatalyzed bead) to that of a signal (catalyzed) bead. The beads are imbedded in a sintered metal housing which prevents the combustion energy from igniting a flammable mixture. It has the advantage of responding to both ammonia and hydrogen.

Westinghouse Hanford Company has considerable experience with the Wittaker Cell, which has been shown to have an adequate response time (App. C). The Wittaker cell has been shown to have adequate sensitivity, and experience has shown that it is very reliable and stable in the current tank farm applications. Calibration is required only every three months.

The SMC detector has not been used in the tank farm environment before, but it has

recently been tested as described in a report by Straalsund.[1] The key points of this report were the following:

- The output is noisy, which can be rectified by electrical processing but still is barely adequate for this application.
- The response of the system was very sensitive to the flow rate of the gas by the sensor.
- The response was sensitive to the orientation of the device.
- The sensor responded to ammonia as well as hydrogen with the ammonia response factor being approximately 40% of the hydrogen response.

Based on the information provided, the sensors, if implemented properly, should provide the required protection against flammability and toxicity hazards during a gas-release event (GRE). The SMC sensor, if set to trip at 5000 ppm hydrogen equivalent, should sense both a 5000 ppm hydrogen concentration and a 12000 ppm ammonia concentration for alarm purposes if the gas was purely hydrogen or ammonia, respectively.

## 3.0. FUNCTIONAL REQUIREMENTS FOR THE SENSORS

The requirements for the Wittaker Cell sensor deployment will be a slightly less stringent than the SMC sensor because the Wittaker cell has better sensitivity and has been demonstrated to be stable and reliable in the tank farm environment.

### 3.1. Wittaker Cell Requirements

- The system must be rated to sample from a Class-I, Division-1, Group-B environment.
- The deployment system must retain the response time requirement of reaching 90% of full scale in less than 2 minutes.
- The configuration must allow for the system to be calibrated in a manner that ensures that zero and calibration gas are exposed to the sensor under the same pressure as during the operation mode. The system must be able to be operated during pressure transients caused by a potential GRE.
- The calibration should be performed at initial setup at each location and every month after that point. The calibration should consist of setting the zero with pure air or nitrogen and calibration with 6000 ppm hydrogen. The calibration procedure with 6000 ppm hydrogen should test the shutoff electronics as well as the sensor reading.

### 3.2. SMC Combustible Gas Sensor Requirements

The requirements for the SMC combustible gas sensor are more stringent for several reasons:

- The sensor is sensitive to both flow and pressure.
- The signal-to-noise and lower detection limit seem to be marginal for the application.
- There is no operational history for exposure to tank farm gases.

The following are the functional requirements for the SMC combustible gas sensor:

- The system must be rated to operate in a Class-I, Division-1, Group-B environment.
- In addition to the electrical qualification, it must be documented that the sensor element itself will not ignite a flammable mixture.
- The deployment system must retain the response time requirement of reaching 90% of full scale in less than 2 minutes.
- The design must assure that the system conservatively responds to a pressure or flow rate transient anticipated during a GRE.
- The configuration must allow for the system to be calibrated in a manner that ensures that zero and calibration gas are exposed to the sensor under the same pressure and flow rate as when the system is in operating mode.
- The initial sensor must be calibrated with both hydrogen and ammonia.
- The functional test should be performed at initial setup at each location and every day the system is used after that point. The functional test must consist of setting the zero with pure air or nitrogen and calibration with 6000 ppm hydrogen. The functional test procedure with 6000 ppm hydrogen should test the shutoff electronics as well as the sensor reading.
- The sensor must be replaced at least once per month with a new sensor that has been calibrated with both hydrogen and ammonia.

## 4.0. CONCLUSIONS

This SA assumes a reliable, fast, accurate and redundant flammable-gas detector system is designed to be operated in steady-state exhauster operating conditions as well as during rapid transient surges. The requirements for the detection system are

listed in this appendix. Without meeting and demonstrating that these requirements are met, this SA should not be used as a safety basis for RMCS operations. After the design is completed, a technical review group designated by the PRC must review the design package to verify that the SA requirements are met. Without PRC approval of the flammable-gas detection system, the RMCS operations must not begin in any of the flammable-gas tanks.

## 5.0. REFERENCES

1. E. Straalsund, "Combustible Gas Sensor Interference Report," Westinghouse Hanford Company report WHC-SO-WM-TRP-249 (January 1996).

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