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Characterization Strategy for the Flammable Gas Safety Issue

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**Characterization Strategy for the
Flammable Gas Safety Issue**

**Hanford Tank Characterization
and Safety Issue Resolution Project**

June 1997

C. W. Stewart, M. E. Brewster,
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Summary

The characterization strategy for resolving the flammable gas safety issue for Hanford waste tanks is based on a structured logic diagram (SLD) that displays the outcomes necessary to reach the desired goal of making flammable gas risk acceptable. The diagram provides a structured path that can identify all information inputs, data as well as models, needed to achieve the goal. Tracing the path from need to outcome provides an immediate and clear justification and defense of a specific need. The diagram itself is a 'picture of a risk calculation' and forms the basis for a quantitative model of risk. The SLD, with the risk calculation, identifies options for characterization, mitigation, and controls that have the maximum effect in reducing risk. It provides quantitative input to risk-based decision making so that options are chosen for maximum impact at least cost.

List of Acronyms and Abbreviations

GRE	gas release event
lfl	lower flammability limit
RGS	retained gas sampler
SLD	structured logic diagram
VFI	void fraction instrument
VOI	value of information

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1.0 Scope

A structured logic diagram (SLD) is described that outlines the steps necessary to calculate the risk associated with flammable gases in Hanford radioactive waste storage tanks. The SLD forms the technical basis for a characterization strategy that ties characterization needs directly to safety issue resolution and other proposed actions through evaluation of risk.

2.0 The Flammable Gas Safety Issue

Flammable gas is a safety issue because of the potential damage resulting from igniting even a small volume of it in the tank dome space. Flammable gases are generated in nearly every tank by radiolysis and by chemical reactions in the waste. Normally the gas migrates through the waste into the tank dome at about the same rate as it is generated where it is diluted below its lower flammability limit (lfl) by natural "breathing" or forced ventilation and does not present a hazard. However, some tanks retain gas in the solid layers of the waste that could be released suddenly by a disturbance such as core sampling or salt well pumping, seismic events, or during retrieval. A few tanks exhibit episodic "natural" gas releases with no external disturbance. A portion of the gas released episodically from the waste into the dome may remain flammable for some time (minutes to days).

If a sufficient volume of gas were released and ignited while it remained flammable, the subsequent burn could produce pressures high enough to damage or even fail the tank structure and potentially release waste to the environment. Even small volumes of flammable gases can be hazardous during some activities if it collects in pockets exposed to ignition sources. A flammable gas burn within the waste itself is also considered possible though very unlikely.

The flammable gas safety issue is resolved by conclusively showing that the probability and magnitude, or risk, of such adverse consequences is acceptably low. This requires that the chemical and physical processes by which the waste generates, stores, and releases flammable gas be understood with sufficient confidence to compute the risk.

Unfortunately, these processes are not well understood and existing knowledge of the waste is insufficient in many cases to develop understanding to the point that the safety issue can be resolved. Development of new knowledge about the waste, or characterization, is difficult, costly, and must be planned carefully to have value. The cost and effectiveness of available options for obtaining specific knowledge must be carefully traded against the need for the data.

3.0 Approach

The structured logic diagram provides the technical basis for making planning decisions leading to a sound, defensible characterization strategy. The SLD reveals the information required to determine the flammable gas risk and reduce it to acceptable levels. Information requirements from the other safety issues are integrated with flammable gas needs by combining their respective SLDs. Where the risk is not acceptable or existing data is insufficient, formal decision analysis using value-of-information techniques (VOI) can define the most effective action. Thus the characterization plan is actually derived from the knowledge required to resolve each of the safety issues based on the overall risk.

The SLD is built by identifying the conditions that must be met for the next condition to be satisfied. The diagram does not have a time implication like a process flow chart. The nodes on the diagram describe the accomplishments of each process, not the processes themselves. Thus an SLD is a "picture of a flow chart," not the actual flow chart. The first or topmost condition states the final objective of the process. In our case the statement is: "Flammable gas risk is acceptable" since that condition will resolve the flammable gas safety issue. In order to determine whether or not the risk is acceptable, the risk must be evaluated. This makes our SLD a "picture of a risk calculation."

Risk is the product of an adverse consequence and its probability. An adverse consequence can be described in many ways. Examples include radiation dose to various populations, toxic exposure, direct injury, cost of cleanup, cost of schedule slippage, and environmental impact. The overall risk is actually the combination of all important consequences. However, since radiation dose is typically emphasized in view of the current risk acceptance criteria, we shall evaluate consequences in those terms.

Since we want the flammable gas safety issue to be resolved permanently, the risk calculation must consider both the current and future states of the waste, tank structure, and installed equipment. Future states should include the effects of aging, actions performed to mitigate the hazard, controls placed on operations to reduce the frequency and mitigate the consequences, and all other occurrences that could affect the risk. This requires models to predict the effects of these actions.

In order to calculate the risk, the physical processes that create the adverse consequences as well as the frequency and effects of their initiators must be understood and quantitative models of the processes must be used. These might involve simply assuming bounding value, running a detailed 3-dimensional numerical simulation, or conducting a large-scale experiment. Since different models have their own specific data needs, they must be selected based on the sensitivity of risk to model uncertainty. The SLD identifies where models are required in the same way it calls out data needs.

An important part of the risk calculation is developing failure scenarios that lead to similar consequences. The physical processes can be very complex and are often specific to a particular operation. The failure scenario is a chain of events ending in the consequence of interest. It defines the length and time scales of the processes and describes the initiators and their frequencies.

There are many flammable gas failure scenarios defined by the volume of gas potentially burned, whether or not it burns, where it burns, and how it is ignited. For the purpose of this effort we chose only scenarios that release radioactive material to the environment. At one end of the spectrum might be a large gas release that raises the dome pressure sufficiently without being ignited to rupture the HEPA filters in the tank's exhaust. The consequence is relatively minor and the frequency is very small. At the other end would be ignition of a large gas release that causes a complete dome collapse resulting in ejection of a large mass of waste. Other scenarios could include ejection of a contaminated mixer pump by ignition of a gas release occurring during removal, unfiltered release by ignition of gas trapped inside a salt well screen, or a gas burn in the waste ignited by a rotary-mode core drill striking a submerged metal object.

For the purpose of illustration, we chose as our scenario a gas burn in the dome resulting in structural collapse into the waste and ejecting radioactive material. The sequence of physical processes leading to the consequence and the computed output quantity of each process is described as follows and is illustrated in Figure 3.1:

- A volume of flammable gas is stored in the waste with potential for release. Output quantity: retained gas volume.
- A significant fraction of the stored gas is released into the dome space at a relatively high rate. Output quantity: volume of gas released.
- The released gas is diluted by ventilation and mixing but is ignited while it is still flammable. The subsequent burn raises the dome pressure. Output quantity: peak dome pressure.
- The dome pressure increase is sufficient to fail the dome structure. The combined potential energy of the elevated pressure and the gravitational energy of the dome structure and overlying soil are released and converted to kinetic energy. Output quantity: mechanical energy available at failure.
- The kinetic energy of the falling structure is transferred to the waste ejecting radioactive material from the tank. The radioactive particulates already in the dome are exhausted as the pressure is relieved. Together these effects create a radioactive plume over the tank. Output quantity: mass of radioactive material released.
- The debris plume is dispersed by the prevailing wind, depositing radioactive particulates over a wide area. A dose is computed for standard receptors at specified locations relative to the tank. Output quantity: radioactive dose.

The specific quantities calculated along the way to determining the dose are chosen to be the most 'diagnostic' of the process they represent. A quantity is diagnostic to a process if the output is directly dependent on that quantity -- a large value of the input indicates a large output value. For example, the gas release volume is diagnostic to the peak dome pressure resulting from a burn, but the composition of the gas is not. This is not to say the peak pressure is independent of gas composition, but the relationship between pressure and volume is most direct.

The next section describes the flammable gas structured logic diagram. In this discussion it is important to realize that this is an illustration of the method, not the method itself. The team that constructed the SLD included experts with experience in flammable gas detection, retention,

release, mixing, and combustion. These portions of the SLD were developed in greatest detail. Structural failure dynamics, mass ejection, debris plume dispersion, and dose calculation logic were left relatively undeveloped. Nevertheless, the process is valid and the product clearly defines characterization needs that are focused directly on the objective. A technically sound and defensible implementation plan can be developed based on the SLD.

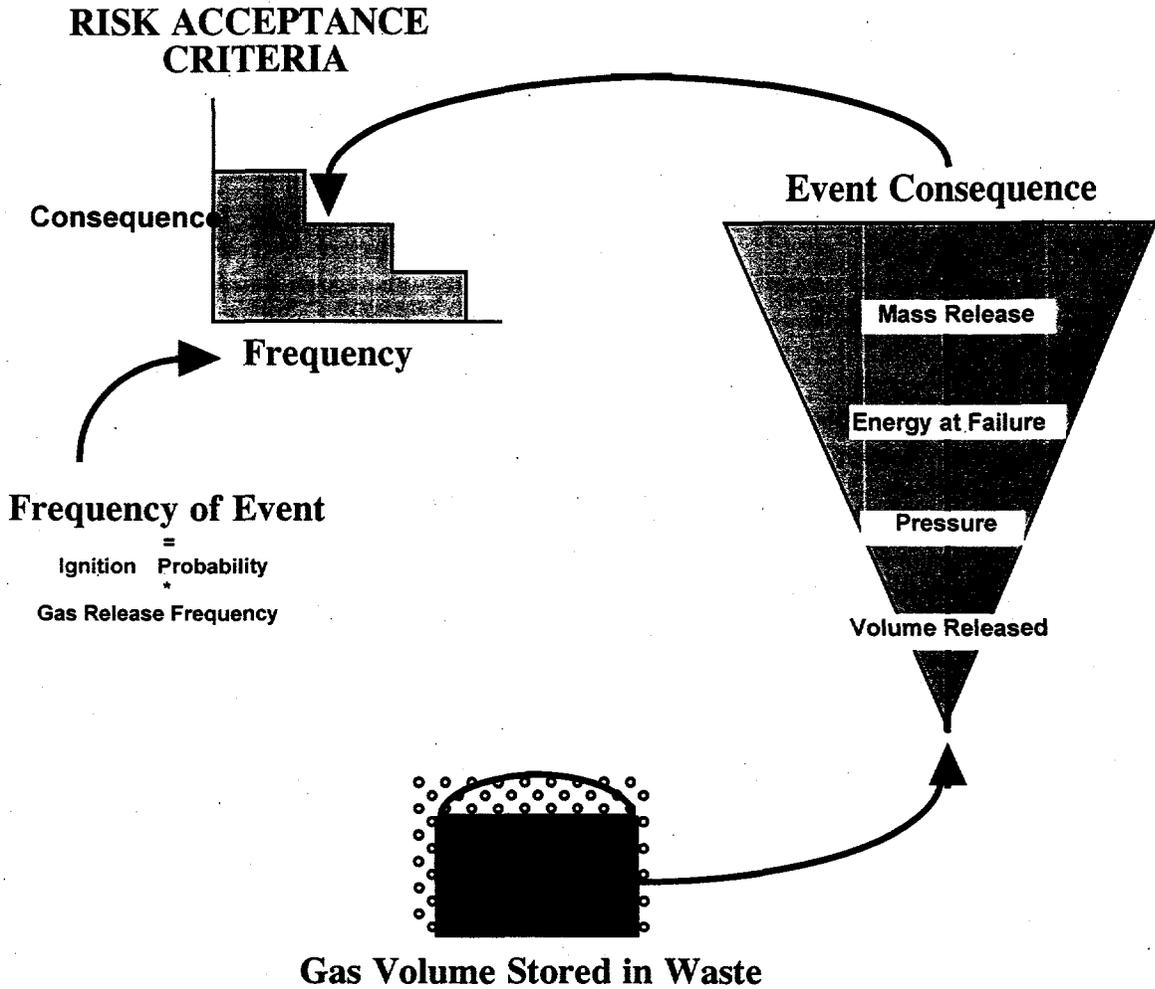


Figure 3.1. Sequence of Events Leading to Radioactive Dose Consequence

3.1 Flammable Gas Structured Logic Diagram

The flammable gas SLD is given in full detail in Appendix A with explanations of each individual process box listed in Appendix B.

The upper section of the SLD, shown in Figure 3.2, provides the basic structure to the entire process. The topmost box contains the desired outcome: that the risk from the flammable gas hazard is acceptable over the entire time concerned. There are four options available to allow us to make this conclusion: 1) the risk can be determined minimal if certain screening conditions are met, 2) the overall risk can be formally determined and compared to a set of acceptance criteria, 3) intervene by mitigating, applying controls, or otherwise altering the waste or its

containment system, or, 4) not shown explicitly, is to perform characterization to refine the estimates upon which the risk calculation is based in the expectation that improved knowledge will reduce the risk. The risk screening step identified in the left-hand box will be described first and then the details of the formal risk calculation.

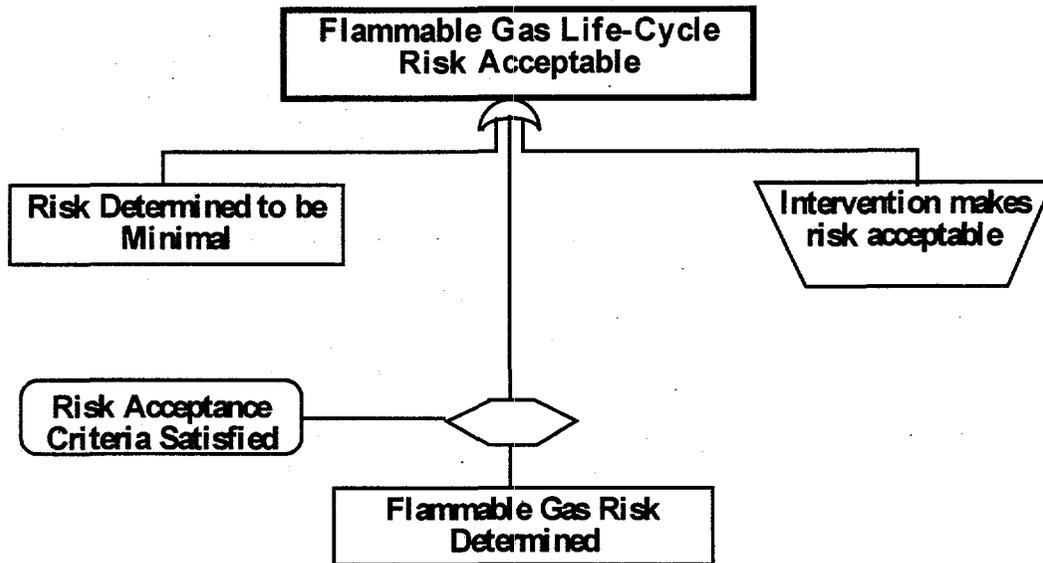


Figure 3.2. Definition Section of Flammable Gas SLD

3.2 Risk Screening

The screening step does not compute a numerical risk value, but simply identifies cases for which the risk is “minimal.” The details of this branch also offer targets for intervention leading to resolution of the safety issue.

The risk screening considers the initial events in the failure sequence as shown in Figure 3.3. Either of the three conditions will make the risk minimal. If the waste does not generate flammable gas, either by absence of the basic radiolysis or chemical reactions or because the mixture generated is not flammable, it cannot be ignited. If the waste generates flammable gas, but does not store it and the generation rate is sufficiently low to be diluted by the existing ventilation (passive or active), a burn is still impossible. If the waste retains gas, but does not release it episodically, or if such episodic releases are too small to fail the HEPA filters if burned, there is minimal potential for release of radioactive material.

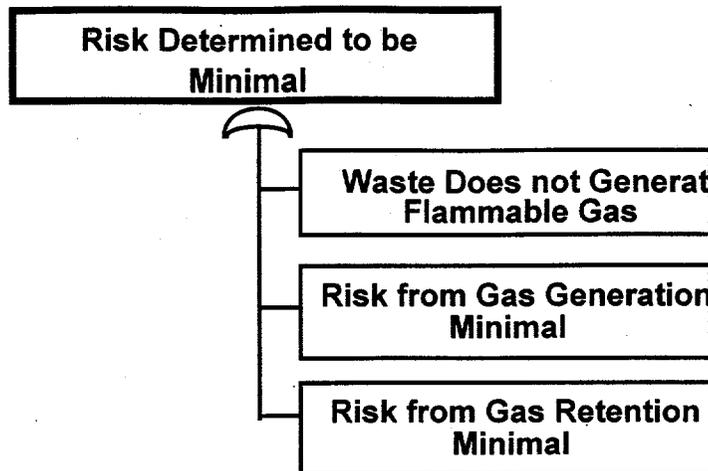


Figure 3.3. Risk Screening Branch

3.3 Risk Calculation

Even if the screening tests fail, the risk may still be acceptable. But there is sufficient uncertainty to require formal comparison of the risk to the given acceptance criteria. The risk calculation branch is outlined in the next level of the SLD shown in Figure 3.4. Risk is calculated for each waste state as if conditions were present and known.

To estimate the risk over the entire life cycle, the waste states occurring over the life cycle must be predicted. This requires knowing the schedule of planned, proposed, or expected activities that affect the risk. The present state can be determined from a variety of data including direct measurements, historical monitoring data, design data, experimental data, and other sources. Models of future states are needed to predict changes in waste state resulting from planned or expected future actions. Models must accommodate simple aging of the waste and tank (no action), mitigating actions affecting the waste or tank operations, controls on operations, and major disturbances to the waste. Once the current and expected future waste states are determined, a risk trajectory is calculated as the risk of the waste state trajectory. The entire risk trajectory represents the life cycle risk to be compared with the acceptance criteria.

Specific failure scenarios are defined on which to base the risk calculations. To estimate the risk, a pathway from existing conditions through necessary intermediate events to the consequence must be defined. Many such event sequences are possible and it is probably not practical to calculate the risk of each one. Instead similar sequences leading to similar consequences are grouped into 'scenarios' to make the problem tractable. Scenarios are established by hazard analysis and require the complete description of the tank operating systems and the specific hardware performing the planned activities. The overall risk consists of the combined risk of each of the selected scenarios.

The specific scenario of a release of radioactive material by a tank dome collapse resulting from a flammable gas burn in the headspace was chosen to illustrate the SLD process. Some other possible scenarios could include

- unfiltered release due to a gas burn within the waste initiated by an overheating drill bit during rotary mode core sampling

- unfiltered release due to ignition of gas accumulated inside the salt well screen during salt well pumping
- unfiltered release through failed HEPA filters due to the pressure spike from a large gas release without ignition
- contamination resulting from ejection of a failed mixer pump caused by ignition of a large gas release induced by pump removal.

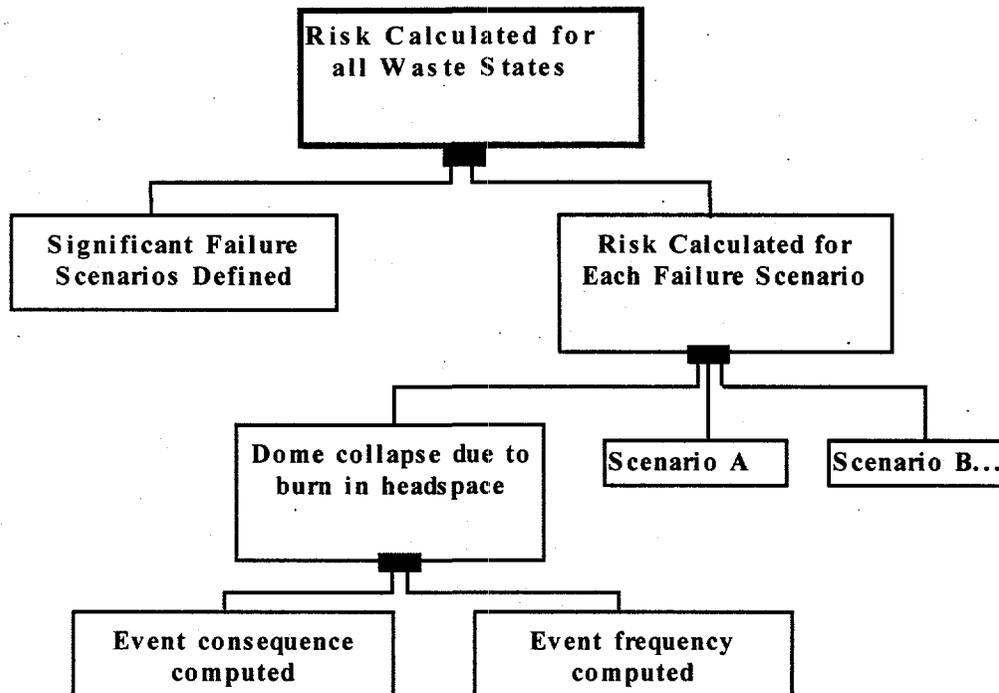


Figure 3.4. Risk Calculation Section of Flammable Gas SLD

Risk consists of a quantifiable consequence and its probability of occurring in a specific time period. A one-year period is generally used as the basis in the risk acceptance criteria. One can therefore express the probability in terms of an event frequency: expected occurrences per year. The next two branches of the SLD describe these two facets of the risk calculation. The consequence to be evaluated depends on how the risk acceptance criteria are stated. The frequency is derived from the frequency of each initiator and the probability of its effect.

3.4 Consequence Branch

The consequence portion of the SLD is shown in Figure 3.5. As discussed above, each step in the consequence calculation is chosen to be most diagnostic to the following step. The result of a calculation is a probability distribution combining the uncertainty of input data, the uncertainty of the models used, and that propagated from prior steps. However, the steps also can be used to describe a purely deterministic calculation.

The first step in the failure sequence computes the gas release volume. This is the total volume of gas, at standard temperature and pressure, episodically released from the waste. It includes all undissolved gas components, not just the flammable portion. The volume of dissolved gas that evolves during the release should also be considered. The release volume can be computed indirectly as a fraction of retained gas volume, directly from historic gas release event (GRE) data, or predicted by computational models.

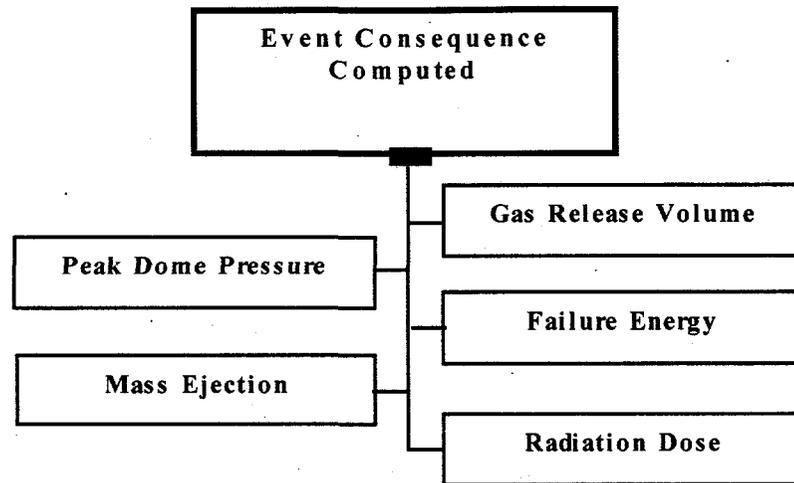


Figure 3.5. Consequence Section of Flammable Gas SLD

The release fraction is typically estimated by simple models based on laboratory experiments or obtained from historic GRE data on other tanks. For release fraction calculations, the retained gas volume can be computed from local measurements such as the void fraction instrument (VFI) or the retained gas sampler (RGS) where the main source of uncertainty is spatial variation. A global estimate of gas volume can be obtained from the response of the waste level to barometric pressure fluctuations. Here uncertainty arises from the level measurement and its correlation to pressure. Level growth can also provide an estimate if appropriate assumptions can be made about evaporation, intrusion, and the initial amount of gas present.

Probably the best determination of the gas release volume derives from historic GRE data, if the tank has exhibited episodic releases. Gas releases are indicated by sudden significant (>3 cm) drops in waste level. Records of waste level for 10 years or more may be available from which a fairly accurate probability distribution of gas release volumes can be developed. However, the level drop only reflects the *in situ* volume. The effective pressure at which the gas was stored must be determined to convert to standard conditions. Fortunately, tanks with regular GREs typically store gas in a sludge layer whose dimensions are defined accurately by the waste temperature profile. Gas release volumes can also be estimated from changes in the response of level to barometric pressure or from the measured gas concentration transient in the dome.

Viscous flow fluid dynamics models were used quite successfully in predicting gas release volumes from buoyancy-driven "rollover" events in Tank SY-101 and have been used to predict similar behavior in other double-shell tanks. Computational simulations of two-phase flow in porous media are currently being used to study gas releases from saltcake in typical single-shell

tanks. Either type of model requires data on waste physical properties that are very difficult to obtain. The waste rheology is needed for a viscous flow simulation and the porosity and particle size distribution is needed for a porous media prediction.

The peak dome pressure is computed via a combustion model and state equation for the combustion products. Ignition is assumed in this calculation. Ignition probability is computed in the frequency section. The volume of gas that is flammable is determined with a dilution model. For small releases, the flammable portion of the release is tracked as it rises and mixes with the ambient dome atmosphere. For larger releases, the flammable volume is the entire headspace, but the concentration is reduced by ventilation. Gas release rate is an important aspect of dilution. For moderate ventilation rates, the release rate is actually more important than the total volume in computing how long the mixture is flammable. This rate can be obtained from historic data or predicted by various models.

The overall risk is very sensitive to the ventilation rate since it determines the time the tank headspace can remain flammable after a large gas release or whether a smaller, slower release creates a flammable atmosphere at all. The flow rate of a forced ventilation system can be measured directly at the tank exhaust. However, a single fan often ventilates an entire tank farm with flow measured only at the stack. Fortunately, the flow rate can be calculated fairly accurately in these tanks from the decay of the headspace concentration of hydrogen (or any other waste gas component) following a GRE.

Passively ventilated tanks 'breathe' in and out as the barometric pressure changes. Pure pressure breathing is easily calculated from weather data and averages less than 20 cu. ft. per hour depending on the headspace volume. Passive ventilation is strongly enhanced by thermal convection depending on the tank heat load and how the tanks are interconnected. Actual passive ventilation rates of 300 to 500 cu. ft. per hour have been estimated from headspace hydrogen concentration decay in two tanks. Thermal convection can be simulated quite accurately with 2- and 3-dimensional fluid dynamic models that consider both seasonal and diurnal ambient temperature variations.

Flammability is determined by computing the lower flammability limit (Lfl) of the mixture with a model that includes the effects of all fuels in a nitrous oxide atmosphere. Fuels include hydrogen, ammonia, and methane. Some bounding calculations assume the waste gas is pure hydrogen though more realistic values would range from 25% to 50%. The amount of ammonia that evolves in addition to that present in the actual gas release is not known very well. The release gas composition is one of the more important characterization options for reducing uncertainty.

The gas composition in the waste is becoming better defined as more in situ measurements are made with the RGS. Laboratory studies of gas generation from actual waste samples also provide good predictions of gas composition. The ratios of major fuel components can be estimated from the tank headspace gas composition. This leads to a conservative estimate of composition since it excludes inert components.

The energy released by combustion that ultimately increases the dome pressure is typically computed with an adiabatic model that neglects heat losses. The pressure is computed with a simple equation of state allowing the combustion products to expand until pressure equilibrium is achieved. Pressure relief through exhaust flow is usually ignored. However, very detailed numerical simulations can also be run that couple the combustion process to tank structural

dynamics. These models can account for 3-dimensional flame propagation, heat losses, pressure relief, and nonuniform mixtures.

In order for the dome collapse scenario to occur, the dome pressure must exceed the maximum value the structure can withstand. When this happens, the potential energy of the dome overpressure and the mass of the dome, overlying soil, and installed equipment above the waste surface is assumed to be available for transfer to the waste. The sum of these two components represents the total potential energy available at failure. The actual value is proportional to the dome pressure and inversely proportional to the waste level. Tank design criteria or structural analysis determine the base value of maximum allowable pressure. But degradation of tank structural integrity by corrosion, fatigue, thermal effects, and specific known damage needs to be included as appropriate. It might be possible to measure structural integrity directly via advanced nondestructive evaluation techniques.

Radioactive mass is ejected during dome collapse through complex energy transfer phenomena that are not well understood. Study of the actual dynamics of dome failure is just now beginning. It is possible that the dome does not collapse at all, but merely fractures, quickly relieving the pressure and filtering the outflow through the soil. The process by which impact of a heavy object generates particulates that could be ejected from the tank has been estimated using data from experiments with very brittle materials of dubious similarity to waste. It is possible that mechanical impact cannot generate sufficiently fine particulates to be hazardous. The filtering effects of falling soil has not been evaluated very effectively. At the other extreme, the overpressure may be sufficiently high to throw most of the debris outward so that little actually falls back in. The entire subject is in need of thorough study. This illustrates the ability of the SLD to reveal deficiencies in the knowledge base and points to a very fruitful area where uncertainty in potential consequences of large flammable gas releases could be reduced.

The radioisotope source term is an important data requirement. The source term is the list of hazardous isotopes present and their concentrations. Since actual assays are available from relatively few tanks, a 'supertank' source term is often prescribed for other tanks that uses the maximum concentration of each species found in the tanks that have been sampled. This source term can be shown to be overconservative by at least two orders of magnitude when samples are available. This may prove an important driver for core sampling.

The final step in determining the consequences is to compute the radiological dose to the onsite and offsite receptors. This portion is left undeveloped in the flammable gas SLD because it is common to all of the safety issues and will eventually be treated separately. The end result will be a probability distribution of the dose for the selected scenario.

3.5 Frequency Branch

The frequency section of the SLD is shown in Figure 3.6. Only two aspects of the flammable gas hazard have an independent frequency attribute: episodic gas release and spark or ignition source. A spark can have no effect in a nonflammable atmosphere and a flammable gas plume is not a hazard in the absence of a spark. Therefore the duration of flammability becomes an important parameter to relate the two. Ventilation rate has a very powerful effect on this parameter.

The gas release frequency is relatively easy to determine if episodic gas releases have been occurring and can be observed in historical data (e.g., significant, sudden waste level drops).

However, most tanks do not show any evidence of episodic GREs. In this case, the frequency can be simply bounded by the nonobservance of releases, or the probability of a future release can be estimated by other means. Many tanks show a waste level rise in their early history that eventually flattens out. A conservative gas retention rate can be derived from this data that determines the frequency of any given release volume. One could also assume that gas release does not occur in the absence of some external disturbance, like a major seismic event, or core sampling. The gas release frequency is then determined by the frequency of the disturbance and the probability that the disturbance will initiate a release.

The spark frequency includes all ignition sources. Spark-like sources would include electrical arcing in a lightning strike, mechanical metal-to-metal impact sparks, nonrated electrical equipment, discharge of static electricity from nonconducting objects, and others. Hot surfaces could include cinders blown in from a nearby range fire, a fuel spill fire above the tank, welding slag, a rotary-mode core sample drill bit striking a metal object, and others.

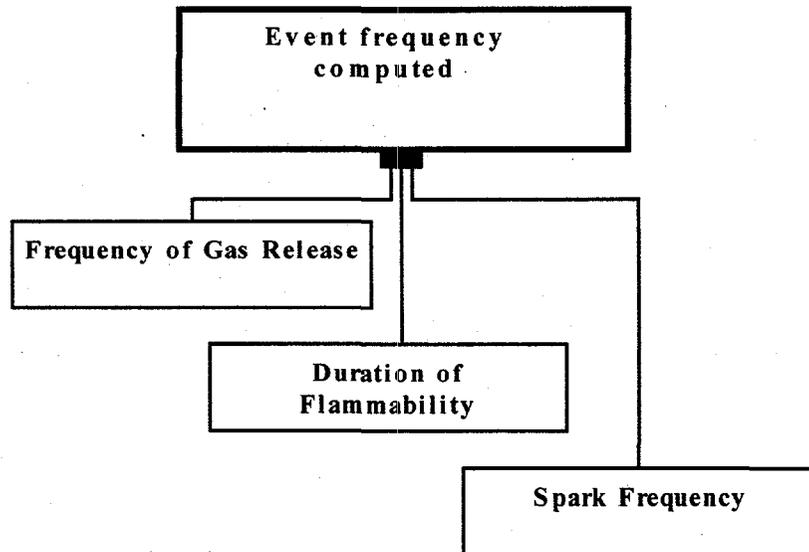


Figure 3.6. Frequency Section of Flammable Gas SLD

The consequences of the other safety issues can act as flammable gas ignition sources. An organic or ferrocyanide burn near the waste surface would be an obvious source. Though propagation of a flammable gas burn in the waste is doubtful, a surface burn would ignite any flammable gas that might be released at the time. A criticality creates high temperatures.

Gas release and ignition sources are often correlated. The same operation (e.g., rotary mode core sampling) may initiate a gas release and also provide the ignition source. In these cases, it is effective to monitor headspace gas concentration and automatically shut down equipment if flammable mixtures are detected. However, it is also common for the ignition source and gas release to occur at slightly different times such that the correlation is reduced. In a seismic event, for example, the ignition sources would typically be active before most of the gas escaped. With even a short delay between gas release and spark, ventilation is a very powerful factor in reducing the hazard by decreasing the time a flammable mixture exists.

4.0 Conclusions

The structured logic diagram is an effective method to display the outcomes necessary to reach a desired goal: to resolve the flammable gas safety issue by making risk acceptable. The diagram provides a structured path that can identify all information inputs, data as well as models, needed to achieve the goal. Tracing the path from need to outcome provides an immediate and clear justification and defense of a specific need. The diagram itself is a 'picture of a risk calculation' and forms the basis for a quantitative model of risk. The SLD, with the risk calculation, identifies options for characterization, mitigation, and control options that have the maximum effect in reducing risk. It provides quantitative input to risk-based decision making so that options are chosen for maximum impact at least cost.

Appendix A

Structured Logic Diagram for the Flammable Gas Safety Issue

NOTICE

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Appendix B

Process Box Explanations for the Flammable Gas Structured Logic Diagram

Appendix B

Process Box Explanations for the Flammable Gas Structured Logic Diagram

FG: Flammable gas life cycle risk acceptable. States the end goal of the logic diagram: that flammable gas risk is known and acceptable within established criteria. The life cycle could be from present to ultimate tank closure, but shorter periods can also be used. Risk is defined in terms of consequence (e.g., radiological dose, toxic exposure, direct injury, etc.) and a frequency (i.e., probability that the consequence occurs in a given time period, usually one year). The overall risk is intended to include consequences covered by risk acceptance criteria. Risk can be determined acceptable by: 1) determining the risk to be minimal by screening criteria, 2) formally comparing computed risk with acceptance criteria, or 3) mitigating, controlling, or otherwise intervening to make the risk acceptable.

FG.NORISK: Flammable gas risk determined to be minimal. This branch is intended to identify tanks for which the risk of flammable gas hazards is minimal without actually performing the detailed risk calculation. Simply stated, the risk is minimal if the waste does not generate flammable gas, or, if generated, flammable gas is not retained in the waste, or, if retained, it is not released episodically, or, if released, the release is not sufficient to fail the HEPA filters if burned.

FG.NORISK.A: Waste does not generate flammable gas. This requires that either no gas is generated or that any gas mixture generated is not flammable (this is probably a null set).

FG.NORISK.A.A: Gas is not generated. The gas generation rate is effectively zero (possibly as compared to a conservative diffusion rate) and no evidence of flammable species is observed in the headspace or waste.

FG.NORISK.A.A1: Flammable gas generation rate is negligible. Gas generation rate is effectively zero.

FG.NORISK.A.A.A: Flammable gas generation rate determined. Includes generation by radiolysis and chemical generation.

FG.NORISK.A.A.A.A: Gas generation rate by radiolysis determined. Requires information on radionuclides, radiolytes, temperature and a predictive model.

FG.NORISK.A.A.A.A1: Waste radionuclide inventory. Determined from core sample analysis. Gamma or neutron scan might also indicate lack of activity.

FG.NORISK.A.A.A.A2: Waste temperature. Radiolysis is affected by temperature. Thermocouple tree data.

FG.NORISK.A.A.A.A3: Chemical composition. Radiolysis or organics generates much more gas than water only.

FG.NORISK.A.A.A.A4: Radiolysis model applied. A model that estimates the rate and species of gas generated by radiolysis from the above data.

FG.NORISK.A.A.A.B: Gas generation rate by chemical reaction determined. Requires information on chemical composition, temperature, and a predictive model.

FG.NORISK.A.A.A.B1: Chemical composition. Identifies what reactions might occur.

FG.NORISK.A.A.A.B2: Waste temperature. Chemical reactions are strongly affected by temperature. Thermocouple tree data.

FG.NORISK.A.A.A.B3: Chemical gas generation model applied. A model that estimates the rate of gas generation by chemical reactions and the species from the above information.

FG.NORISK.A.A.B: Evidence of flammable gas generation is not present. Regardless of radiolysis or chemical reactions, if there is no evidence of flammable gas in waste or headspace, the flammable gas risk is demonstrated minimal.

FG.NORISK.A.A.B1: Headspace gas composition history. Gas composition versus time for at least hydrogen and ammonia for a sufficiently long period to show flammable gases are not being generated.

FG.NORISK.WGC: Waste gas composition determined. Composition of the gas retained in the waste determined in view of showing no flammable gas is being generated in the waste. (See separate subsection FG.WGC below.)

FG.NORISK.A.A.B2: Evaluation model applied. Evaluates headspace and waste composition evidence whether flammable gas generation evidence is present. This is not an evaluation of flammability but whether flammable gas species are being generated.

FG.NORISK.A.B: Gas mixture generated is not flammable. Gas cannot be ignited in situ nor is any mixture with air flammable.

FG.NORISK.A.B1: LFL model applied. A model to determine the lower flammability limit of the gas mixture.

FG.NORISK.WGC: Waste gas composition determined. Composition of the gas retained in the waste determined in view of showing gas being generated in the waste is not flammable when mixed with air. (See separate subsection FG.WGC below.)

FG.NORISK.B: Risk due to gas generation without retention determined to be minimal. If the waste does not retain gas and the generation rate is sufficiently low (with sufficiently high ventilation rate) to prevent flammability in the steady state, the flammable gas risk is minimal.

FG.NORISK.B.A: Waste does not retain gas. Gas is released from the waste surface at the same rate it is generated and none is stored in the waste except a small volume in transit. Either show the waste is all liquid, all dry, or no evidence that stored gas is present.

FG.NORISK.B.A.A: Waste yield strength is zero (all liquid). Gas bubble rises quickly through a liquid.

FG.NORISK.B.A.A1: Waste rheology profile. Evidence or measurement of zero yield strength through the entire waste column.

FG.NORISK.B.A.A2: Waste configuration profile. Evidence that the waste is entirely convective from core sample, temperature profile, ball rheometer, or other method.

FG.NORISK.B.A.A3: Evaluation model applied. A model evaluating above evidence whether gas retention is possible.

FG.NORISK.B.A.B: All gas space is connected (dry waste). If the waste is not liquid saturated, diffusion will release gas as soon as it is generated.

FG.NORISK.B.A.B1: Waste configuration profile. Evidence that the waste has no layers saturated with liquid from core sample or potentially cone penetrometer.

FG.NORISK.B.A.B2: Waste moisture profile. Moisture measurements to quantify liquid saturation.

FG.NORISK.B.A.B3: Evaluation model applied. A model evaluation of the above data whether gas retention is possible.

FG.NORISK.B.A.1: Retained gas volume is negligible. If no gas can be found, conclude it has not and cannot be retained.

FG.RGV: Retained gas volume determined. Retained gas volume measurements and calculations obtained to show no gas is present. (See separate subsection FG.RGV below.)

FG.NORISK.B.B: Headspace is not flammable in steady state. Steady state headspace is below LFL. Flammability is not possible due to gas generation alone.

FG.NORISK.B.B1: Headspace gas composition history. Headspace composition vs. time for a sufficiently long period to demonstrate headspace is not flammable.

FG.NORISK.B.B2: LFL model applied. A model to determine the lower flammability limit of the headspace gas mixture.

FG.NORISK.C: Risk due to gas retention is minimal. If the waste retains gas but does not release it episodically and a gas burn cannot be ignited in the waste, or if any episodic release could not be ignited above the waste, or would not fail the HEPA filters if burned, the risk is minimal.

FG.NORISK.C.A: Retained gas is not hazardous in the waste. Gas cannot be ignited or a gas burn cannot propagate beneath the waste surface.

FG.NORISK.C.A1: No ignition sources present.

FG.NORISK.C.A2: Flammable gas burn cannot propagate in the waste. No propagation is possible if retained gas exists as individual bubbles. Heat sinks and moisture needs to be evaluated for potential burns in interconnected dendritic bubbles.

FG.NORISK.C.B: Retained gas creates no hazard in the headspace. If the gas cannot be ignited or a burn is not sufficient to blow the HEPA filters, there is no hazard.

FG.NORISK.C.B.A: Headspace is not flammable. Headspace cannot become flammable if retained gas is not released episodically and the generation rate is sufficiently low that gas is diluted by ventilation to prevent it reaching flammability.

FG.NORISK.C.B.A1: Gas is not released episodically. Combination of no historical evidence nor a credible mechanism for episodic release.

FG.NORISK.C.B.A.A: Headspace is not flammable in steady state. Steady state headspace is below LFL. Flammability is not possible do to gas generation alone in the absence of episodic releases.

FG.NORISK.C.B.A.A1: Headspace gas compositon history. Heaspace composition versus time for a sufficiently long period to demonstrate headspace is not flammable.

FG.NORISK.C.B.A.A2: LFL model applied. A model to determine the lower flammability limit of the headspace gas mixture.

FG.NORISK.C.B.B: Gas in headspace cannot be ignited. Given a flammable gas release, this requires absence of ignition sources or zero flammability time following the release.

FG.NORISK.C.B.B.A: No ignition sources exposed to plume. No sources located where they might contact the release plume while it is flammable.

FG.NORISK.C.B.B.A1: Ignition source location.

FG.NORISK.C.B.B.A2: Ignition evaluation model applied. A model evaluating ignition source location whether they could contact the release plume while flammable.

FG.NORISK.C.B.B1: Time flammable is negligible. If the release plume is never flammable, it cannot be ignited.

FG.NORISK.C.B.B.B: Dome flammability time determined. The time required for the release to mix with the dome atmosphere and for ventillation to dilute the flammable gases in the dome is computed.

FG.NORISK.C.B.B.B1: Release rate. Volumetric rate of episodic gas release.

FG.VW: Gas release volume determined. Volume of episodic gas release at standard temperature and pressure. (See separate subsection FG.VW below.)

FG.PLUME: Flammable plume described. The gas release plume is modeled to determine the time it is flammable. (See separate subsection FG.PLUME below).

FG.NORISK.C.B.C: Episodic gas release insufficient to fail HEPA filters if burned in dome. Gas volume required to create sufficient pressure when burned to fail the HEPA filters is compared to the expected episodic release volume.

FG.VW: Gas release volume determined. Volume of episodic gas release at standard temperature and pressure. (See separate subsection FG.VW below).

FG.NORISK.C.B.C.A: Release volume is less than failure threshold. HEPA failure threshold must be determined.

FG.NORISK.C.B.C.A1: Headspace volume. Peak burn pressure is sensitive to the available headspace volume.

FG.NORISK.C.B.C.A2: HEPA design pressure. Failure pressure difference from manufacturer specifications.

FG.RGC: Release gas composition determined. Composition required to determine burn energy. (See separate subsection FG.RGC below.)

FG.NORISK.C.B.C.A3: Adiabatic combustion model applied. A model to compute the volume of gas required to burn to reach the given HEPA design pressure threshold.

FG1: Risk acceptance criteria satisfied. The frequency of each consequence is sufficiently low. If not, better data, controls, mitigation, or other action is required to make the risk acceptable. The logic is not tied to any specific risk acceptance criterion.

FG.A: Flammable gas risk determined over life cycle. The overall risk is calculated as a function of time for a tank or group of tanks based on scheduled activities over a given time period. Consequences and frequencies are determined given the changing waste state over the given life cycle by direct calculation.

FG.RISK.A: Significant failure scenarios selected. Failures scenarios are essentially groups of similar event sequences that result in the same class of failure (e.g. dome collapse). Failures are selected as those most likely to challenge the risk acceptance criteria by either the magnitude of the consequence or by high frequency or both.

FG.RISK.A1: Tank installed hardware and operating systems described. All information needed to perform a hazards analysis for a given waste/system state. This includes pertinent dimensions, materials, operational characteristics such as spark potential, and operating procedures and controls.

FG.RISK.A2: Life cycle action plan and contingencies described. See FG.STATE1 above. The life cycle plan is used here to define failure scenarios and perform hazards analyses.

FG.RISK.A3: Hazards analysis performed: Hazards analysis determines event sequences that define specific failure 'scenarios'. The failure scenarios are the basis for risk calculation. Only dome collapse due to flammable gas burn in dome is illustrated in this logic diagram.

FG.RISK.B: Risk calculated for each failure scenario and waste state. Risk is calculated by calculating the probability/frequency of the target consequences by following the events in the failure scenario. A dome collapse due to flammable gas burn in the dome is illustrated in this branch.

FG.RISK.B1: Scenario is FG burn in dome causing dome collapse and radioactive mass release. This scenario is selected as potentially the most important and most analyzed flammable gas failure event.

FG.DOME: Risk determined (for dome collapse scenario): Risk is calculated by mapping the target consequence backward through the event sequence to the volume of gas retained in the waste necessary

to produce the consequence. The probability of the consequence is then determined by comparing the required retained gas volume to the actual volume. The frequency of the target consequence is computed considering all important initiators, and the overall frequency of the consequence is determined for the given waste state.

FG.DOME.A: Probability distribution of event consequence (radiation dose) determined. The radiation dose consequence is determined through a series of steps following the failure scenario: gas release, pressure increase due to burn, mechanical energy released by structural failure, mass ejected from the tank, and finally to radiation dose received by specific receptors.

FG.VW: Gas release volume determined. This is the first step of calculating the radiation dose. The volume of gas retained in the waste is directly diagnostic to the volume of gas likely to be released. (See FG.VW subsection below.)

FG.VR: Peak dome pressure determined from gas release volume. This is the second step of calculating the radiation dose. The volume of gas released from the waste is directly diagnostic to the dome pressure with or without combustion. A wide range of calculational models have been applied from simple energy balances to coupled structural and thermo-fluid-dynamics simulations. The chain of events from gas release to the pressure pulse resulting from combustion is the primary flammable gas hazard.

FG.VR.A: Energy added by combustion determined. Oxidation of major fuel species releases combustion energy to the combustion products. It is typically assumed conservatively that all this energy serves to increase the pressure, neglecting heat losses. The details of the combustion process are typically ignored.

FG.VR.A1: Combustion reactions identified. Reactants and products of combustion reactions identified that may occur when waste gas is ignited. Several reactions are commonly approximated by converting to equivalent hydrogen fuel value.

FG.VR.A2: Time to ignition determined. The gas release plume will begin diluting by mixing and ventilation as soon as it leaves the waste. The elapsed time to ignition determines the extent of dilution and determines the flammability exposure probability.

FG.PLUME: Flammable plume described in space and time. The total volume that is flammable vs. time following the initial release. For large releases the entire dome may be flammable for some period. For smaller ones, only a local plume is flammable for a few minutes. Release plumes are buoyant and rise to the top of the dome quickly. (See separate subsection FG.PLUME below.)

FG.VR.A3: Combustion model applied. A model to compute the thermal energy released from combustion of a given volume of waste gas via the reactions identified. A simple adiabatic combustion model is commonly used though more complex simulations have also been performed to account for heat sinks, dome geometry, flame propagation, pressure relief, coupled structural dynamics, etc. **Additional effects in a more detailed model might include 3-D flame propagation effects, and heat sinks for the combustion energy.**

FG.VR.B: Peak pressure calculated from energy addition. The pressure resulting from combustion is computed by expanding the combustion products to pressure equilibrium. The time is usually assumed sufficiently short that pressure relief by outflow is negligible. Isentropic expansion is typically assumed.

FG.VR.B1: Headspace volume. Volume of gas above the waste is required to compute the dilution of the release plume, and the pressure energy.

FG.VR.B2: State equation for combustion products. Equations describing the relationship between pressure, temperature, mass and volume corresponding to the thermodynamic state at which the combustion products exist. This is required to compute the dome pressure from the energy added via combustion.

FG.VR.B3: Dome pressure model applied. A model to compute the peak dome pressure from the energy released during combustion. It is common to simply apply the state equation to expand the combustion products. However, more complex combustion models include a detailed transient pressure calculation. Additional effects for a more detailed pressure calculation could include pressure relief by outflow, coupled structural expansion, and non-ideal gas behavior.

FG.PF: Mechanical energy available at failure determined from peak dome pressure. The third step of mapping the dose into retained gas volume. The dome pressure is directly diagnostic to the mechanical energy released at failure. It is typically assumed that the dome will fail catastrophically if the peak dome pressure exceeds the design value.

FG.PF1: Failure scenario defined. The sequence of events assumed for the failure being considered. Includes external factors such as operations involving additional masses on the dome (e.g., core sample trucks, heavy equipment being installed, etc.), large risers being opened, changes in ventilation, etc.

FG.PF.A: Mechanical energy available at failure determined. Estimate the mechanical energy that can be liberated at failure by the postulated dome pressure. Essentially, this is a threshold calculation: when the peak pressure reaches the design maximum, all the gravitational potential energy of the tank dome and overburden is released at failure. The pressure energy (PV) is included.

FG.PF.A1: Dome volume. Volume of gas above the waste is required to the pressure energy.

FG.PF.A.A: Failure criteria determined. The failure criteria model translates allowable stresses to the maximum allowable dome pressure. It may include detailed structural mechanics calculations.

FG.PF.A.A.A: System defined. The tank structure, including overburden, installed equipment, suspended hardware, and potential waste deposits is defined for the purpose of relating internal pressure to maximum stress levels that would cause failure.

FG.PF.A.A.A1: Tank structural design. Sufficient design detail to determine peak stresses in the dome structure imposed by elevated dome pressure for comparison to allowable stresses.

FG.PF.A.A.A2: Installed hardware design. Sufficient design detail to determine the contribution of installed hardware on peak stresses in the dome structure imposed by elevated dome pressure. This should also include estimated mass of significant waste deposits on suspended hardware.

FG.PF.A.A1: Tank structural integrity determined. An estimate of the current condition of the tank allowing for damage and degradation for the purpose of determining allowable stresses and peak dome pressures. It is suggested that tank structural integrity could be evaluated by NDE. Issues considered in this estimate include: tank damage history, dome loading history, chemical corrosion of steel liner and rebar, and thermal degradation of concrete.

FG.PF.A.A2: Structural failure criteria model applied. A model defining the reduction in allowable dome pressure that corresponds to the reduction in allowable stresses caused by degradation of tank structural integrity

FG.PF.A2: Potential energy model applied. A model describing the mechanical energy available to be released in a collapse as a result of dome pressure exceeding allowable values. The energy consists of the pressure energy in the dome (PV) plus the gravitational potential energy of the dome structure and overburden which depends on structure mass and its potential drop height.

FG.EF: Ejected mass determined from failure energy. This is the fourth step in the process. The mechanical energy available at failure, both pressure energy and gravitational potential energy, is directly diagnostic to the mass of material released. The mechanical energy is taken to include both pressure energy (i.e. from a flammable gas burn) and gravitational potential energy of the dome structure and overburden. This step assumes mass release will actually be calculated considering the dome collapse process in some detail. In current practice, the condition of dome collapse is often assumed by itself to be sufficient to exceed offsite dose criteria.

FG.EF.A: Mechanical energy transfer processes during failure described. The motions and impacts occurring during failure are described as well as the transfers of energy between mechanical and thermodynamic forms.

FG.EF.A.A: System defined. The tank structure, the waste, and installed hardware must be described in terms of failure modes, likely motions and impacts during failure.

FG.EF.A.A1: Tank structural design. Sufficient design detail to determine probable failure modes, and masses and energies of failing components.

FG.EF.A.A2: Waste dimensions. Elevation and major configuration of waste surface for calculating impact energy absorption and damping of suspended hardware motion.

FG.EF.A.A3: Waste physical properties. Includes density, strength, and viscosity for calculating impact energy absorption and damping of suspended hardware motion.

FG.EF.A.A4: Installed hardware design. Sufficient design detail to determine probable failure modes, suspended hardware vibration modes, projectile mass and shape, and other failure energy transfer concerns. This should also include estimated mass of significant waste deposits on suspended hardware.

FG.EF.A1: Failure scenario defined. The sequence of events assumed for the failure being considered. Includes external factors such as operations involving additional masses on the dome (e.g. core sample trucks, heavy equipment being installed, etc.), large risers being opened, changes in ventilation, etc.

FG.EF.A2: Dome collapse model applied. A model to describe the motions and energy transfer processes that evolve during a dome collapse event.

FG.EF.B: Mass ejection determined from mechanical energy release. Estimate the mass of material entrained as aerosols in the ejected debris plume. Entrainment is estimated from the energies and masses impacting the waste surface. High velocity gas-particulate flows over surfaces could also be considered. This area is currently not well established.

FG.EF.B1: Energy delivered to waste determined. Undefined models are applied to estimate how the mechanical energy liberated during failure is actually delivered to the waste. That is, the impacts, abrasions, and other conditions likely to entrain waste are quantified.

FG.EF.B2: Dome radioactive particulate loading determined. The dome loading represents the particulates already suspended in the headspace prior to actual collapse. One example is the fines suspended from rotary core sampling.

FG.EF.B3: Bulk waste source term. The concentration of radionuclides in the waste expected to be ejected during an accident.

FG.EF.B4: Waste physical properties. Includes density, strength, and particle size distribution for calculating particulate ejection via impact energy absorption.

FG.EF.B5: Mass ejection model applied. The actual mass of radionuclides ejected with the debris plume is estimated given the impact energies delivered to the surface. Additional effects that could be included are thermal effects, mass entrained from tank walls, counter-flow filtering of ejecta by falling overburden, and long-term entrainment from open waste pools.

FG.MR: Radiation dose determined from mass ejection. The final step in dose calculation. The mass of radioactive material released from the tank to the atmosphere at failure is directly diagnostic to the dose to a receptor either onsite or offsite. The physical source term and configuration of the plume leaving the tank has been determined in the prior step (see FG.EF).

FG.MR1: Plume dispersion calculated. A model to compute how the radioactive plume is dispersed by winds and where the radioactive aerosols settle out.

FG.MR2: Dose model applied. A model to estimate the actual radioactive dose to a person exposed to the plume at the site boundary or other specified distance from the source.

FG.FREQ: Event frequency determined. The event frequency is calculated assuming the required retained gas volume is available. Contributing to the frequency are gas release frequency, fraction of time sufficient volume is flammable, and frequency of an ignition source exposed to the flammable plume.

FG.FREQ1: Frequency of gas release from waste. The frequency of a gas release sufficient to cause the target consequence. Currently the frequency is determined from historical gas release events as evidenced by the waste level history, bounded by non-observance of significant gas releases, or estimated by net gas retention rates determined from waste level growth.

FG.FREQ.A: Probability of ignition of given gas release determined. A flammable gas burn can occur only if a flammable volume is ignited. This requires an ignition source to be active during the time and at a location where the flammable mixture exists. The flammable plume has been described above (see FG.VR).

FG.FREQ.A.A: Plume time flammable determined. The ignition probability depends on the fraction of time a flammable gas plume exists that can be ignited. The gas release plume is calculated from when the gas leaves the waste until the gas in the dome is no longer flammable.

FG.PLUME: Plume described in space and time. The dilution of the release plume is described. (See separate subsection FG.PLUME below.)

FG.FREQ.A.A1: LFL model applied. The flammability of the plume is determined as it is diluted in order to compute the time the plume remains flammable.

FG.FREQ.A1: Ignition sources exposed to plume characterized. A flammable hydrogen gas mixture is very easily ignited. Essentially any spark or surface with a temperature about 400 °C will initiate a flame. Failure scenarios from other safety issues may also represent ignition sources. The important factors in determining risk are the source frequency and location relative to the flammable plume.

FG.FREQ.A2: Ignition probability model applied. A model to compute the ignition probability from the duration of flammability and the location and frequency of ignition sources.

FG.FREQ2: Frequency model applied. A model to compute the frequency of the dome collapse scenario. The frequency of a gas release of sufficient size to cause the consequence is combined with the probability that the given gas release will be ignited.

FG.DOME1: Probability model applied: A model to compute the overall risk of the selected scenario by combining the probabilities determined in mapping the failure sequence from dose to retained gas volume, the frequency of the scenario given sufficient retained gas, and the probability of that gas volume existing in the tank.

FG.RISK.B2: Other scenarios. Examples of other flammable gas failure scenarios could include: FG burn in waste causing large unfiltered release, FG burn in dome ejecting contaminated hardware during removal, large FG release without burn causing unfiltered release through blown HEPA filters.

FG.RISK.B3: Risk determined for other scenarios. Expected to follow a calculational sequence similar to dome collapse scenario.

FG.RISK.A1: Risk "summed" over all failure scenarios: A risk combination model to compute the overall risk from all significant failure scenarios for a given waste/system state.

FG2: Intervention makes risk acceptable. Intervention accomplishes the actions prescribed to reduce the risk. This might include applying operational controls, modifying equipment, altering the waste (e.g., salt-well pumping, mixing, dilution, etc.), reducing the uncertainty by increasing knowledge (e.g., waste sample & analysis, laboratory studies, modeling, etc.), or retrieval.

The Branches Described Below are used Repeatedly in the Base SLD Above.

FG.PLUME: FLAMMABLE PLUME DESCRIBED IN SPACE AND TIME. The total volume that is flammable versus following the initial release. For large releases, the entire dome may be flammable for some period. For smaller ones, only a local plume is flammable for a few minutes. Release plumes are buoyant and rise to the top of the dome quickly. Gas release volume, composition, and volumetric flow rate were determined in the prior step (see FG.VW).

FG.PLUME.A: Dilution determined. Gas released from the waste mixes with the air in the dome space and the total flammable volume is reduced by ventilation. Even a small local plume remains flammable for several minutes before mixing by convection and diffusion.

FG.RGC: Release gas composition determined. The composition of the gas leaving the waste and entering the headspace. (See separate FG.RGC subsection below.)

FG.PLUME.A1: Headspace volume. The nonwaste volume of the tank available for gas mixing.

FG.VENT: Ventilation rate determined. The effective volumetric flowrate of outside air through the tank. This quantity can be measured for actively ventilated tanks, inferred from concentration decays following known gas releases, or estimated based on 'breathing' during atmospheric pressure changes. (See separate FG.VENT subsection below.)

FG.PLUME.A2: Dilution model applied. A model to calculate the dilution of the released gas in the dome including the effect of ventilation. The output is hydrogen concentration versus time. Detailed fluid dynamics simulations are also performed that provide 3-dimensional concentration distributions versus time.

FG.PLUME1: LFL model applied. A model to determine the lower flammability limit (lfl) of a gas mixture from the lfl of component fuel/oxidizer reactions and their concentrations. Used with a dilution model to determine the fraction of the release plume that is flammable.

FG.RGC: RELEASE GAS COMPOSITION DETERMINED. The chemical composition of the flammable gas released from the waste into the tank headspace. This considers only undissolved free gas released as bubbles. It does not include dissolved gas evolving from exposed liquid surfaces during any disturbance coincident with the release.

FG.RGC1: Bounding composition estimated. Estimated chemical composition of released gas based on expert opinion or general bounding assumptions. For example, 100% hydrogen might be assumed.

FG.RGC.A: Release composition determined from headspace gas composition. The chemical composition of the flammable gas released from the waste based on chemical composition of the headspace.

FG.RGC.A.A: Headspace data obtained. Chemical composition of the tank headspace obtained from knowledge of other tanks or from specific data collected at the tank of interest.

FG.RGC.A.A1: Headspace composition from other tanks. Chemical composition of the headspace in tanks other than the tank of interest.

FG.RGC.A.A.A: Complete analysis obtained. Chemical composition of the tank headspace based on analysis of samples from the tank headspace of interest.

FG.RGC.A.A.A1: Grab sample analysis. Discrete samples of gas taken from the tank headspace analyzed in the laboratory for chemical composition. This provides as complete a composition analysis as possible.

FG.RGC.A.A.A2: New methods. Other methods for directly measuring the chemical composition of a tank headspace may be developed.

FG.RGC.A.A.B: Composite analysis obtained from available sources. Various continuous monitoring instruments are available (not all on the same tank) that provide the concentration of one or two components. If more than one of these instruments is available, a more complete composition can be determined.

FG.RGC.A.A.B1: Whitaker cell data (H_2). Whitakers are typically high-range instruments that do not sense low concentrations.

FG.RGC.A.A.B2: FTIR data (N_2O , NH_3 , CH_4 , CO ,...). The Fourier transform infrared spectrometer can be calibrated to indicate the listed components although the spectra recorded contains the effects of all gas species.

FG.RGC.A.A.B3: GC data (H_2 , N_2O). The gas chromatograph typically is set up to measure hydrogen and nitrous oxide very precisely.

FG.RGC.A.A.B4: SGFET (H_2 , NH_3). The synthetic gate field effect transistor is currently being developed to sense hydrogen and ammonia, though other gases can also be measured.

FG.RGC.A.A.B5: B + K data (NH_3). The B and K ammonia monitors are relatively high-range instruments.

FG.RGC.A.A.C: Composition determined from lumped measurements. Chemical composition of the tank headspace is inferred from measurements of the gas flammability.

FG.RGC.A.A.C1: Flammable gas monitor data. Measurement of the gas flammability in the tank headspace are made by a heat sensor calibrated to indicate flammability of a selected species. Depending on the calibration and the gas species actually present, it may be possible to extract gas concentration from monitor data.

FG.RGC.A.A.C2: Interpretive model. A model predicting the chemical composition of headspace gas based on the gas flammability and instrument calibration.

FGC.RGC.A1: Release gas composition model applied. A model predicting the chemical composition of the gas released from the waste based on the chemical composition of the tank headspace. The headspace composition represents the release gas diluted by air and contaminated with any dissolved gas diffusing from the liquid surface. Therefore, only some of the ratios of various gases may be determined from headspace gas. An estimate of the release gas can be obtained by making assumptions about the nitrogen fraction in the waste, for example.

FG.RGC.B: Release composition determined from waste gas composition. The chemical composition of the gas released from the waste based on composition of gas retained in waste.

FG.WGC: Gas composition in waste determined. The chemical composition of the gas retained in the waste determined from direct measurement, indirect methods, or based on knowledge from similar tanks. (See separate subsection FG.WGC below.)

FG.RGC.B1: Release gas composition model applied. A model predicting the chemical composition of released gas based on retained gas composition in the waste. Usually the release gas can be assumed to have the same composition as the waste gas.

FG.WGC: GAS COMPOSITION IN WASTE DETERMINED. The composition of the gas actually retained in the waste. This can be determined from direct measurement, indirect methods, or based on knowledge from similar tanks.

FG.WGC1: Waste gas composition from other tanks. Composition measurements or other data obtained from tanks other than those of interest.

FG.WGC.A: Waste gas composition measured. Direct measurements of in situ gas composition.

FG.WGC.A1: RGS analysis. The retained gas sampler was designed specifically to obtain a detailed in situ composition measurement of a pressurized waste sample. The RGS is actually a modified version of the universal sampler employed in push-mode and rotary core sampling. RGS segments are interspersed with normal segments. RGS analysis includes not only free gas but dissolved and absorbed gas as well as the void fraction.

FG.WGC.A2: Drill string grab sample analysis. Gas collecting in the drill string during push-mode sampling is essentially a sample of retained gas. During rotary sampling, nitrogen purge gas dilutes the drill string gas, but ratios of major components are still available.

FG.WGC.A3: New measurement methods. New methods may be developed that provide accurate in situ gas composition measurements (e.g., Raman spectroscopy).

FG.WGC.B: Waste composition data obtained indirectly. If samples are not available, the composition can be estimated from laboratory experiments, expert opinion, or physiochemical models.

FG.WGC.B.A: Gas generation experiments performed. Gas generation experiments on simulants or actual waste samples provide generation rates of major components as a function of temperature and radiation (typically a gamma source).

FG.WGC.B.A.A: Laboratory data obtained. Experiments on actual waste samples in the hot cell or with chemical simulants.

FG.WGC.B.A.A1: Actual waste analysis. Gas generation tests have been performed on SY-101 and SY-103 waste. Further tests are planned on S-102 and AW-101 waste.

FG.WGC.B.A.A2: Waste simulant analysis. Gas generation tests have investigated the effects of temperature, radiation, organics concentration, and other effects.

FG.WGC.B.A1: Interpretive model applied. Since the gas generation tests do not perfectly represent tank conditions, the data must be interpreted carefully to make predictions about actual gas concentrations.

FG.WGC.B1: Expert opinion elicited. Gas composition estimated based on knowledge of the chemistry, radiolysis, tank waste experience, etc.

FG.WGC.B2: Waste gas composition obtained from physiochemical models. Models representing the chemical, thermodynamic, and radiolytic processes might be able to predict the gas composition.

FG.VENT: VENTILATION RATE DETERMINED. The ventilation rate is the net volumetric rate of exchange of headspace atmosphere with ambient air. Ventilation can be forced by an installed fan or by passive 'breathing.' Some forced ventilation systems connect an entire tank farm and individual tank ventilation rates are not measured. The ventilation rate is very important in calculating dilution of the release gas.

FG.VENT.A: Ventilation rate measured. The ventilation rate is measured directly or inferred from gas composition transients.

FG.VENT.A1: Direct flow measurement. The ventilation flow rate is measured directly in the exhaust of the tank of interest. Typical flow rate measurements are accurate to about 100 cfm. An exhaust stack measurement for an entire tank farm does not provide individual tank ventilation rate.

FG.VENT.A.A: Flow determined from fan curves. Flow can be determined from manufacturer's fan performance curves and an appropriate pressure measurement in the vent system.

FG.VENT.A.A1: Ventilation pressure measurement. An appropriate pressure measurement in the vent system.

FG.VENT.A.A2: Fan performance specifications. Manufacturer's specifications relating fan rpm to pressure rise and flow rate.

FG.VENT.A.B: Flow determined from tracer injection. The ventilation flow rate can be calculated from the decay transient of concentration of a tracer gas injected into the dome.

FG.VENT.A.B1: Tracer concentration transient. The concentration of the tracer gas versus time measured in the exhaust stream or other location representative of the mixed dome.

FG.VENT.A.B2: Decay model applied. The flow rate is computed from the exponential decay constant of the tracer concentration.

FG.VENT.A.C: Flow determined from concentration decay following a GRE. Major gas components injected into the tank headspace via a small (or large) GRE serve as a tracer gas for determining ventilation rate as above, providing continuous gas monitoring is available and the GRE occurs over a short period relative to the time required for concentration decay.

FG.VENT.A.C1: Hydrogen concentration transient in dome. Hydrogen, or other monitored component, concentration versus time in the exhaust or other location representative of the mixed dome.

FG.VENT.A.C2: Decay model applied. The flow rate is computed from the exponential decay constant of the tracer concentration.

FG.VENT.B: Ventilation rate calculated. Passive breathing ventilation can be calculated directly including only atmospheric pressure breathing or by computational simulation including thermal effects. Computational simulation can also resolve individual tank ventilation rates from the overall tank farm flow rate.

FG.VENT.B.A: Atmospheric breathing rate determined. Air flows in and out of the tank headspace in response to barometric pressure fluctuations. Ventilation occurs only on the outflow.

FG.VENT.B.A1: Dome pressure history. Pressure versus time inside the dome measured so as to assess the flow resistance between the dome and ambient barometric pressure. Useful only if sensitive pressure transducers are available (measuring to within 1 inch water).

FG.VENT.B.A2: Dome volume. The ventilation flow rate is proportional to the headspace volume in the tank.

FG.VENT.B.A3: Barometric pressure history. Barometric pressure versus time for one average annual cycle.

FG.VENT.B.A4: Overall flow loss coefficient. The flow loss coefficient between the dome and ambient determined by calibration of flow inferred from decay of pressure difference.

FG.VENT.B.A5: Breathing model applied. The breathing rate is the product of the rate of barometric pressure change (in atmospheres) and the headspace volume calculated only when the pressure rate is negative (outflow). The loss coefficient can also be included with a simplified momentum equation.

FG.VENT.B.B: Computational simulation performed. The ventilation process can be simulated directly with computational fluid dynamics models. These models consider the thermal convection as well as pressure breathing and flow losses.

FG.VENT.B.B1: Interconnection to other tanks. Air flow connections to other tanks defined in terms of areas and loss coefficients. These connections must be included where there are significant differences in heat load or when dividing the tank farm ventilation flow.

FG.VENT.B.B2: Ambient pressure and temperature transient and wind. All atmospheric parameters that affect ventilation versus time.

FG.VENT.B.B3: Waste temperature. The temperature of the waste surface for thermal calculations. A more complete simulation would substitute waste heat load and compute a transient temperature distribution.

FG.VENT.B.B4: Tank design. Includes the headspace dimensions, riser location, and any other geometric information affecting ventilation.

FG.VENT.B.B5: Leak paths. Flow paths to the atmosphere not specifically designed as ventilation flows, if they can be identified.

FG.VENT.B.B6: Computational model applied. The ventilation flow rate is computed by solving coupled equations for the conservation of mass, energy, and momentum.

FG.VW: GAS RELEASE VOLUME DETERMINED. The probability distribution of the volume of episodic gas releases at standard temperature and pressure. Gas releases are considered that are rapid relative to the headspace ventilation rate with a potential for creating a flammable mixture.

FG.VW1: Bounding volume estimated. The bounding volume is usually stated as a fraction of the stored gas volume. The fraction may be derived from assumed porosity or related to another tank whose releases are considered 'bounding.'

FG.GREV: Volume determined from GRE history. If a tank has been exhibiting episodic gas release events (GREs) the probability distribution of gas release volumes can be derived from prior occurrences. Usually this is indicated by waste level drops. (See separate FG.GREV subsection below.)

FG.VW.A: Volume determined from release fraction. The episodic gas release volume is stated as a fraction of the stored gas volume. Typical release fraction ranges from 15 to 50% in tanks that release gas by buoyant instability.

FG.RGV: Retained gas volume determined. The volume of gas stored in the waste is determined at standard temperature and pressure. The volume can be determined from direct local measurements or from waste level changes. (See separate FG.RGV subsection below.)

FG.VW.A.A: Release fraction determined. The fraction can be based on behavior of similar tanks, obtained by modeling, or from laboratory experiments with waste analogs.

FG.VW.A.A.A: Release fraction determined for other tanks. Release fraction is determined for tanks with similar behavior. This requires determining their GRE volume and their retained gas volume.

FG.GREV: Gas release volume determined from GRE history of other tanks. The waste level immediately prior to the GRE is also required. In this case, no correction to standard pressure and temperature is necessary since only a ratio of volumes is required. This removes the uncertainty in effective pressure from the calculation. (See subsection FG.GREV below.)

FG.RGV: Retained gas volume determined for other tanks. The waste level at which the retained gas volume is determined needs to be recorded. As above, no correction to standard temperature and pressure is needed here. (See subsection FG.RGV below.)

FG.VW.A.A.A1: Release fraction model applied. Release fraction is the gas release volume of a tank divided by the retained gas volume in the tanks immediately prior to the release. The pre-GRE gas volume is obtained from the retained gas volume at a known waste level and the waste level immediately prior to each GRE. The difference in the levels multiplied by the tank cross-sectional area is the difference in the in situ gas volume between the two levels. It is desirable to have a sufficient number of release fraction calculations to determine a probability distribution.

FG.VW.A.A1: Laboratory experiment performed. Gas release fractions can be determined from gas retention and release experiments with waste analogs such as bentonite clay mixtures and fine glass beads. Gas generation is simulated by catalysis of hydrogen peroxide or by nucleation of dissolved gas under a controlled pressure reduction. Parametric studies of yield strength, rate of pressure reduction and vessel diameter are being investigated.

FG.VW.A.A.B: Release fraction obtained by modeling. Models are derived from porous media literature relating the minimum and maximum amount of gas left after liquid displaces gas and vice versa. New models are possible that include the opposing effects of material strength and hydrostatic pressure difference.

FG.VW.A.A.B.A: Minimum void model. This model ratios the minimum void fraction in a porous media (on the order of 12 to 20% of the porosity) when liquid displaces gas to the maximum gas content (around 60 to 80% of the porosity) when gas displaces liquid. Maximum release fractions of 40 to 60% are typical of this model. It does not apply to buoyancy induced rollover gas releases.

FG.VW.A.A.B.A1: Spatial distribution of waste porosity. The actual minimum and maximum void fraction depend on the porosity and estimated pore size. This could be determined from appropriate analysis of a full core sample.

FG.VW.A.A.B.A2: Minimum void model applied. Actual application of the minimum void model to compute the release fraction.

FG.VW.A.A.B1: New models. The minimum void model assumes the solid material is fixed so the porosity is constant. However, the hydrostatic pressure difference acting on gas-bearing regions of sufficient depth will exceed the material yield strength and close off the pores. Including this physical mechanism would lead to a lower release fraction than the minimum void model.

FG.VW.A.A2: Expert opinion elicited. Expert opinion can be obtained through formal processes that establish the value and uncertainty of a parameter. This would combine information from all sources considered above.

FG.VW.A1: Release model applied. The release model is essentially a simple multiplication of the retained gas volume by the release fraction to yield the release gas volume. An uncertainty calculation is also implied and application of a certain level of judgment to ensure the calculation is consistent with all other information available on the waste in a particular tank.

FG.VW.B: Volume determined by computational simulation. The actual dynamics of the gas release process are modeled in detail with computational fluid dynamics models. A viscous flow model can be applied to those tanks whose primary GRE mechanism is buoyancy-induced 'rollover.' Porous media models are more suitable to single-shell tanks without appreciable supernatant liquid.

FG.VW.B.A: Viscous flow simulation. Computational simulation of a flammable gas release involving deformation of the waste structure. In such a release, the waste acts as a viscous liquid. This only applies to the rollover mechanism.

FG.VW.B.A1: Waste rheology. A physical property of the waste describing its deformation in response to shear stress. Mainly viscosity, but also yield strength is needed.

FG.VW.B.A2: Other data. Additional data required to complete the description of the waste and tank for viscous flow modeling. This data includes dimensions of the tank, presence of equipment penetrating the waste.

FG.VW.B.A3: Temperature profile. Waste temperature as a function of depth below the waste surface is needed to set the proper values for temperature dependent properties. Local gas volume also depends somewhat on temperature.

FG.VW.B.A4: Waste configuration. The distribution of distinguishable waste types with different rheology and initial gas content throughout the tank.

FG.VW.B.A5: Waste density distribution. The mass per unit volume of a waste layer without retained gas present. The density is critical to correctly predicting buoyant instability.

FG.VW.B.A6: Viscous flow simulation performed. Simulation of a viscous flow event that releases flammable gas into the tank dome space. The simulation provides gas release as a function of time and describes the dynamic character of the release.

FG.VW.B.B: Porous media simulation. Computational simulation of a flammable gas release involving gas and liquid flow through the pore spaces within the waste. This simulation assumes the solid particle matrix of the waste is not disturbed during this release. The porous media simulation may also be used to compute steady-state gas retention within the waste.

FG.VW.B.B1: Other data. Additional data required to complete the description of the waste and tank for porous media modeling. This data includes dimensions of the tanks, presence of equipment penetrating the waste.

FG.VW.B.B2: Temperature profile. Waste temperature as a function of depth below the waste surface is needed to set the proper values for temperature-dependent properties. Local gas volume also depends somewhat on temperature.

FG.VW.B.B3: Waste porous media properties. Waste matrix physical properties required to calculate the flow of liquid and gas through the waste. These properties may include absolute permeability, porosity, capillary pressure, and relative permeability to gas and liquid flow.

FG.VW.B.B4: Liquid physical properties. Physical properties of the gas and liquid present in the waste. These include viscosity, density, surface tension, solubility.

FG.VW.B.B5: Waste configuration. The distribution of distinguishable waste types with different physical properties throughout the tank.

FG.VW.B.B6: Porous media simulation performed. Simulation of a porous media flow event that releases flammable gas into the tank dome space. This simulation provides gas release as a function of time.

FG.VW.B1: New models. Other computational models that predict the release of flammable gas into the tank dome space that are not defined at this time. An example might be a combined structural mechanics and viscous flow simulation.

FG.VW2: Lumped-parameter models. Models have been developed that treat the GRE process in a more global sense by considering structural mechanics of buoyant instability, bubble growth in a lithostatic column, and the effects of a sequence of GREs.

FG.GREV: VOLUME DETERMINED FROM GRE HISTORY. If a tank has been exhibiting episodic GREs the probability distribution of gas release volumes can be derived from prior occurrences. GREs are usually indicated by waste level drops occurring over one or a few days. However, they can also be indicated by changes in the response of waste level to barometric pressure, headspace gas concentration spikes, or by dome pressure transients given a sufficiently sensitive pressure measurement.

FG.GREV.A: Gas release volume determined by level change. A continuous waste level history is typically available for ten years. GREs are indicated by sudden level drops of about 2 cm or more. This makes the minimum detectable GRE about 20 m³ (700 ft³) assuming an effective pressure of 2 atm. Care must be taken to discard spurious indications due to level instrument maintenance such as flushes or probe replacement. In some tanks the minimum level does not occur until up to a week after the initial drop. Judgment must be exercised to determine the proper level drop to assign.

FG.GREV.A1: Level history. Record of daily waste level readings for the period of interest. Level readings from the FIC contact probe or manual tape are typically available since 1986-87. The FIC can detect waste level changes to ± 0.5 cm and the manual tape to within ± 1 cm. Within the last year the much more precise and reliable Enraf buoyancy gage has been installed in more tanks.

FG.PEFF: Effective pressure. The absolute pressure at which the gas is stored is needed for correction to standard conditions. (See separate FG.PEFF subsection below.)

FG.GREV.A2: Temperature profile. The absolute temperature at which the gas is stored is needed for correction to standard conditions.

FG.GREV.A3: L model applied. The gas release volume is equal to the product of level drop, tank cross-sectional area, effective pressure ratio, and effective absolute temperature ratio.

FG.GREV.B: Gas release volume determined by dL/dP. The gas release volume can be estimated by comparing the response of waste level to barometric pressure before and after the GRE. Since a relatively long period is required to determine dL/dP on either side of the GRE, this method is limited to tanks that burp at low frequency.

FG.GREV.B.A: dL/dP determined before and after GRE. Waste level is correlated to barometric pressure during an appropriate period before and after the GRE. Hourly level measurements are preferable if available. One month's worth of data may be required to get a good correlation unless large swings in barometric pressure have occurred.

FG.GREV.B.A1: Level history. Record of waste level measurements during the desired period.

FG.GREV.B.A2: Pressure history. Record of barometric pressure during the desired period.

FG.GREV.B.A3: Statistical model applied. The probability distribution of pressure-level correlation is determined from the recorded data.

FG.PEFF: Effective pressure. The absolute pressure at which the gas is stored is needed for correction to standard conditions. (See separate FG.PEFF subsection below.)

FG.GREV.B1: Temperature profile. The absolute temperature at which the gas is stored is needed for correction to standard conditions.

FG.GREV.B2: dL/dP model applied. The standard volume of retained gas is equal to the product of tank cross-sectional area, the square of the effective absolute pressure (in atmospheres), the absolute pressure ratio, and the negative of the dL/dP slope. The released volume is simply the difference of the volume calculated before and after the GRE.

FG.GREV.C: Gas release volume determined by concentration and ventilation flow. If a sufficiently sensitive gas monitor is installed and the ventilation rate can be accurately determined, the gas release volume can be determined as the product of gas concentration and ventilation flow.

FG.GREV.C1: Dome hydrogen concentration history. The concentration transient covering the period surrounding the GRE is needed. The monitoring instrument must be sufficiently sensitive and record at a high enough frequency to resolve the details of the event. Actually, any release gas component that is not present in air can be used. The more components measured, the more accurate the volume estimate.

FG.WGC: Waste gas composition. The waste gas composition (assumed to be the same as release gas composition) is needed to relate the headspace concentration transient to the gas mixture exiting the waste. (See separate subsection FG.WGC above.)

FG.VENT: Ventilation rate determined. The ventilation rate can be determined quite accurately from the exponential decay of headspace gas concentration, if it is reasonably uniform during the GRE decay. For a passively ventilated tank, the decay period may cover several diurnal cycles and make averaging difficult. (See separate subsection FG.VENT above.)

FG.GREV.C2: Concentration model applied. The estimated gas release volume is the integral of the headspace hydrogen concentration multiplied by the calculated ventilation flow rate and divided by the hydrogen concentration of the gas in the waste.

FG.GREV1: GRE indicated by pressure. It is theoretically possible to compute the gas release volume from the dome pressure transient knowing the total flow area and the overall loss coefficient. With the high-precision pressure monitors being installed, such a calculation may become practical in the near future.

FG.PEFF: EFFECTIVE PRESSURE DETERMINED. The effective pressure is the absolute pressure at which gas is stored in the waste. Therefore it is essentially a gas volume weighted average pressure. This requires some knowledge or assumption about the stored gas distribution.

FG.PZ: Pressure profile determined. The pressure profile is computed from waste density as the hydrostatic pressure. (See separate subsection FG.PZ below.)

FG.PEFF.A: Relative void profile determined. The void fraction profile is a measure of the local gas content as a function of depth. This is required to obtain the correct volume-weighted average pressure.

FG.PEFF.A1: VFI void fraction. The void fraction instrument provides the local void fraction profile directly around one or more riser locations in the tank. Uncertainty due to data scatter and sampling error is 20 to 30%.

FG.PEFF.A2: RGS void fraction. The retained gas sampler provides a measure of the gas content of several core segments, three to four for each riser. The uncertainty has not yet been established but should be comparable to the VFI.

FG.PEFF.A.A: Void profile determined from waste configuration. The void fraction profile can be estimated from the waste configuration, especially in tanks that have a well-defined nonconvective, convective, and crust layers. In this case it is appropriate to assume all the gas is distributed between the nonconvective and crust layers. It may eventually be possible to estimate the void profile from the appearance of core extrusions.

FG.PEFF.A.A.A: Waste layers described. Define what layers are present, their sequence, and thickness.

FG.PEFF.A.A.A1: Core sample analysis. Identifies material found in each 19-inch segment. A full core provides a description of waste layers.

FG.PEFF.A.A.A2: Cone penetrometer. When it is deployed in late 1996, the cone penetrometer should be able to distinguish waste layers.

FG.PEFF.A.A.A3: Ball rheometer. The force and distance data from the ball rheometer give very precise measurements of the location of the transition from convective to nonconvective layers. Point accuracy of ± 4 cm is typical.

FG.PEFF.A.A.A4: Temperature profile. A convective layer has a uniform temperature profile and a nonconvective layer that generates heat exhibits a parabolic temperature profile. The transition between the two is clearly evident on the temperature profile. This locates the layers to within thermocouple spacing, or about ± 30 cm.

FG.PEFF.A.A1: Void fraction in waste layers estimated. Given the layer location, the relative void fraction in each layer is estimated. The relative void fraction is the ratio of the layer void fraction to average void fraction or layer gas volume to total gas volume.

FG.PEFF1: Effective pressure model applied. The effective pressure calculation depends on which model requires it. For the dL/dP retained volume calculation, the effective pressure is defined by

$$P_{\text{eff}} = \alpha \sum_i (P_i)$$

where a_i is the void fraction of layer i , α is the overall average void fraction and P_i is the layer pressure. For the level change retained volume calculation, the effective pressure is

$$P_{\text{eff}} = \sum_i (P_i)$$

FG.PZ: PRESSURE PROFILE DETERMINED. Hydrostatic pressure within the waste as a function of depth.

FG.PZ.A: Estimated from hydrostatic pressure. Hydrostatic pressure estimated from waste density and configuration.

FG.PZ.A.A: Density determined. The mass per unit volume of a waste layer.

FG.PZ.A.A1: Estimated from other tanks. Waste density estimated based on knowledge of waste density from other similar tanks.

FG.PZ.A.A2: Core sample analysis. Density of both the solids and the drainable liquid can be made from a core sample.

FG.PZ.A.A3: RGS X-ray analysis. The X-ray images recorded prior to RGS sample extraction can theoretically be calibrated to indicate density.

FG.PZ.A.A4: Ball rheometer buoyancy analysis. The ball rheometer provides an accurate density measurement in liquid waste with no yield strength. Density measurements are not reliable if the solid material partially supports the ball.

FG.PZ.A1: Hydrostatic pressure model applied. Local hydrostatic pressure calculated as a function of location with the tank. Common practice is to ignore lithostatic support and compute the pressure as if the entire column were liquid. This overpredicts the pressure by as much as 15%.

FG.PZ.B: Direct measurement. Hydrostatic pressure measured directly a specific location by a pressure sensor.

FG.PZ.B1: VFI pressure measurement. The pressure recorded by the void fraction instrument after the sample chamber is opened following a void measurement is essentially the local hydrostatic pressure. But the VFI traverse has disturbed the waste column above and the pressure may represent mostly supernatant liquid.

FG.PZ.B2: Pressure transducer. It may be possible to mount pressure transducers on other equipment or to insert one into the waste with minimal disturbance for a good local pressure measurement.

FG.PZ.B3: RGS pressure measurement. The retained gas sampler captures a core sample in a gas-tight chamber at the local pressure. Initial plans called for a pressure measurement prior to extracting the sample which would have been a direct measure of in situ pressure. However, this capability was deleted from the final design.

FG.RGV: RETAINED GAS VOLUME DETERMINED. The volume of gas, at standard temperature and pressure stored in the waste. This volume only considers undissolved, 'free' gas or 'void.' Gas that is dissolved in the liquid or potentially absorbed on solid surfaces is not included.

FG.RGV.A: Volume determined from local void measurements. The void fraction is the volume fraction that is not liquid or solid, but 'void.' The gas volume is calculated from an average void fraction determined statistically from these local measurements.

FG.RGV.A.A: Void profile determined. The void fraction varies most with depth and the vertical profile must be determined to compute an average. Profiles from two or more risers also help resolve spatial maldistribution.

FG.RGV.A.A1: VFI analysis. The VFI provides void measurements approximately every 50 cm or less in two or three vertical traverses separated laterally up to 2 m under each of two risers. Typical uncertainty in average void fraction is 20 to 30%.

FG.RGV.A.A2: New methods applied. Other methods might be developed to make void measurements away from existing risers or with less disturbance of the waste.

FG.RGV.A.A3: RGS analysis. The RGS provides the average void fraction in several segments of each core. Approximately three segments spaced two segments apart are devoted to RGS analysis. The uncertainty in void fraction has not yet been established.

FG.PZ: Pressure profile determined. The pressure profile is required to correct local gas volume to standard pressure. (See separate subsection FG.PZ above.)

FG.RGV.A1: Temperature profile. The absolute temperature profile is needed to correct the local gas volume to standard conditions.

FG.RGV.A2: Standard volume model applied. The retained gas volume is the sum of the standard gas volume in each layer. The layer gas volume is the product of the layer depth, tank cross-sectional area, the average void fraction in the layer, the local absolute pressure (in atmospheres), and the absolute temperature ratio.

FG.RGV.B: Volume determined from global measurements. The total retained gas volume in the tank can also be determined from the waste level. This exchanges uncertainty about the lateral distribution of void for uncertainty about its average vertical location.

FG.RGV.B.A: Barometric response analysis obtained. The response of waste level to fluctuations in barometric pressure is directly proportional to the stored gas volume and the inverse of the square of the effective pressure. Thus the volume can be determined from a reasonably precise and frequent waste level measurement and the corresponding barometric pressure.

FG.RGV.B.A.A: **dL/dP determined.** The correlation of waste level change to barometric pressure fluctuation. Hourly level measurements are preferable if available. One month's worth of data may be required to get a good correlation unless large swings in barometric pressure have occurred.

FG.RGV.B.A.A.A: **Level data obtained.** Waste level versus time. Waste must be such that it responds directly to gas expansion and contraction. A level measurement on top of solid saltcake resting on the tank bottom will not respond to pressure changes. A liquid level measurement that is below the solid surface, as in a liquid observation well, must be corrected by the estimated porosity of the solid.

FG.RGV.B.A.A.A1: **Enraf.** The Enraf buoyancy level gage is the most precise and reliable of those available for dL/dP calculations. Level changes can be resolved to within 0.2 cm and it is not subject to stalactite accumulation.

FG.RGV.B.A.A.A2: **FIC.** The food instrument corporation contact probe can resolve level changes to less than 0.5 cm but, since each reading depends on making and breaking contact with the waste surface, it slowly grows a stalactite of waste that must periodically be flushed off. Flushing over several years can erode a hole into the waste that introduces as much error as the stalactite.

FG.RGV.B.A.A.A3: **Neutron log.** Neutron logs are used to measure liquid level in a liquid observation well. Uncertainty may be as high as half a meter. It is questionable whether current neutron log measurement is suitable for gas volume calculations.

FG.RGV.B.A.A.A4: **Manual tape.** The manual tape resolves level changes to within about 1 cm. This uncertainty makes volume measurements questionable.

FG.RGV.B.A.A.A5: **New methods.** Better level measurement methods may be developed that integrate the level change over the entire waste surface and do not depend on actual contact with the waste.

FG.RGV.B.A.A1: **Barometric pressure history.** Barometric pressure measurements corresponding to available waste level measurements.

FG.RGV.B.A.A2: **Statistical model applied.** A statistical model determines the probability distribution of waste level response to barometric pressure.

FG.RGV.B.A1: **Tank diameter.** The tank cross-sectional area is computed from the diameter.

FG.RGV.B.A2: **Temperature profile.** Waste temperatures as a function of depth below the waste surface. The temperature profile is required to correct for standard conditions.

FG.PEFF: **Effective pressure for dL/dP determined.** The effective pressure is the absolute pressure at which gas is stored in the waste. Therefore it is essentially a gas volume weighted average

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