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Change Justification	RPP-6213 and the related DSA section are undergoing review by the DOE-ORP independent review team in anticipation of DOE-ORP developing a safety evaluation report on the Documented Safety Analysis, RPP-13033. A complete revision is provided to facilitate the DOE-ORP review.		

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Hanford Waste Tank Bump Accident and Consequence Analysis

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Richland, WA 99352
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Abstract: This report provides a new evaluation of the Hanford tank bump accident for incorporation into the Safety Basis. The analysis scope is for the safe Storage of waste in its current configuration in Single-Shell and Double-Shell tanks.

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Hanford Waste Tank Bump Accident and Consequence Analysis

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

CH2MHILL
Hanford Group, Inc.

Richland, Washington

Contractor for the U.S. Department of Energy
Office of River Protection under Contract DE-AC27-99RL14047

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RPP-6213
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TERMS

ALC	air lift circulator
HEPA	high-efficiency particulate air (filter)
HVAC	heating, ventilation, and air conditioning
DST	double-shell tank
LCO	Limiting Condition for Operation
RAM	reliability, availability, and maintainability
SST	single-shell tank

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1.0 PURPOSE AND SCOPE

This report provides a new evaluation of the Hanford tank bump accident analysis (HNF-SD-WM-SAR-067 2001). The purpose of the new evaluation is to consider new information and to support new recommendations for final safety controls. This evaluation considers historical data, industrial failure modes, plausible accident scenarios, and system responses.

A tank bump is a postulated event in which gases, consisting mostly of water vapor, are suddenly emitted from the waste and cause tank headspace pressurization. A tank bump is distinguished from a gas release event in two respects: First, the physical mechanism for release involves vaporization of locally superheated liquid, and second, gases emitted to the head space are not flammable. For this reason, a tank bump is often called a steam bump. In this report, even though non-condensible gases may be considered in bump models, flammability and combustion of emitted gases are not.

The analysis scope is safe storage of waste in its current configuration in single-shell tanks (SSTs) and double-shell tanks (DSTs). The analysis considers physical mechanisms for tank bump to formulate criteria for bump potential, application of the criteria to the tanks, and accident analysis of bump scenarios. The result of consequence analysis is an estimate of the mass of waste that might be released from tanks for specific scenarios even though bumps are not credible under current tank conditions (Addendum 1). Conversion to health consequences is performed elsewhere using standard Hanford methods (Cowley et al. 2000). The analysis forms a baseline for future extension to consider waste retrieval.

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2.0 SUMMARY OF FINDINGS

Postulated physical scenarios leading to tank bumps are comprehensively examined here. We conclude that a combination of a substantial supernatant layer depth, supernatant temperatures close to saturation, and commensurate sludge temperatures are required for a tank bump to occur. We have ruled out scenarios postulated at various times for sludge layers lacking substantial supernatant, such as superheat within the layer and fumarole formation leading to a bump.

A graded set of criteria is presented to screen tanks for bump potential. These screening criteria may be applied as tank waste inventories are changed. Bump scenarios and criteria can explain observations of historical bump events and show the difference in tank bump potential earlier in tank life compared to the present day, essentially due to high historical tank power and in some cases gas injection.

Applying criteria for non-negligible supernatant layers and non-negligible non-convective layers, all but two SSTs in their present state may be considered immune to a tank bump, as can some DSTs. Simple screening for tank power removes the remaining SSTs and many DSTs from consideration. The only DSTs not screened by these simple criteria are 241-AZ-101, 241-AZ-102, and 241-AY-102. Tanks 241-AZ-101 and 241-AZ-102 were further analyzed for the time to heat up to saturated conditions. All three of these DSTs were analyzed for waste releases (the source term) during tank bump scenarios.

Extended loss of cooling is required to develop initial conditions sufficient for a tank bump during safe storage. Tank 241-AZ-101 has the highest heat load and therefore the fastest heat-up rate during a loss of cooling event. Based on a heat load of 60.4 kW, the calculated heat-up rate for Tank 241-AZ-101 is 0.31 °C/day [0.56 °F/day]. Based on a heat load of 32.4 kW, the calculated heat-up rate for Tank 241-AZ-102 is 0.13 °C/day (0.23 °F/day).

Although Tank 241-AZ-101 has the fastest heat-up rate during a loss of cooling event, tank bump consequences are influenced by other waste conditions, notably the settled solids or non-convective layer depth. Source term analysis was performed for all three of the DSTs that did not pass the screening criteria. Accidents were evaluated using a best-estimate approach for separate phenomena, including models for the amount of material released, consideration of successive releases, and mixing of formerly non-convective material with supernatant. The number of bumps, bump size, and the interval between bumps turn out to be complicated functions of waste properties, especially sludge depth, which means that accident progression differs from tank to tank.

DST 241-AZ-101, which has the thinnest sludge layer at 48 cm, a postulated tank bump accident leads to a series of relatively small bumps in short order. Releases amount to 2.5 kg in a few minutes, with 0.4 more kilograms released over the next several hours. DST 241-AZ-102 results in a series of large bumps with an interval of 1.5 hours in between. This interval is large enough for some settling to occur between bumps. For Tank 241-AZ-102, 3.7 kg are released in about 12 hours. DST 241-AY-102 has large postulated bumps (0.6 kg per bump) with a very long interval between bumps.

Sensitivity analyses show these results to be robust and not unduly dependent on measurements of waste properties, such as supernatant depth or shear strength.

Revision 3 documents that tank pumps cannot occur under current tank conditions for reasons stated in Addendum 1.

3.0 HISTORICAL AND PRESENT EVALUATION DATA

3.1 HISTORICAL EVENTS

Since the early 1950's, aging waste has been stored in underground storage tanks at the Hanford site. In the mid-1950's, a tank bump was first observed, which led to installation of air lift circulators (ALC) that provide liquid agitation and solid suspension. Air lift circulators, also referred to as air lift pumps, have successfully prevented bumps, and the few bumps that have occurred since the mid-1950's were initiated by ALC shutdown and restart. Discussion below presents a brief history of the documented events, which are listed in Table 3-1.

Table 3-1. History of Events.

Tank, 241-	Date	Heat Rate (Kw)	Waste Temp. at Bottom (°F)	Dome Pressure (psig)	Duration (min)	No. of Documented Events	ALC	Initiator	Contam-ination	Vent System	Ref.
S-104	10/53 -5/54	200	> 240	< 1.6	8 to 42	Many	0	None	Yes	No	[1]
S-101	1/54-8/54	200	> 240	< 1.6	8 to 42	Many	0	None	Yes	No	[1]
SX-101	2/55-4/55	400	300	0.7 - 1.8	3 to 13	> 40	Auger	None	Unknown	No	[1]
SX-104	7/55	600	290	Unknown	70	2	Proto-type	ALC shutdown/ restart	Unknown	No	[2]
SX-114	8/58	650	357	2.6	Unknown	4	4	ALC shutdown/ restart	Yes	Yes	[3]
A-105	1/65	2300	310	1.8	30	1	4	Bottom of tank bulged	Yes	Yes	-
AX-101	1968-1969	2300	260	Unknown	20	1	22	ALC shutdown/ restart	No	Yes	[1]

[1] Bendixsen, R. B., 1989, *History of Tank Bumps in Aging Waste Tanks*, Letter report to D. A. Clapp.

[2] Kuhn, W. L., 1988, *Independent Review of Aging Waste Tank "Bump" Analyses*, Final letter report from Pacific Northwest Laboratory, Richland, Washington, found within WHC-SD-WM-TI-406, Rev. 0.

[3] Jones, B. L., 1988, *Aging Waste Tank Bump Sensitivity to Thermal Conductivity and Heat Capacity, Incorporating the Assumption of N-Reactor Shutdown* (Internal Memo to L. A. Mihalik), Westinghouse Hanford Company, found within WHC-SD-WM-TI-406, Rev. 0.

In a passage describing waste tank operations history, Jo (1990) states that prior to August of 1952, conduction to underlying soil prevented boiling. In addition, air cooled heat exchangers for the S tanks were installed above ground. During August of 1952, Tank 241-S-110 boiled and water was sprayed on the air condensers, which was sufficient to condense vapor. In 1953,

Tank 241-S-107 also boiled, but because water spray could not keep up with the boiling rate, a water jacket was installed on the air condenser. In both cases, contamination was not found.

According to Tomlinson (1955), "In July, 1953, Tank 241-S-104 was filled and its contents started boiling at a rate which exceeded the heat exchange capacity of the water-jacketed air condensor." Despite installation of auxiliary water cooled condensers on Tanks 241-S-104 and 241-S-101 circa August 1953, occasional mild eruptions were observed, followed by increased evaporation rates and contamination. Eruptions were preceded by disturbing the waste in some cases, and in other cases by no observed cause. In January of 1954, "bumping" eruptions, in the form of a series of 5 to 25 abrupt pressure surges at roughly 100 second intervals, first took place in Tank 241-S-101. Bump initiation was concomitant with a temperature at the bottom of the tank greater than 240°F – the recorder temperature limit. The same phenomena were observed in Tank 241-S-104, including the greater than 240 °F temperature at the tank bottom. Tank overpressure never exceeded 1.6 psig. The two tanks were boiled down to approximately half-volume and refilled, which suggests the tanks were nearly full when the bumps first started. Bumps continued for another eight months and then gradually diminished to a simmer.

From May 1954 to February 1955, Redox waste (excepting coating waste) filled the 241-SX-101-102-103 cascade. In February 1955, bumping was observed in Tank 241-SX-101. It consisted of 5 to 25 abrupt pressure surges at intervals of about 30 seconds, with maximum pressures of 0.7 psig to 1.8 psig. These pressure surges occurred about once per day naturally, but could be initiated two or three times daily by starting an auger installed in the tank. Tank liquid level fell from 30 ft to 25 ft during the next two months, even though no waste was added.

In June of 1955, Tank 241-SX-104 was boiling but no bumps occurred. Boiling can be distinguished from a tank bump because boiling is gentle by comparison and involves only the supernatant rather than the settled solids. To prevent bumps, the prototype ALC was installed. Initial ALC operation increased the condensate flow rate from the normal 3 gpm to 7 gpm, but only for about six hours. On July 14, 1955, the ALC became inoperative because of a failed gasket (Hanson 1955). Upon ALC restart on July 15, 1955, a bump occurred, resulting in an instantaneous increase in the condensate flow rate from 0.8 gpm to 17.2 gpm; the bump lasted for about 70 minutes and released heat at a rate of 4.7×10^6 Btu/hr, or 1.38 MW. The bumping was attributed to the interruption in ALC operation (Hanson 1955).

Tank 241-SX-114 bumped four times during August of 1958. During the week of August 18, 1958, 241-SX-114 tank temperature gradually increased, despite the operation of four ALC at 10 cfm each. On August 22, operators shut off air and ran 2 cfm of water through each of the ALC. By this time, waste temperature was 357 °F. The tank bumped three times during the next couple of days, and once on August 25. In Harmon (1958), the bumps are attributed to turning off the ALC in Tank 241-SX-114. Contamination was extensive both inside and outside the tank farm, although no site employees were exposed (Harmon 1958). Bumps in Tank 241-SX-114 ejected "contaminated vapors" out of the Tank 241-SX-113 pump pit. Contamination within the tank farm spread over about 15,000 ft^2, with a maximum dose rate of 5 Rads/hr.

The most publicized event occurred in January of 1965, in Tank 241-A-105. This bump is attributed to evaporation of water trapped in between the liner and concrete floor. Waste

temperature was high enough that the vapor pressure just underneath the liner exceeded the hydrostatic head of the waste. In effect, the liner bulge was responsible for the bump, which means that this event is not applicable to the current analysis.

In an internal memorandum, Bendixsen (1989) reports that Tank 241-AX-101 bumped once between 1968 and 1969. The event was never recorded because there was no finding of any contamination near the tank. Waste temperature was estimated to be 260 °F. ALC shutdown and restart was identified as the event initiator.

These events led to three historically postulated scenarios for bump initiation (Jo 1990): (1) an organic crust, (2) liner bulge, and (3) ALC restart. In the first scenario, an organic crust forms over the supernatant and causes pressurization and super-heating. When the pressure is large enough to crack the crust, the supernatant is released until it depressurizes and the boiling point returns to normal. Single-shell liner instability was known prior to the 241-A-105 event (Brownell 1958). In several of the events described above, ALC restart after a long period resulted in vapor generation by heat released from the superheated waste. The organic crust and liner bulge scenarios are of historical interest only, and for current operations, only the ALC restart scenario has been retained.

Given current aging waste tank operations, the following tank bump scenario was accepted in 1990 as the only credible one (Jo 1990):

- Initiator: the initiator is an equipment failure that allows particle settling or loss of heat removal
- Heat build-up: a temperature rise in the solid and/or liquid phase caused by decay heat
- Heat release: ALC or mixer pumps agitate superheated solids and/or liquid, thereby releasing stored heat
- Vapor generation: superheated liquid rises and rapidly generates vapor
- Environmental release: vapor generation is rapid enough to overwhelm the tank ventilation system, pressurize the tank, and release vapor and particles to the environment through unfiltered pathways.

Discussion below proceeds with this scenario in mind.

3.2 PREVIOUS ANALYSIS

Previous analyses consist of the Fauske and Associates, Inc. reports of 1989 (FAI 1989) and 1999 (Epstein et al. 1999), Waters et al. (1991), and the GOTH analyses carried out by Westinghouse Hanford Company (Sathyanarayana 1996). The 1989 Fauske and Associates, Inc. document (FAI 1989) presents conclusions inferred from the documented events and supported by relatively straightforward hand calculations for the several bump heat transfer phenomena. As part of the technical basis for safe storage after sluicing and cessation of water addition, Epstein's et al. (1999) report considers the steam bump potential in Tank 241-C-106, although

the conclusions drawn in it can be applied generally. Using HEATING7, Waters et al. (1991) performed a series of parametric calculations to determine tank bump potential during-in-tank washing operation proposed for the AZ tanks. HEATING7 is a multi-dimensional code for finite difference solutions of the conduction equation in cylindrical, spherical, or rectangular coordinate systems. The Westinghouse Hanford Company report (Sathyanarayana 1996) contains parametric calculations based on the GOTH code, which was derived from EPRI's GOTHIC code. GOTH is a finite volume program that solves the transient equations expressing mass, momentum, and energy conservation for multi-component, multiphase fluid flow. The FAI (1989) report is considered first, as it provides a succinct overview of tank bump phenomenology.

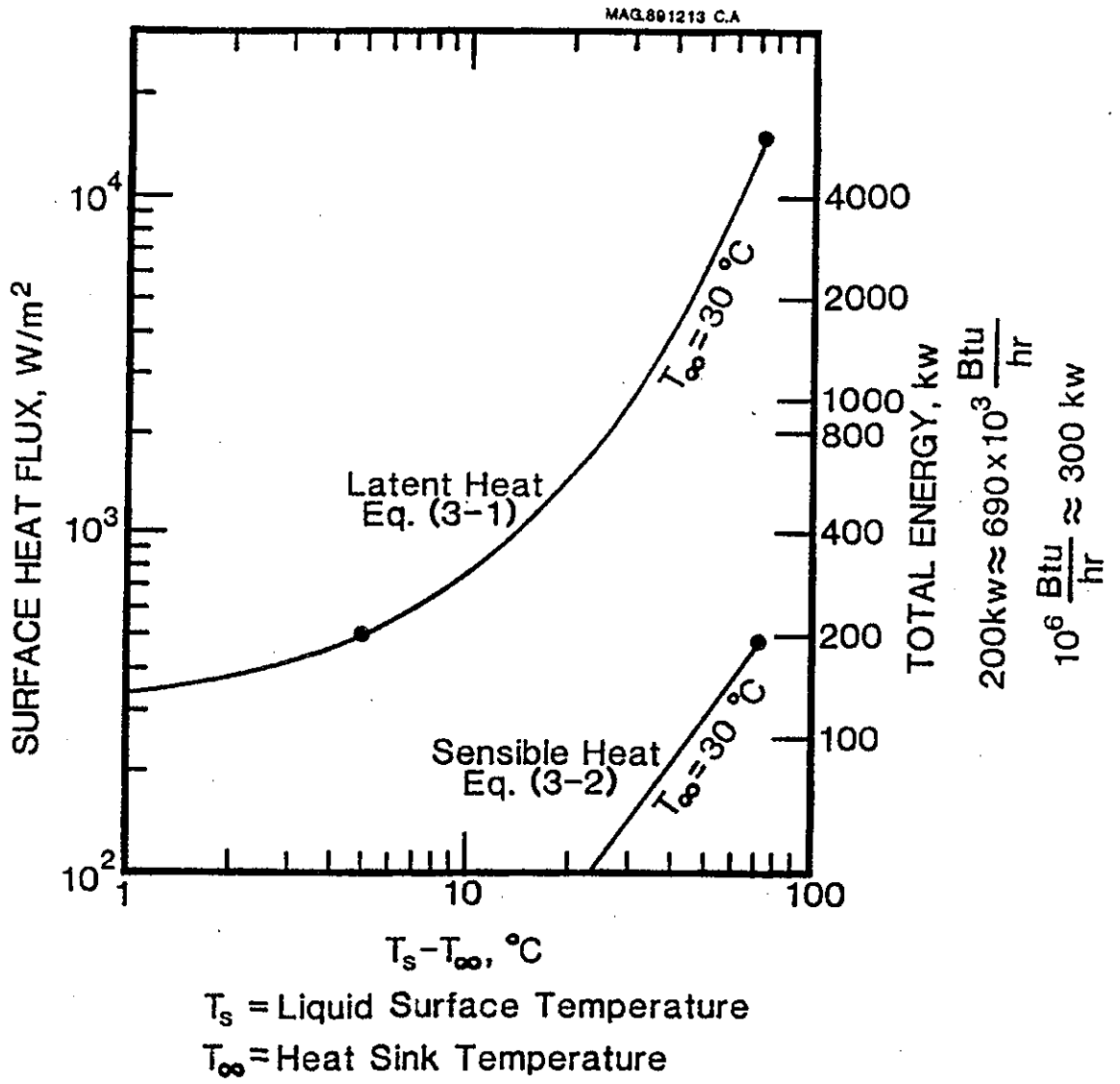
3.2.1 Fauske and Associates, Inc., 1989

In December of 1989, Fauske and Associates, Inc. issued an *Independent Review of Aging Waste Tank "Bump" Phenomena*, which considered the background material on tank bumps and presented new observations regarding bump heat transfer mechanisms (FAI 1989). Some of the conclusions stated in the report could be inferred from the documented events, but hand calculations were presented to characterize several bump heat transfer mechanisms. The report's conclusions are as follows:

- Tank bumps require that the pool surface reach the boiling temperature
- Tank dome ventilation should be sufficient to keep pool surface temperature below the boiling temperature
- Setting aside ALC restart, it is likely that the waste depth must exceed some minimum value for the tank bump to occur
- There is probably some minimum tank power level below which tank bumps cannot naturally occur, regardless of pool surface temperature.

To augment the basis for these conclusions, phenomena considered by hand calculation include surface evaporation, pool circulation, dryout in settled beds, and gas injection on restart of ALC. A surface evaporation calculation was used to show tank ventilation should be sufficient to keep pool surface temperature below the boiling temperature. By the evaporation heat transfer analogy of Epstein (1988), latent and sensible heat transfer from the pool to some sink temperature were computed as a function of pool surface temperature, T_s, assuming that water mass fraction at infinity was zero and the water mass fraction at the surface was related to vapor pressure at T_s. The results shown in Figure 3-1 indicate that surface evaporation can remove a pool heat rate of 200 kW at a surface temperature of only 35 to 40 °C, if the dome has low relative humidity.

Figure 3-1. Surface Heat Removal.



To demonstrate that convective motion in the pool is virtually certain, the Rayleigh number was calculated as follows:

$$Ra = \frac{g\, d^4\, \beta\, \Delta T}{h\, \nu\, \alpha} \qquad (3\text{-}1)$$

where g is the acceleration of gravity, d is the pool diameter (23 m), β is the thermal expansion coefficient for water (6×10^{-4} K^{-1}), h is the height of the pool (10 m), ν is the liquid kinematic viscosity (3×10^{-5} m^2/s), and α is the liquid thermal diffusivity (3×10^{-5} m^2/s). If the temperature difference is only 1°C, Ra = 10^{15}. This is orders of magnitude higher than the Rayleigh number required for the onset of convection, which is somewhere between 100 and 10,000, depending on the thermal boundary conditions. The report then goes on to conclude that

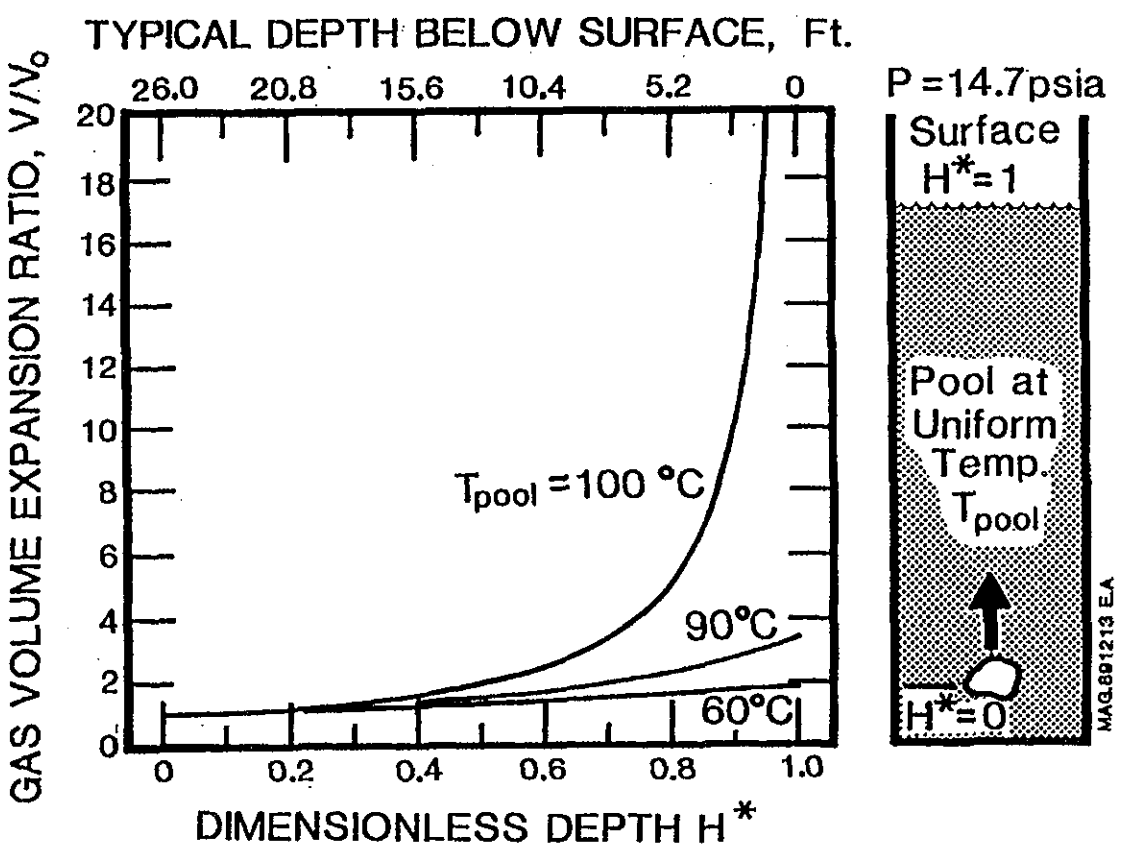
natural convection should suffice to keep the pool isothermal and that dome relative humidity determines bulk pool temperature. This conclusion means that a submerged air supply is not absolutely necessary.

Phenomena relating to gas injection on restart of ALC were considered in both FAI (1989) and Epstein et al. (1999). Consider the ascent of a cavity volume in an isothermal pool.
A relationship for the relative volume (local volume divided by initial cavity volume, V_o) as a function of height is:

$$\frac{V}{V_o} = \frac{\beta + 1}{\beta + \left(1 - H^*\right)} \tag{3-2}$$

where $H^* = 1 - H / H_o$ is the dimensionless height, H_o is the pool depth, and the term $\beta = [P_{surf} - P_{sat}(T_o)] / \alpha H_o$ represents the difference between the pool surface pressure and the vapor pressure of the liquid at temperature T_o, divided by pressure increase at the depth of gas release. Evaluation is shown in Figure 3-2, assuming $\alpha = 0.41$ psi/ft and $H_o = 26$ ft Figure 3-2 illustrates that tank bump events are doubtful if the pool surface temperature is just 10°C below the boiling point. This expression also demonstrates that in the limit of a shallow pool ($\beta \rightarrow \infty$), $V / V_o \rightarrow 1$. In other words, there is no expansion for a shallow pool and a tank bump cannot occur.

Figure 3-2. Cavity Expansion During Rise in a Constant Temperature Pool.



3.2.2 Tank 241-C-106 Steam Bump Evaluation, (Epstein et al. 1999)

In this document, Epstein et al. (1999) give numerical examples to show that tank bumps cannot occur for shallow pools. If liquid temperature is 99°C (P_{sat} = 97,780 Pa) and pool depth is 1.0 m, V / V_o is 3.7 at most, assuming the pool surface pressure is one atmosphere. If the pool depth is increased to 10.0 m but other assumptions remain unchanged, the maximum expansion ratio is 28. If liquid temperature is 95 °C (P_{sat} = 84,550 Pa) and pool depth is 1.0 m, maximum expansion ratio is 1.6, assuming other assumptions remain unchanged. A pool depth of 1.0 m is most relevant because the 241-C-106 waste will be sluiced to this depth, more or less. In regard to Tank 241-C-106, tank bumps by inert gas injection are impossible because the supernatant is only a few inches deep.

3.2.3 GOTH Analyses (Sathyanarayana 1996)

The purpose of the Westinghouse Hanford Company calculations using GOTH was to provide a technical basis for tank bumps and estimates of the consequences (releases of steam and solid particles) of tank bump events. The document begins by stressing that although current tank conditions preclude a tank bump event if normal ventilation is operating, loss of ventilation combined with increased non-convective layer thicknesses and heat load might lead to favorable conditions for a bump. Without dome ventilation, local non-convective layer temperature can increase to saturation temperature. Two types of non-convective layer vertical temperature distributions are envisioned by the report: "best-estimate" and "conservative". A best-estimate temperature distribution is defined as the vertical temperature distribution just when the first piece of non-convective waste reaches the local saturation temperature. This temperature distribution is said to exist for the first plume release only. Repeated bumps are expected because without dome ventilation the heat load continues. After the first bump, hot non-convective waste mixes with cooler waste until it is everywhere near the local saturation temperature; this is referred to as the conservative temperature distribution.

Sathyanarayana (1996) lists the following parameters and assumptions as critical to the magnitude of the bump and mass of airborne aerosol:

- Thickness: larger non-convective layer thicknesses produce larger bumps and releases. GOTH analyses assumed three thicknesses: 18 and 48 in. thicknesses with Tank 241-AZ-101 solid and liquid waste properties (see Table 3-2) for each, and a thickness of 11 ft with composite properties of Tank 241-C-106 and 241-AY-102 wastes (see Table 3-2).

- Initial Temperature Distribution: the two assumed distributions – best-estimate and conservative – have been described above. The strength of the bump is proportional to the fraction of waste that is near the saturation temperature.

- Ventilation and Flow Paths: simulations were performed with three assumed flow areas, as shown in Table 3-3. In addition, preliminary calculations were made using the AZ tank farm 702-A ventilation system.

Table 3-2. Waste Properties for GOTH Analysis.

	241-AZ-101	**241-AY-102/ 241-C-1066**
Tank		
Primary Tank Dia., ft (m)	75 (22.9)	75 (22.9)
Secondary Tank Dia., ft (m)	80 (24.4)	80 (24.4)
Tank Contents		
Solids Density, lbm/ft^3 (kg/m^3)	243.4 (3898.9)	113.9 (1822.4)
Aqueous Solution Density, lbm/ft^3 (kg/m^3)	75.5 (1209.4)	75.5 (1209.4)
Sludge (Mixture) Density, lbm/ft^3 (kg/m^3)	104.0 (1665.9)	81.2 (1299.2)
Total Waste Depth, ft (m)	30 (9.14)	30 (9.14)
Supernatant Depth, ft (m)	28.5/26 (8.7/7.9)	19 (5.8)
Sludge Depth, ft (m)	1.5/4 (0.46/1.22)	11 (3.35)
AY-102 Heat Load, Btu/hr (W)		33,000 (9671)
C-106 Sludge Heat Load, Btu/hr (W)		92,400 (27080)
Total Heat Load, Btu/hr (W)		125,000 (36634)
Supernatant		
Heat Capacity, Btu/lbm-F (J/kg-K)	0.8 (3349)	0.8 (3349)
Thermal Conductivity, Btu/hr-ft-F (W/m-K)	0.35 (0.61)	0.35 (0.61)
Heat Generation Rate, Btu/hr-lbm (J/s-kg)	0.019 (0.0123)	0.0 (0.0)
Insoluble Solids		
Heat Capacity, Btu/lbm-F (J/kg-K)	0.2 (837)	0.2 (837)
Thermal Conductivity, Btu/hr-ft-F (W/m-K)	5.0 (8.5)	5.0 (8.5)
Heat Generation, unwashed, Btu/hr-lbm (J/s-kg)	0.37 (0.2391)	0.14 (0.09)
Volume Fraction of Solids, unwashed, %	17	16
Particle Size, washed	1 - 10 microns, 5 micron average	1 - 10 microns, 5 micron average

Source:

Sathyanarayana, K., 1996, *Evaluation of Potential and Consequences of Steam Bump in High Heat Waste Tanks and Assessment and Validation of GOTH Computer Code*, WHC-SD-WM-CN-022, Rev. 0-B, Westinghouse Hanford Company, Richland, Washington.

Table 3-3. GOTH Runs Flow Path Descriptions.

Dome Flow Path Assumptions		
Riser Flanges, Cover Block Open	**Five 4 in. Diameter Inleakage Paths**	**One 6 in. Diameter Inleakage**
1. 42 in. dia. Pump Pit Path	Five 4 in. dia. Inleakage Paths	6 in. dia. Inleakage Path
2. 20 in. dia. Vent Path	20 in. dia. Vent Path	20 in. dia. Vent Path
3. Four 42 in. dia. Sluice Pits Path		

- Aerosol Deposition: the only deposition in the system is settling in the tank waste following release.
- Supernatant Depth: deeper pools result in higher tank bottom pressures and correspondingly higher saturation temperatures, which means that the bump will be more energetic when it finally happens. No attempt was made to study the effect pool depth. The total waste depth was 30 ft for all simulations.
- Non-Convective Layer Viscosity: 8,000 lbm/ft-s (12,000 kg/m-s) was assumed for all cases. Viscosity partially determines the ability to trap steam bubbles.
- Non-Convective Waste Yield Strength: the assumption is that yield strength is zero, for the sake of conservatism. High yield strength would hold some waste in place and prevent it from participating in the rollover.
- Supernatant Temperature: pool sub-cooling has a dramatic effect on the strength of a bump. Various sub-cooled temperatures were considered.

Thermal hydraulic simulations were performed with the GOTH code.

Initial conditions were generated by a set of one-dimensional GOTH runs to find the vertical temperature distribution in the waste when the peak temperature (at the bottom) exceeds the local saturation temperature. Prior to GOTH simulation for a bump, a preliminary run was needed to find conditions that would initiate the bump. These preliminary runs simulated the transient heat up of the waste assuming normal ventilation is replaced by an air inlet flow at 53.3 °F, which is the Hanford annual average temperature. For example, a GOTH calculation resulted in the best-estimate initial conditions for 11 ft of consolidated non-convective layer from Tanks 241-AY-102 and 241-C-106, as shown in Figure 3-3. The conservative temperature profile shown in Figure 3-4 results from assuming that at each point, the waste temperature corresponds to saturation. These calculations were repeated for the 18 and 48 in. depths, although only the 11 ft temperature profile is shown here because the temperature distribution is more apparent.

Figure 3-3. Best-Estimate Initial Temperature Profile for 11 ft of Consolidated Non-Convective Waste.

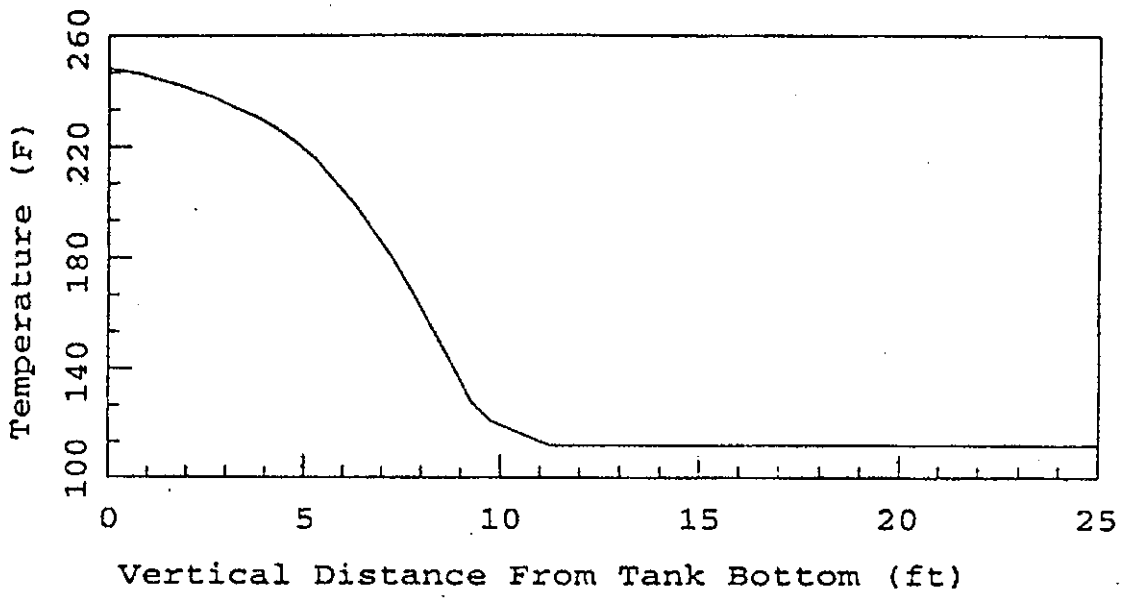
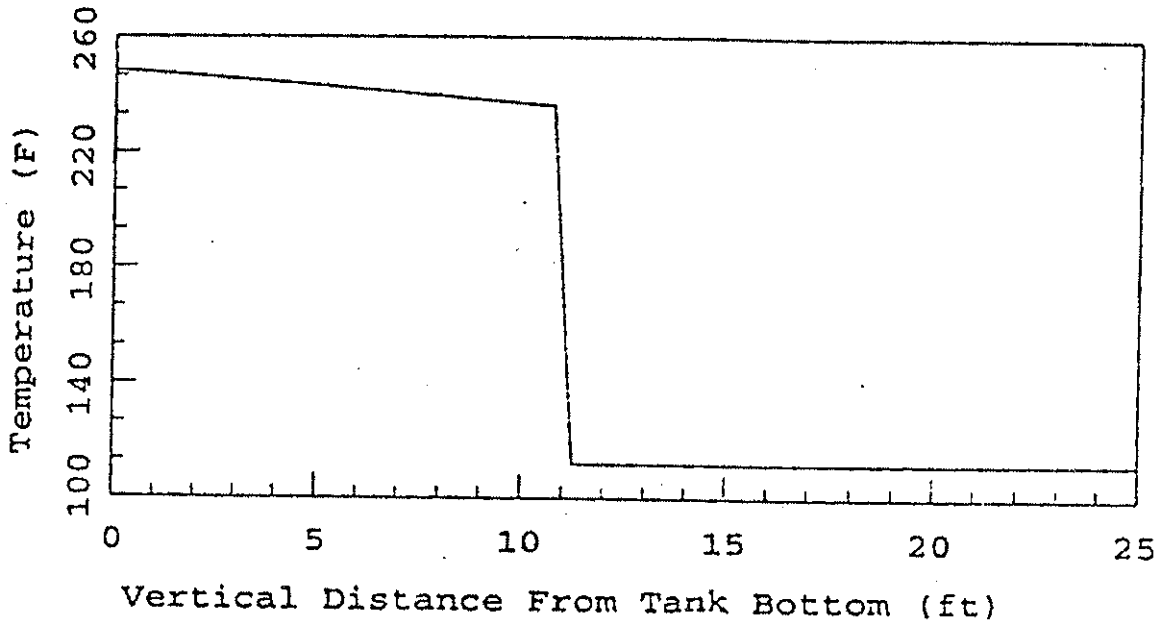


Figure 3-4. Conservative Initial Temperature Profile for 11 ft of Consolidated Non-Convective Waste.



The results of a GOTH run for the 18-in. non-convective layer with no condensation are shown in Figure 3-5, which represents the development of steam concentration contours in the waste. The figure shows gas volume fraction contour snapshots at four different times. Starting with the top left-hand corner, the frames show the start of the steam bump and development of hydrodynamic instability in the waste. In this figure, the maximum void fraction plotted is 0.9 and the minimum is 0.1. The top left-hand frame shows that 40 seconds into the run, the void fraction at the height of the original non-convective layer is about 0.1. Hydrodynamic instabilities start about five seconds later, as shown by the top right-hand frame, with a superheated plume identifiable at 50 seconds. Contours at 70 seconds show a plume breaking the waste surface and dispersing liquid droplets and solid particles to the dome space. Although not shown here, Sathyanarayana (1996) plots both liquid droplet and solid particle flowrate through the respective tank vent paths as a function of time. Results are also reported as integrated, total releases of liquid and particle mass. The report also goes on to state that bumps will repeat until ventilation is restored.

The matrix of GOTH runs and a brief description of results are shown in Table 3-4. Important results culled from the table are as follows:

- For the conservative temperature profile with no condensation, dome pressurization is significant and particle releases can be enormous. Release quantity depends on the size and location of flow paths, but as a general trend releases are largest for "Riser Flanges, Cover Blocks Open" cases, which have the largest flow area. Releases for "One 6" Dia. Inleakage Path" cases are much smaller, although still significant. GOTH calculations are multi-dimensional, which means that the location of the bump with respect to the openings is important for determining releases.

- For 18 and 48-in. non-convective thicknesses, best-estimate cases do not result in bumps, regardless of assumptions about condensation.

- For the 11 ft thickness, no bump occurs in the best-estimate case with condensation.

- Comparing Run 13 (peak pressure = 25.0 psia, release = 2,100 lbm) with Run 22 (peak pressure = 22.2 psia, release = 450 lbm) shows that a simple model provides a conservative estimate with respect to a complete ventilation model that considers all four tanks in the farm and other ventilation equipment.

In cases where bumps occur, the severity of predicted releases can be traced to the conservative assumptions made for the analyses. Total waste depth is 30 ft in all cases, which means that the small dome free volume cannot accommodate a large bump and that liquid slugs or droplets are pushed out dome flow paths. With a non-convective waste shear yield strength of zero, all of the waste participates in the bump event, which means that the void created is much larger than if only a small portion participated.

Figure 3-5. Gas Volume Fraction Contours for GOTH Run With 18 in. Non-Convective Layer and No Condensation.

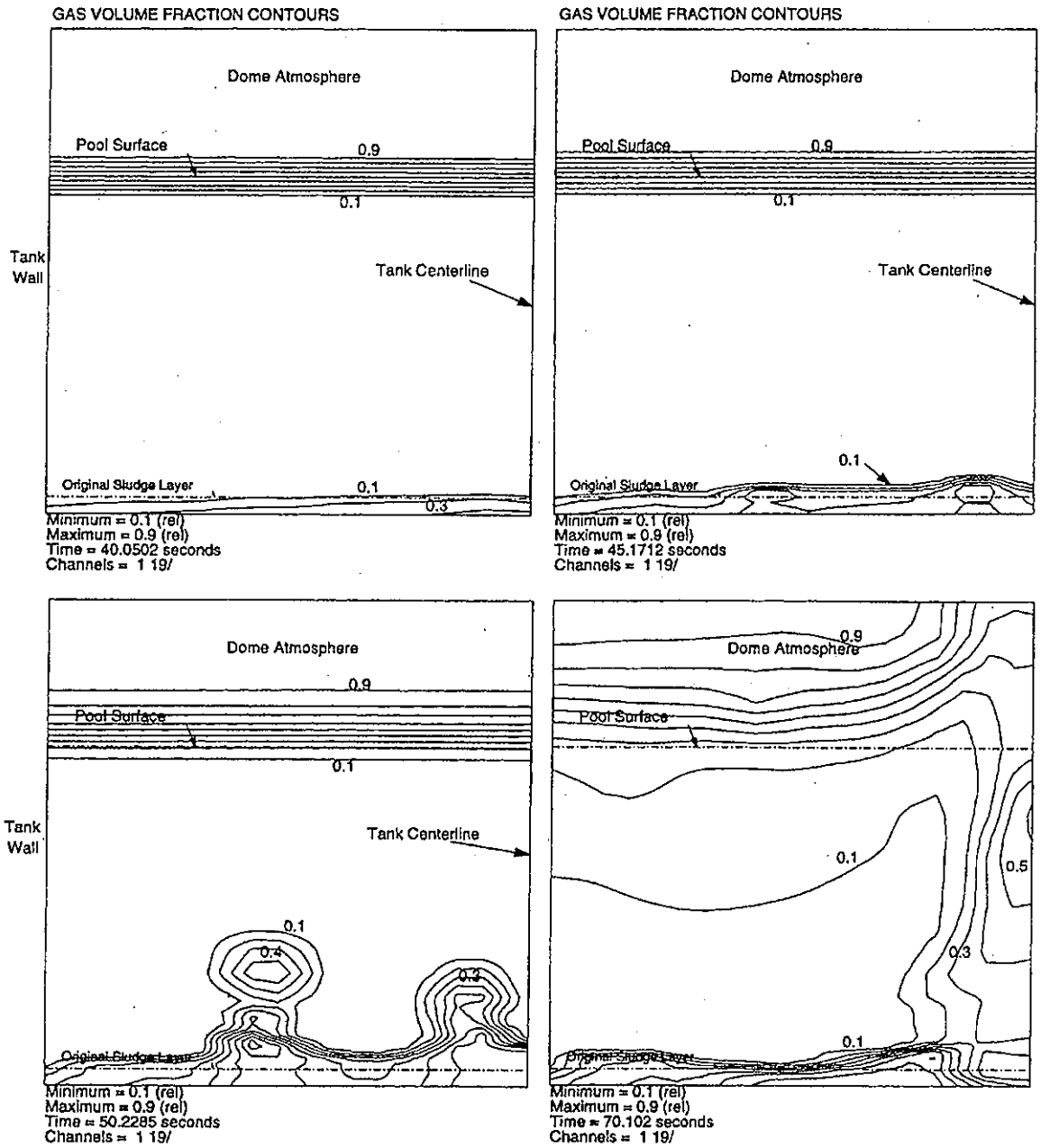


Table 3-4. GOTH Run Summary.

Run	Sludge Depth (ft)	Waste Properties	Temperature I.C.	Conden-sation	Flow Area[1]	Peak Dome Pressure (psia)	Particle Release (lbm)
1	1.5	241-AZ-101	Conservative	No	Riser Flanges, Cover Blocks Open	15.0	150
2	1.5	241-AZ-101	Conservative	No	Five 4 in. Dia. Inleakage Paths	15.7	1.3
3	1.5	241-AZ-101	Conservative	No	One 6 in. Dia. Inleakage Path	15.5	7
4	1.5	241-AZ-101	Conservative	Yes	No bump	No bump	No bump
5	1.5	241-AZ-101	Best-Estimate	No	Riser Flanges, Cover Blocks Open	No bump	No bump
6	4	241-AZ-101	Conservative	No	Riser Flanges, Cover Blocks Open	22.5	6,300
7	4	241-AZ-101	Conservative	No	Five 4 in. Dia. Inleakage Paths	17.3	85
8	4	241-AZ-101	Conservative	No	One 6 in. Dia. Inleakage Path	19.5	165
9	4	241-AZ-101	Conservative	Yes - 164°F Supernatant			
10	4	241-AZ-101	Best-Estimate	No	Riser Flanges, Cover Blocks Open	-	Minimal
11	4	241-AZ-101	Best-Estimate	Yes	Riser Flanges, Cover Blocks Open	No bump	No bump
12	11	241-C-106 / 241-AY-102	Conservative	No	Riser Flanges, Cover Blocks Open	27.0	97,000
13	11	241-C-106 / 241-AY-102	Conservative	No	Five 4 in. Dia. Inleakage Paths	25.0	2,100
14	11	241-C-106 / 241-AY-102	Conservative	No	One 6 in. Dia. Inleakage Path	25.0	1,050
15	11	241-C-106 / 241-AY-102	Conservative	Yes	Riser Flanges, Cover Blocks Open	28.0	6,200
16	11	241-C-106 / 241-AY-102	Conservative	Yes	Five 4 in. Dia. Inleakage Paths	30.0	260
17	11	241-C-106 / 241-AY-102	Conservative	Yes	One 6 in. Dia. Inleakage Path	32.0	2.5
18	11	241-C-106 / 241-AY-102	Best-Estimate	No	Riser Flanges, Cover Blocks Open	18.8	90
19	11	241-C-106 / 241-AY-102	Best-Estimate	No	Five 4 in. Dia. Inleakage Paths	19.2	78
20	11	241-C-106 / 241-AY-102	Best-Estimate	No	One 6 in. Dia. Inleakage Path	19.7	32
21	11	241-C-106 / 241-AY-102	Best-Estimate	Yes – 112 °F Supernatant	Riser Flanges, Cover Blocks Open	No bump	No bump
22	11	241-AZ-101	Conservative	No	AZ/AY Vent Farm Model	22.2	450

[1]See Table 3-3 for details.

3.2.4 Tank Bump Potential During In-Tank Washing Operations Proposed for the AZ Tanks (Waters et al. 1991)

Waters et al. (1991) prepared this work to support "in-tank sludge washing" in DSTs 241-AZ-101 and -102. The report identified the physical conditions needed for a bump as follows:

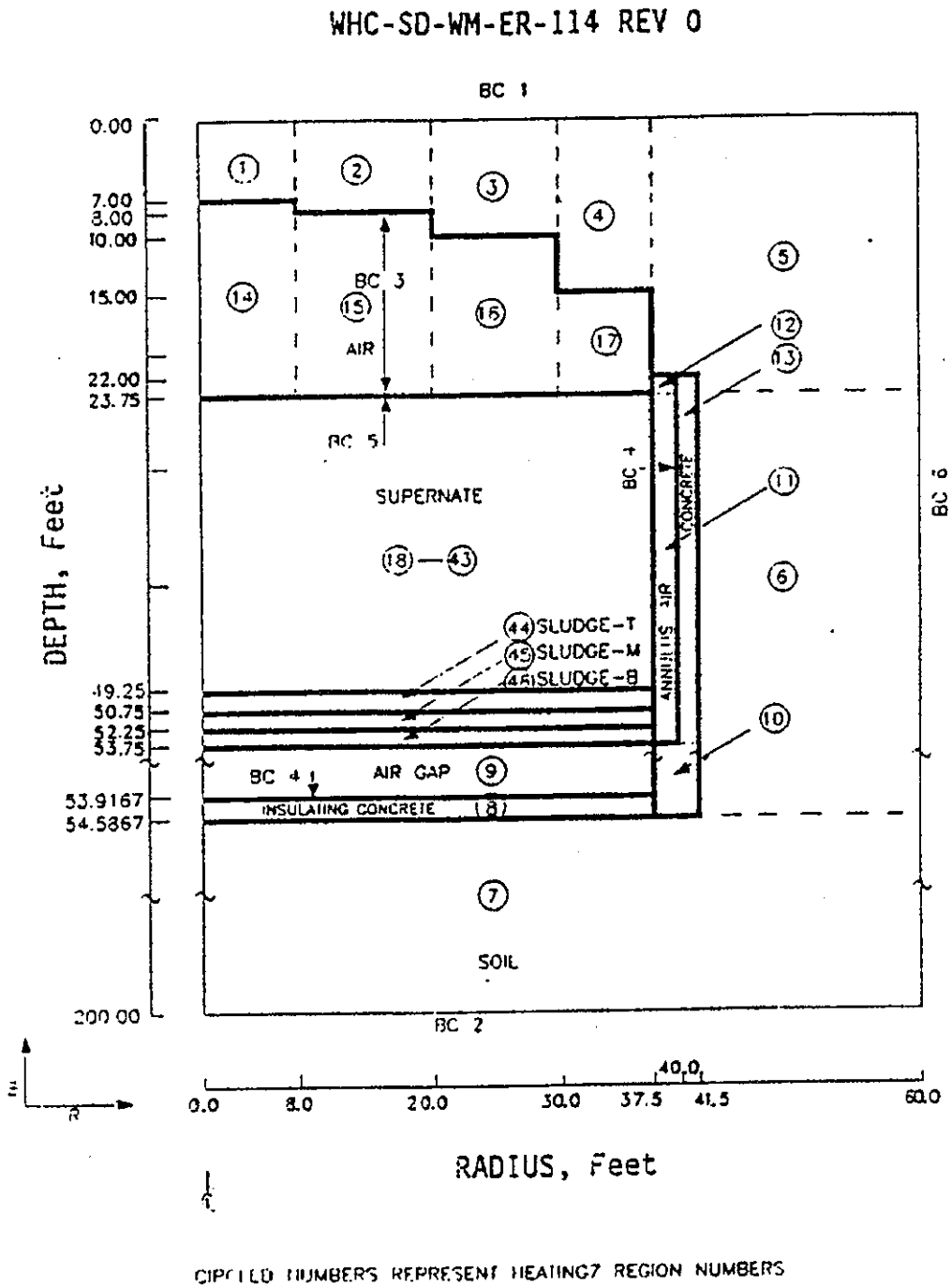
1. Supernatant temperature must be near the boiling point
2. There must be a heat generating non-convective layer
3. Non-convective layer temperature must exceed saturation at the local hydrostatic pressure
4. Radiolytic heat load must be greater than 300 kW (1 Mbtu/hr)
5. Steaming rate must exceed the capacity of the vent line, which is about 4.43 m^3/s (9,400 ft^3/min)
6. Superheat with respect to the supernatant atmosphere boiling point must be 2.1×10^{10} J (20 Mbtu).

The first three items are essentially the same as the conclusions in the FAI report of 1991, while the remaining three items are based on historical tank bump events. At the time of the report, Tank 241-AZ-101 heat generation rate was projected to be 83.2 kW for April of 1993 and 73 kW for October of 1997.

Motivation for the report was the in-tank sludge washing procedure that used four mixer pumps dissipating a total of 800 kW (2.73×10^6 Btu/hr or 1073 hp). Waters et al. (1991) used HEATING7 (Childs 1991) to determine if normal and off-normal sludge washing conditions lead to tank bump conditions. The first simulation performed was to determine if the waste temperatures will remain below saturated conditions under normal ventilation and prolonged input of 800 kW. Subsequent runs postulated power outages of various duration that begin after prolonged mixer pump operation has increased waste temperatures. And finally, a run was made with initial conditions prior to mixing and a 100-day outage of the airlift circulators and normal ventilation systems.

The HEATING7 model for transient thermal analysis in the three-dimensional cylindrical coordinate system is shown here as Figure 3-6. Six boundary conditions are required. The first (BC1 in Figure 3-6) is forced convection from the soil to the Hanford environment, assuming a heat transfer coefficient of 11.4 W/m^2-K and average site temperature of 12.8 °C (55 °F). The second boundary condition (BC2) is a constant temperature of 12.8 °C at the water table. Boundary condition 3 represents the radiative heat transfer and natural convection processes at the supernatant-dome interface. Boundary condition 4 approximates heat removal from the steel primary tank by the annulus ventilation system. Boundary condition 5 incorporates evaporative cooling as explained below, and heat transfer to bubbles rising through the supernatant by way of

Figure 3-6. Dimensional HEATING7 Model (Waters et al. 1991).



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ALC operation. Boundary condition 6 is an adiabatic condition to simulate an array of tanks with a 120-ft center-to-center spacing.

Evaporative cooling was included in the model based on the following relationship from Perry (1950):

$$W = 0.0138\left(P_{svp} - P_p\right)^{1.20} \tag{3-3}$$

where W is the evaporation rate in lb/hr-ft^2, P_{svp} is the vapor pressure of the waste liquid at the surface in mm Hg, and P_p is the partial pressure of water vapor in the airspace above the surface. Waters et al (1991) was able to reconcile this equation with the results shown in Figure 3-1. Flow rates were 634 scfm for normal primary ventilation and 500 scfm for annulus flow, with inlet temperature and relative humidity of 70 °F and 50%, respectively. Airlift circulators flow rate was 154 scfm before and during mixer operation. In outage scenarios, all flow rates were set to zero.

Results of the HEATING7 runs show the following:

1. Primary ventilation controls the equilibrium waste temperature by evaporative cooling,
2. Given ventilation system operation, waste temperatures remain below saturation, even with prolonged 800 kW power input,
3. Bump conditions do not result from a 72 hr power outage that begins after mixer pump operation has increased waste temperature,
4. Bump conditions do not arise after a 100 day outage that begins prior to mixer pump operation, and
5. A permanent outage could result in tank bump conditions under certain circumstances.

Waters et al. (1991) did not specify what circumstances lead to tank bump conditions.

3.3 CHARACTERIZATION DATA

The brief survey above suggests that the following waste parameters are needed for analysis of tank bump potential: non-convective layer depth, supernatant depth, and total waste volume. We present values for these parameters from various sources for the sake of comparison and perspective, but rely on Hu and Barker (2002) for needed calculation inputs.

The analyses surveyed in the previous section show that only tanks with a deep supernatant layer are relevant. SSTs with appreciable amounts of liquid are listed in Table 3-5; a value of 400 kL (about 110 kgal) is the criterion here because this amount of liquid would result in a 1.0 m deep supernatant layer, assuming that the waste in these tanks is separated into distinct non-convective and supernatant layers. Core samples suggest that for the SSTs listed here, this is not really the case. For example, 241-A-101 and 241-AX-101 were found to have solids floating on the free

liquid (Stewart et al. 1996). These SSTs are nevertheless considered in Section 6.0, where tank inventories and heat loads will be compared against bump criteria to develop a short list of tank that are susceptible to bumps. DST supernatant depths are generally significant for tank bump phenomenology. Supernatant layer depths range from 20 cm to 10.3 m, and non-convective layer depths range from 0 m to 5.4 m. A few DSTs have deep supernatant layers but trivial non-convective layer depths; e.g., 241-AP-102 has 10 m of supernatant but no non-convective waste. In Section 6.0, supernatant and non-convective layer depths will be compared against bump criteria to develop a list of tanks potentially susceptible to tank bumps.

Table 3-5. Single-Shell Tanks With Liquid Inventory >400 kL.

Tank	Liquid Volume (kL)	Waste Volume (kL)
241-A-101*	1,923	3,608
214-AX-101*	1,461	2,831

*Solids atop liquid.

Waste properties are also key to evaluation of tank bump potential and consequences, in particular the thermophysical properties of heat capacity, viscosity, thermal conductivity, density, and heat generation rate. Thermophysical properties are highly uncertain, and vary from tank to tank, as well as at different locations within the same tank. The mechanical property of shear yield strength, also referred to as shear strength or simply yield strength; is an input to predictive models for the size of the "gob" released from the non-convective layer. A summary of the available property data is presented below.

Using an analysis of variance tool, Willingham (1994) compiled a statistical analysis of waste properties and listed the total variability of several key properties. Source data came from characterizations for individual tanks. Data were available from only 33 of the 177 tanks and were not grouped into SST and DST categories; i.e., the statistical summary includes data from both tank types to calculate mean, standard deviation, etc. Sources of variability include tank-to-tank variation, core-to-core (radial difference) variation, segment-to-segment (axial difference) variation, and measurement error. Willingham's (1994) compilation is presented here for completeness, but it is difficult to apply here because it does not distinguish between DSTs and SSTs, and has been obviated.

Since by and large only the double-shell tanks have significant supernatant depths, discussion can be narrowed to a survey of DST waste properties. Based on ball rheometer and void fraction instrument measurements taken between December 1994 and May 1996, Meyer et al. (1997) reported DST waste properties pertinent to gas retention and release behavior: density, yield stress, and viscosity. Meyer et al. (1997) list supernatant and non-convective densities based on data for five DSTs (241-SY-103, 241-AN-103, 241-AN-104, 214-AN-105, and 241-AW-101). These five salt cake tanks exhibit episodic gas releases that are typically less than 30 m^3, although there have been episodes of releases as large as 100 m^3 in 241-SY-101, the sixth tank on the list. Supernatant densities are in the range between 1,430 kg/m^3 and 1,600 kg/m^3, with an uncertainty of roughly $\pm$ 2% about any one value. Non-convective layer densities are in the range 1,570 kg/m^3 and 1,730 kg/m^3, with an uncertainty of $\pm$ 6% or so about any one value.

Meyer et al. (1997) also list non-convective layer yield strength (referred to as shear strength by Willingham [1994]) as a function of depth for the same five tanks. The non-convective layer is a viscoplastic material with a finite yield strength and shear rate dependency that can be measured by a ball rheometer. Yield strength is largest near the bottom; maximum yield stress is somewhere between 200 and 325 Pa, depending on the tank.

Another compilation of DST waste property data is given in Barton and Bingham (1999). Descriptive statistics were developed from this compilation, with the six salt cake DSTs differentiated from the other (sludge) DSTs. For the six salt cake DSTs, the mean and standard deviation of the convective layer density are 1.48 and 0.06 g/ml, respectively; mean and standard deviation of the non-convective layer density are 1.62 and 0.08 g/ml, respectively. For the remaining twenty-two DSTs, mean and standard deviation for the convective layer density are 1.13 and 0.12 g/ml, respectively. Mean and standard deviation for non-convective layer are 1.51 and 0.09 g/ml, respectively. Only fourteen DSTs were used for non-convective layer averaging because eight of the DSTs have only a trivial amount of settled solids. Waste yield strength is listed for many of the tanks, but in other instances a probability density function is used. This function is a truncated normal distribution with mean equal to 120 Pa, standard deviation equal to 30 Pa, minimum equal to 50 Pa, and maximum equal to 200 Pa. Tank-specific yield strengths listed range from 81 to 225 Pa.

To conclude, Table 3-6 provides a summary of DST waste property data. Table 3-6 shows values obtained from averaging over the salt cake DSTs and sludge DSTs. Both the Hu and Barker (2002) database and the pedigreed database were considered and found to be in reasonable agreement. The differences between values for the salt cake DSTs and values for the other DSTs should be noted. Mean non-convective layer and supernatant densities in the salt cake DSTs are higher, and the difference between non-convective layer density and supernatant density (e.g., 1.63 minus 1.50 g/ml) is smaller than the corresponding difference for a sludge DST (e.g., 1.51 minus 1.13 g/ml). The table therefore illustrates an important difference between salt cake and sludge tanks: the sludge tanks have a higher neutral buoyancy void fraction.

Table 3-6. Double-Shell Tank Waste Properties. (2 sheets)

Property	Units	Source	Mean	Uncertainty
Non-Convective Layer Density	g/ml	Six Salt Cake DSTs[2]	1.61	Stand. Dev. = 0.07
		Five Salt Cake DSTs[3]	1.63	± 6%
		Six Salt Cake DSTs[1]	1.62	Stand. Dev. = 0.08
		Fourteen Sludge DSTs[1]	1.51	Stand. Dev. = 0.09
		Fifteen Sludge DSTs[2]	1.53	Stand. Dev. = 0.10
Supernatant Density	g/ml	Six Salt Cake DSTs[2]	1.43	Stand. Dev. = 0.05
		Five Salt Cake DSTs[3]	1.50	± 2%
		Six Salt Cake DSTs[1]	1.48	Stand. Dev. = 0.06
		Twenty-Two Sludge DSTs[1]	1.13	Stand. Dev. = 0.12
		Twenty-Two Sludge DSTs[2]	1.23	Stand. Dev. = 0.10

Table 3-6. Double-Shell Tank Waste Properties. (2 sheets)

Property	Units	Source	Mean	Uncertainty
Shear Strength	Pa	Five Salt Cake DSTs[3]	263 (Max. Value)	± 62
		[1]	120	Truncated Normal: Stand. Dev. = 30, Min. = 50, Max. = 200
Liquid Heat Capacity	J/kg-°C	Refer to Table 3-2[4]	3349	-
Solid Heat Capacity	J/kg-°C	Refer to Table 3-2[4]	837	-

[1]Barton, W. B., and J. D. Bingham, 1999, *Gas Release Event Safety Analysis Tool Pedigree Database for Hanford Tanks*, HNF-SD-WM-TI-806, Rev. 2-A, Lockheed Martin Hanford Corporation, Richland, Washington.

[2]Hu, T. A., and S. A. Barker, 2002, *Steady State Flammable Gas Release Rate Calculation and Lower Flammability Level Evaluation for Hanford Tank Waste*, RPP-5926, Rev. 2, CH2M HILL Hanford Group, Inc., Richland, Washington.

[3]Meyer, P. A., M. E. Brewster, S. A. Bryan, G. Chen, L. R. Pederson, C. W. Stewart, and G. Terrones, 1997, *Gas Retention and Release Behavior in Hanford Double-Shell Waste Tanks*, PNNL-11536, Rev. 1, Pacific Northwest National Laboratory, Richland, Washington.

[4]Sathyanarayana, K., 1996, *Evaluation of Potential and Consequences of Steam Bump in High Heat Waste Tanks and Assessment and Validation of GOTH Computer Code*, WHC-SD-WM-CN-022, Rev. 0-B, Westinghouse Hanford Company, Richland, Washington.

DST = double-shell tank.

3.4 TANK CONFIGURATION DATA

SST and DST configurations are pictured here in Figures 3-7 and 3-8, respectively. Tank configuration data are important to consequences of the tank bump. These data include the headspace volume, headspace flowpaths, and decontamination factors for flowpaths from the headspace. For a given tank bump magnitude, the headspace volume obviously has a first-order effect on consequences by determining the peak overpressure. Headspace free volume is known by subtracting the waste volume, which is listed in Appendix A, from the total tank volume, which can be obtained from the Barton and Bingham (1999) database; the total tank volume as listed in the Barton and Bingham (1999) database includes the dome space and is not the designed waste capacity. This calculation gives the total free volume available in the headspace.

The size and nature of flowpaths from the tank headspace determine the final overpressure and magnitude of releases. These flowpaths are in the form of ventilation ducts, risers, cascade lines, pit cover, flanges, etc., as described in the rise configuration document (Alstad 1993). Ventilation flowrate and duct diameter are listed in the Barton and Bingham (1999) database. Consequences depend on the flow resistance and decontamination factor provided by a riser high-efficiency particulate air (HEPA) filter. Releases are greatly mitigated if the HEPA filter remains intact. HEPA filter failure pressure is specified at 1.3 psig in DOE-HDBK-3010-94

Figure 3-7. Single-Shell Tank Instrumentation Configuration.

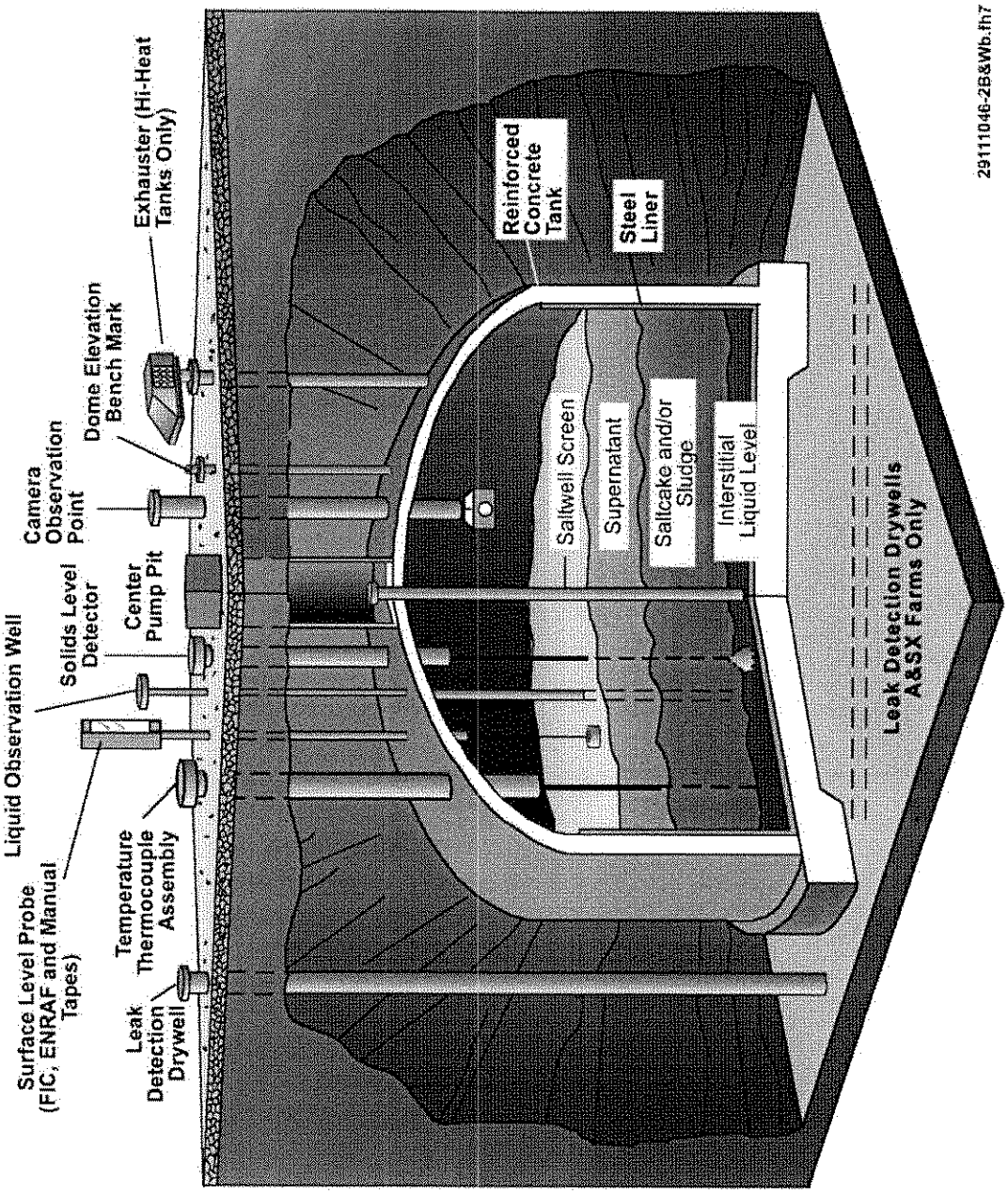


FIGURE D-3. SINGLE-SHELL TANK INSTRUMENTATION CONFIGURATION

Figure 3-8. Double-Shell Tank Instrumentation Configuration.

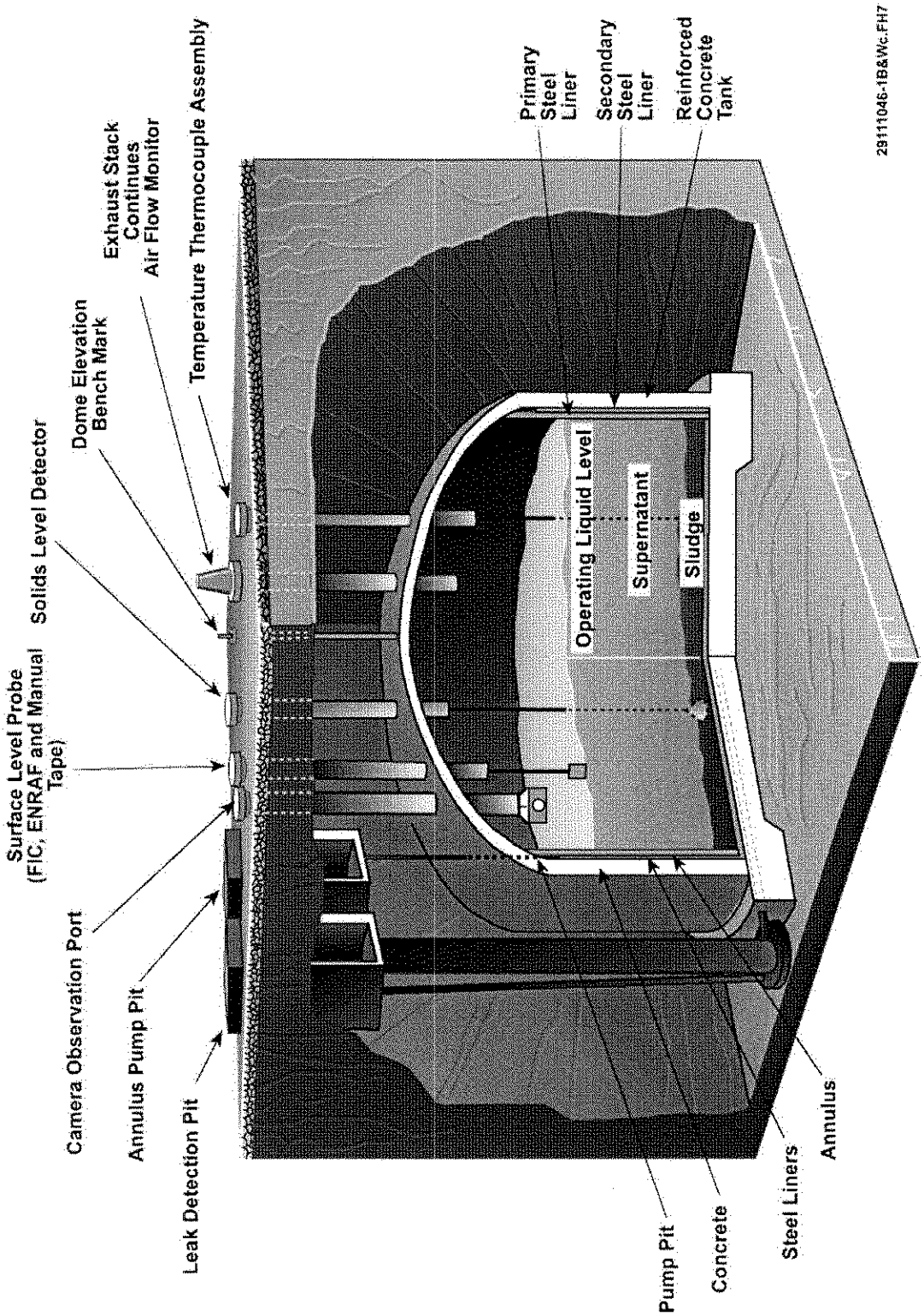


FIGURE D-2. DOUBLE-SHELL TANK INSTRUMENTATION CONFIGURATION

(DOE 1994), but Barton and Bingham list 5 psig as the HEPA filter failure pressure to account for pressure drop between the headspace and the filter. This distinction is worth noting, but the precise value is unimportant here, as we perform all calculations as if the HEPA filters are immediately blown out.

Some tank-specific information for 241-AZ-101 and 214-AZ-102 are mentioned here because it will be used later. Units are presented in British or SI as obtained from the original reference, for clarity in tracing. Pit and riser information is obtained from drawings (H-2-68304, H-2-68305, H-2-68423, and H-Unknown-1), and from Barton and Bingham (1999).

Normal flowpaths between tank headspace and ambient are the filtered 8 in. diameter inlet and 20 in. diameter outlet. Unfiltered release paths from Barton and Bingham (1999) do not apply due to pit riser configuration details, as follows.

Each of the four sluice pits and the center pump pit contain a 42 in. riser for sluicing and a drain riser of 3 in. diameter in sluice pits and 4 in. diameter in the pump pit. The 42 in. risers terminate close to the tank dome and communicate with the headspace, while the drain risers extend to within 5 ft of the tank bottom and are immersed in waste. The 42 in. risers have concrete and steel shield plugs that are 5 ft thick and weigh 8,500 lb or 3,864 kg.

Steel flanges on these 42 in. risers and shield plugs have 16 bolt holes of 7/8 in. diameter for sealing, but the sealing status of these risers is not known. If unsecured, a pressure difference of about (3,864 kg) (9.81 m/s^2) / (0.89 m^2) = 42.5 kPa from tank to ambient will cause the plugs to lift.

Sluice pits measure about 6.5 ft wide x 8 ft long x 7 ft deep with pit covers of 2.0 ft thickness in place. So open volume in sluice pits is about 10 m^3 and the pressure to lift a pit cover is about 13.8 kPa (using a concrete density of 2,300 kg/m^3). Pump pits have dimensions of about 8.5 ft wide x 12 ft long x 7 ft deep with pit covers of 2.5 ft in place, so open volume is about 20 ^{3} and cover lift pressure is about 17 kPa.

Following the Barton and Bingham (1999) assumption of 1/64 in. gap around unsealed risers, the leakage area for a single such riser is π (42 x 0.0254) (0.0254 / 64) = 1.33 x 10^{-3} m^2, which is the equivalent of a 1.6 in. diameter hole. The reference pit leakage gap is 1/4 in., which applied to a sluice pit (perimeter = 29 ft) yields 87 in^2 = 0.056 m^2 and to a pump pit (perimeter = 41 ft) yields 123 in^2 = 0.079 m^2.

4.0 TANK BUMP PHYSICAL MODELS AND CRITERIA

Tank bumps are related to rapid steam generation in the waste liquid and the release of energy when the steam, in the form of a large bubble (or numerous bubbles), passes through the waste surface. These eruptions are not sufficient to threaten the mechanical integrity of the tank, but may lead to undesirable discharge of radioactive contaminants.

It is difficult to imagine a tank bump event in the absence of a deep layer of supernatant at a temperature approaching 100°C overlying a heat-producing normally non-convective waste layer. This concept will be developed and proven here in this section. Two physical scenarios for tank bump are deemed plausible and are investigated here:

> In Section 4.1, we will demonstrate that tanks lacking a fairly deep, nearly saturated supernatant layer cannot have a significant tank bump. The scenario developed here is for gas injection from a (normally) non-convective lower waste layer into an overlying supernatant layer, Figure 4-1. The gas injection may be natural release of radiolytically and thermally generated non-condensible gases, such has hydrogen, or it may be gas injection due to some operation in the tank. A bump criterion for this scenario is the combination of significant gas injection, deep supernatant layer, and nearly saturated supernatant layer.
>
> In Section 4.2, we will demonstrate that a buoyant displacement event (Figure 4-2) is a mechanism that can result in a significant steam bump providing that the non-convective layer is capable of self-heating to nearly its boiling point at the local static pressure and providing that non-condensible gas generation can bring the non-convective layer to a buoyant state.

Two additional physical scenarios for tank bump postulated over the years are deemed not plausible based on analysis presented in Appendix B:

> In Appendix B.1 we investigate a hypothetical scenario for steam bump due to interstitial liquid super heating in stationary sludge, Figure B-1. The purpose of this investigation is to prove that significant sudden release of vapor cannot occur from a stationary sludge layer alone.
>
> In Appendix B.2 we examine steam bubble growth due to local convection in an otherwise non-convective layer, Figure B-3. This scenario corresponds to concerns raised at one time for Tank 241-C-106, when an increase in waste temperature was observed following a process test. Local convection, or fumaroles as the phenomenon was called at the time, are shown not to be a source for a significant steam bump.

Figure 4-1. Steam Bump By Gas Injection.

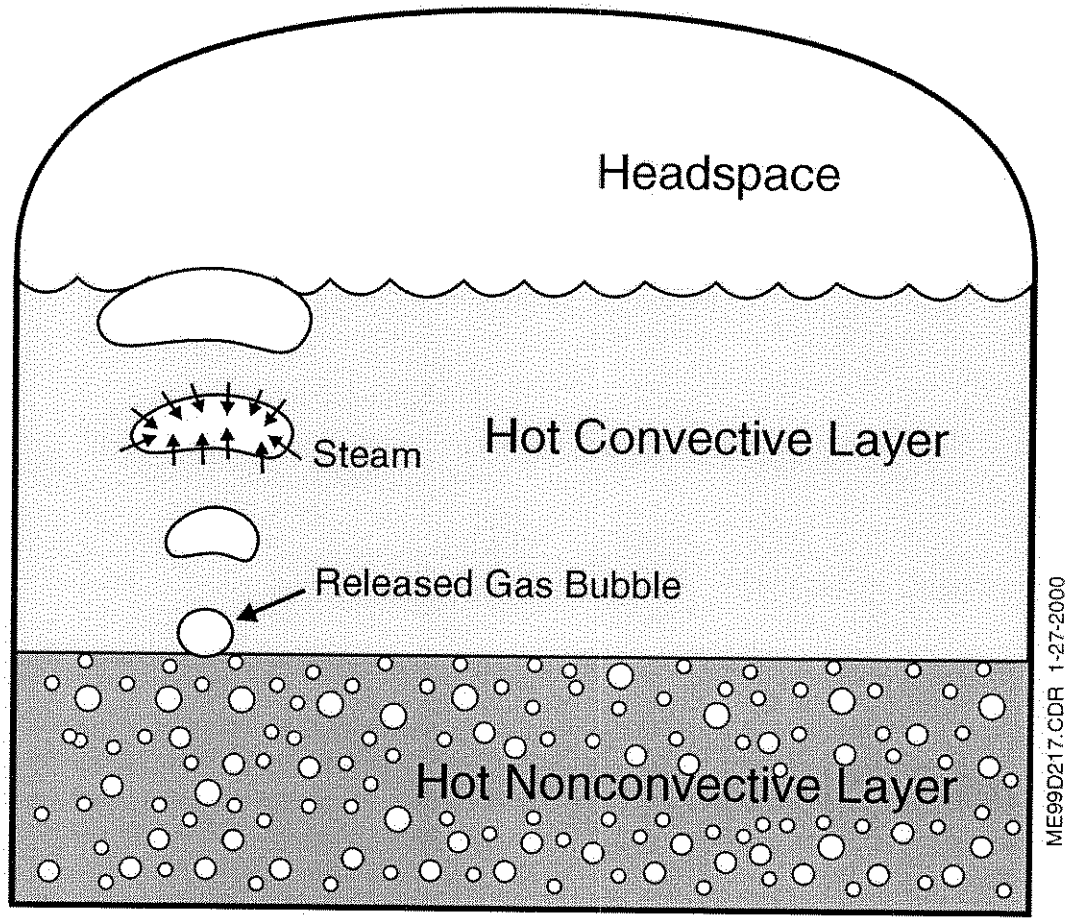
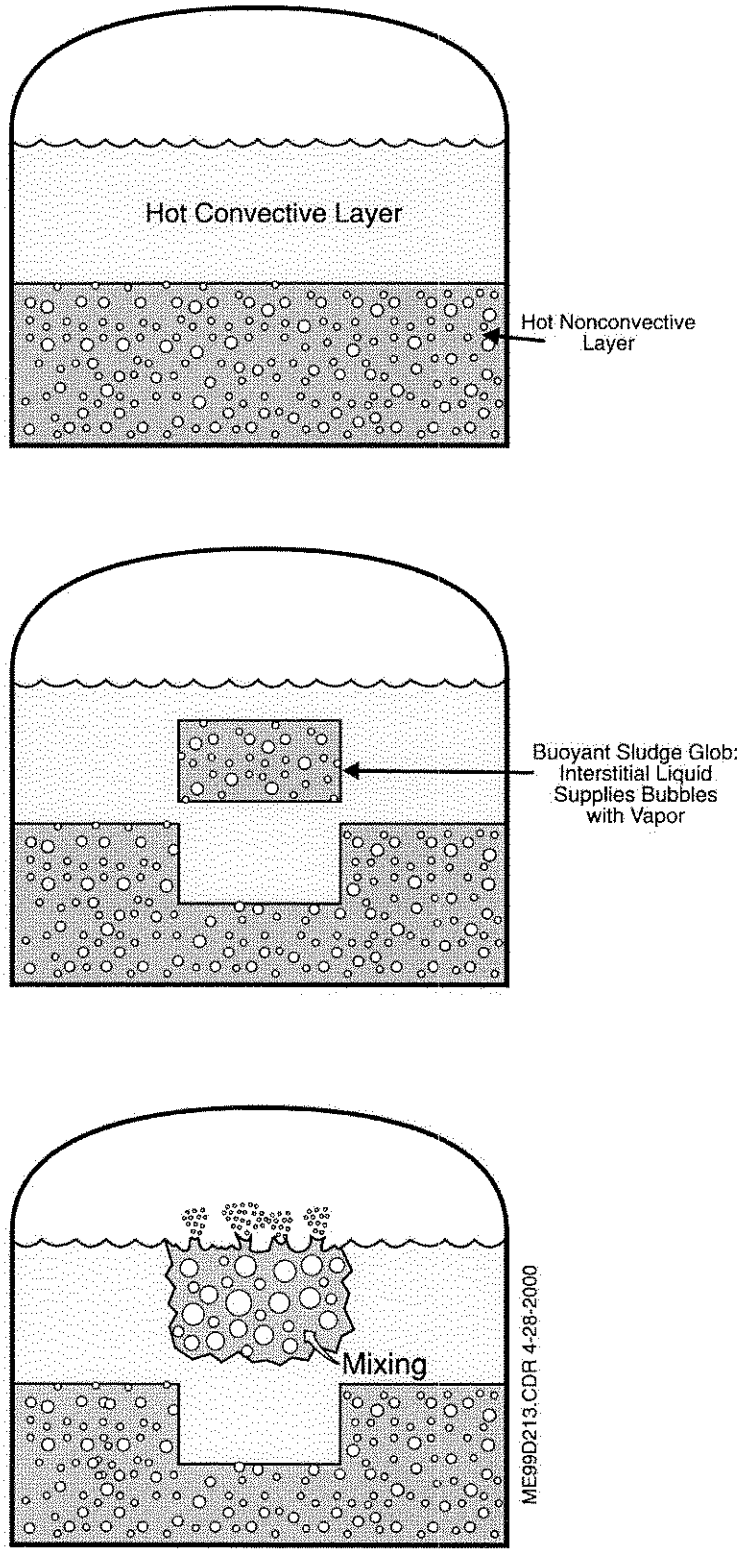


Figure 4-2. Steam Bump During a Buoyant Displacement.



4.1 STEAM BUMPS BY GAS INJECTION

Consider the growth of a gas cavity of volume $V_b(0)$ that suddenly appears at the bottom of a supernatant layer of depth H and uniform temperature T_ℓ, Figure 4-1. The cavity is filled with the vapor of the surrounding water and by the non-condensible gas generated in the underlying non-convective layer. It is well known that natural convection currents within the water layer are more than sufficient to maintain the liquid at a nearly isothermal condition. The magnitude of the cavity expansion during its ascent through the liquid layer is a measure of the severity of the tank bump event and this is the problem treated below.

In keeping with our objectives, we consider the transient growth of a spherical cavity (bubble), initially containing the gas and water vapor (steam) it gradually accumulated before it was released at the bottom of the supernatant layer. The initial partial pressure of steam in the bubble, $P_{eq}(T_\ell)$, is specified by demanding thermodynamic equilibrium between steam and liquid at the bubble surface. As the bubble rises into regions of lower hydrostatic pressure, due to the presence of non-condensible gas (hereafter referred to as "gas"), the bubble expands and the steam partial pressure in the interior of the bubble falls below the equilibrium steam partial pressure at the bubble surface. This results in a concentration gradient within the bubble and steam transport from the surface of the bubble to its interior. In turn, water must evaporate and pass from the supernatant and into the bubble. The evaporation process tends to cool the liquid so that its temperature decreases from T_ℓ in the immediate vicinity of the bubble surface and a thermal boundary layer develops on the liquid side of the bubble. Thus the growth of the bubble is controlled by heat and mass transport; it is limited by the rate at which latent heat can be supplied by liquid convection at the bubble surface and by the rate at which steam can diffuse (convect) into the bubble from its surface. The bubble growth problem is obviously complicated.

To simplify matters and still retain a conservative approach, it is assumed that bubble growth is limited by steam transport within the bubble. The resistance to growth imposed by the thermal boundary layer on the liquid side is ignored. From this assumption it follows that the steam partial pressure at the bubble surface equals $P_{eq}(T_\ell)$ throughout its motion. Thus, the rate at which steam enters the bubble is given by a mass transport law of the form

$$\frac{d\,m_v}{dt} = 4\,\pi\,r^2\,h_m\,\rho_{mix}\,\ln\left[1+\frac{\rho_{eq}\,(T_\ell)-\rho_v}{\rho_{mix}-\rho_{eq}\,(T_\ell)}\right] \tag{4-1}$$

where m_v is the instantaneous mass of steam within the bubble at time t, r is the bubble radius, ρ_v is the bulk steam density within the bubble, ρ_{mix} is the bulk gas/vapor mixture density within the bubble, $\rho_{eq}(T_\ell)$ is the equilibrium density of steam at the inside surface of the bubble evaluated at the supernatant temperature T_ℓ, and h_m is the coefficient for steam transport from the bubble surface into its interior.

A maximum rate of bubble-gas side mass transfer can be predicted by postulating a model in which the bubble interior is well mixed and the entire resistance to mass transfer restricted to a thin gas/steam boundary layer at the bubble surface. Such a model was analyzed by

Ruckenstein et al. (1971). A Hill's vortex bubble flow field was linearized near the bubble surface and the final expression for h_m was found to be

$$h_m = \left(\frac{2\, U_b\, D}{\pi\, r} \right)^{1/2} \tag{4-2}$$

where U_b is the bubble rise velocity relative to the surrounding liquid and D is the binary diffusion coefficient for the bubble mixture (steam + gas).

The mass of vapor in the bubble in equation (4-1) can be expressed as the product of the bulk (bubble-interior) steam density and bubble volume V_b

$$m_v = \rho_v\, V_b \tag{4-3}$$

Assuming that steam behaves as an ideal gas, we may write

$$\rho_{eq}\left(T_\ell\right) = \frac{P_{eq}\left(T_\ell\right)}{R\, T_\ell} \quad ; \quad \rho_{mix} = \frac{P_{mix}}{R\, T_\ell} \tag{4-4}$$

$$\rho_v = \frac{P_v}{R\, T_\ell} \tag{4-5}$$

where R is the ideal gas constant for steam, P_{mix} is the total bulk pressure within the bubble, and P_v is the steam partial pressure in the well-mixed bubble interior. The second relation in equation (4-4) is based on the justifiable assumption that the steam contribution to the value of the bubble mixture molecular weight far exceeds that due to the inert gas. The bubble is assumed to rise through the supernatant as part of an ensemble (cluster) of bubbles. A constant "terminal" speed of the cluster is assumed and denoted by the symbol U. Thus time may be replaced by vertical distance traversed by the bubble as follows:

$$t = \frac{z}{U} \tag{4-6}$$

where z is measured from the bottom of the supernatant pool. The constant U assumption will be relaxed later on when a more complete steam bump model is constructed. Combining equations (4-1) to (4-6) gives

$$\frac{d\left(P_v\, V_b\right)}{d\, z} = \left(\frac{24\, D\, U_b}{U^2} \cdot V_b \right)^{1/2} P_{mix}\, \ln\left[1 + \frac{P_{eq}\left(T_\ell\right) - P_v}{P_{mix} - P_{eq}\left(T_\ell\right)} \right] \tag{4-7}$$

To close the problem, we need a relationship between P_v and the bubble volume V_b. This relationship is obtained by the following liquid (supernatant) statics analysis. The gas partial pressure P_g plus the steam pressure P_v within the bubble must equal the local hydrostatic pressure imposed by the supernatant; that is,

$$P_{mix} = P_v + P_g = P_{hs} + \rho_\ell \, g \, (H - z) \tag{4-8}$$

where P_{hs} is the pressure in the tank headspace, g is the gravitational constant, and ρ_ℓ and H are, respectively, the density and depth of the supernatant layer. The mass of inert gas in the bubble remains constant so that by virtue of the ideal gas law

$$P_g(0) \; V_b(0) = P_g \, V_b \tag{4-9}$$

where $P_g(0)$ and $V_b(0)$ denote the values of P_g and V_b at the bottom of the supernatant layer (i.e., at z = 0). Evaluating equation (4-8) at z = 0 and making the reasonable assumption that the bubble emerges from the non-convective layer with an equilibrium concentration of steam throughout its volume, so that,

$$P_v(0) = P_{eq}(T_\ell) \tag{4-10}$$

yields

$$P_{eq}(T_\ell) + P_g(0) = P_{hs} + \rho_\ell \, g \, H \tag{4-11}$$

Eliminating P_g between equations (4-8) and (4-9) and inserting $P_g(0)$ from equation (4-11) into the result gives

$$\frac{V_b}{V_b(0)} = \frac{P_{hs} + \rho_\ell \, g \, H - P_{eq}(T_\ell)}{P_{hs} + \rho_\ell \, g \, (H - z) - P_v} \tag{4-12}$$

Equations (4-7) and (4-12) are sufficient to solve for the unknowns V_b and P_v as a function of elevation z. Unfortunately, the system cannot be integrated in closed form; a numerical solution of equation (4-7) is required. Note, however, that in the limit of no mass transfer resistance to bubble growth, equation (4-12) alone can be used to calculate the bubble volume as a function of vertical distance. This is accomplished by replacing P_v on the right-hand side of equation (4-12) with $P_{eq}(T_\ell)$. Note also that P_{hs} in equation (4-12) is not constant during a steam bump but increases in response to the rising and expanding bubble cluster within the supernatant. For the purpose of illustrating the conditions required for a strong steam bump due to gas injection, it is convenient to first ignore the coupling between the bubble cluster and the headspace atmosphere and assume that P_{hs} remains at its near-atmospheric value.

The various property values used in the illustrative calculations are: $P_{hs} = 0.1013$ MPa, $\rho_\ell = 1{,}100$ kg m^{-3}, $D = 9.2 \times 10^{-5}$ m^2 s^{-1}, and $U = 1.0$ m s^{-1}. The diffusion coefficient D for mass transfer within the bubble was estimated for a hydrogen gas/steam mixture at 373 K and

0.14 MPa pressure by the method outlined in Reid and Sherwood (1966) for polar/non-polar gas pairs. The maximum possible bubble velocity relative to the cluster liquid is the terminal rise velocity of an isolated bubble in a quiescent liquid. The terminal rise velocity of an isolated bubble is typically about $U_b = 0.2\ ms^{-1}$. The rise velocity of a collection of bubbles can be estimated from the formula

$$U = 0.68\left(g\,D_{eff}\right)^{1/2} \tag{4-13}$$

where D_{eff} is the diameter of a large, fictitious bubble having the same volume as the total volume of the bubble ensemble (Moody 1986). The formula implies a bubble ensemble rise velocity of at least $U = 1.0\ m\ s^{-1}$ for gas injections capable of producing a steam bump. Finally, the equilibrium vapor pressure of steam $P_{eq}(T_\ell)$ was estimated as a function of supernatant temperature T_ℓ by using steam table values.

Figures 4-3 and 4-4 illustrate the results of the numerical calculations. Computational details are shown in Appendix D. In both figures, the bubble volume $V_b(H)$ at the end of the bubble's ascent through the supernatant layer divided by its initial volume $V_b(0)$ at the bottom of the layer is plotted against the depth H of the layer. Figure 4-3 shows the effect of supernatant temperature on bubble expansion while Figure 4-4 shows the effect of initial bubble size (diameter d_0) on bubble expansion. Mass transfer resistance becomes important as the supernatant temperature T_ℓ approaches its boiling point (100 °C). Clearly, the bubble expansion ratio is sensitive to the initial bubble size. Observations of retained gas in simulants and actual wastes indicate that the average bubble diameter is approximately 1.0 mm and that the upper end of the size range of retained round gas bubbles in waste is about 5.0 mm (Gauglitz et al. 1996). The larger bubbles should serve as the sites from which the bubbles grow during a spontaneous gas release event or waste disturbing operation as the free energy required to initiate bubble growth decreases by an amount proportional to the volume of the embryo bubble. It follows that conservative estimates of the bubble expansion ratio may be based on the choice $d_0 = 1.0$ mm. It should be mentioned that during a spontaneous gas release event there will be a significant reduction in the bubble size (and in total release void volume) due to vapor condensation as the bubbles are transported from the non-convective layer to the relatively cooler supernatant.

Regardless of the dimensions of the bubbles, it is clear from Figures 4-3 and 4-4 that a significant tank bump event by gas injection requires a deep supernatant layer whose temperature approaches the boiling point.

In the preceding example, the ambient temperature was assumed to be a standard atmosphere. Also, the effect of salt in solution to increase the boiling point was neglected. These simplifications do not change conclusions when values pertinent to a given tank and ambient pressure are used.

Figure 4-3. Bubble Expansion Ratio Versus Depth of Supernatant Pool; Pool Temperature T_λ as a Parameter. Dashed curves refer to zero mass transfer resistance.

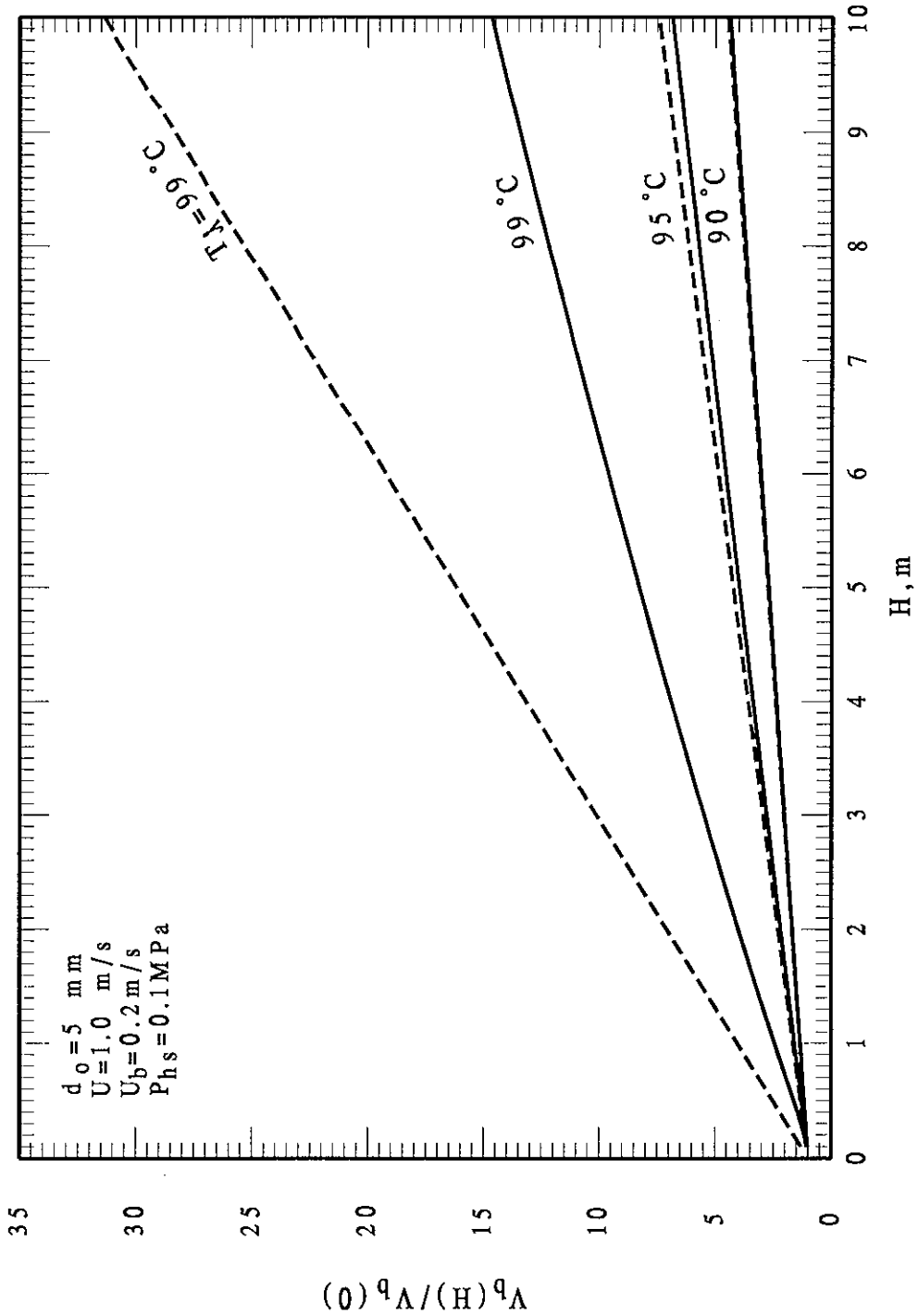
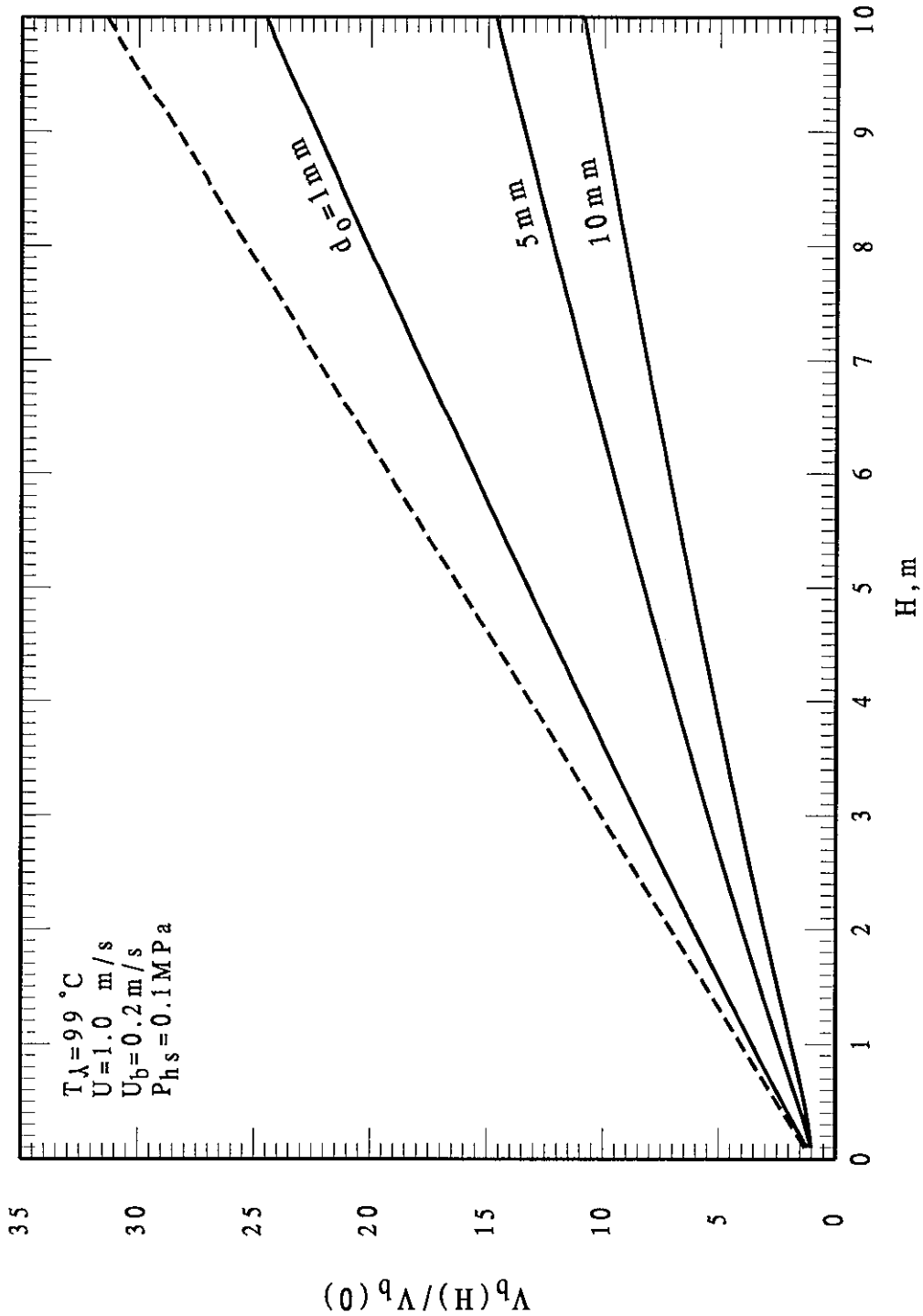


Figure 4-4. Bubble Expansion Ratio Versus Depth of Supernatant Pool; Initial Bubble Diameter as a Parameter. Dashed curve refers to zero mass transfer resistance.



While the volume expansion ratio $V_b(H) / V_b(0)$ results given in Figures 4-3 and 4-4 were obtained for a single bubble in a bubble ensemble, the results are also applicable for the bubble ensemble itself providing that bubble coalescence is ignored and an effective mean bubble size is specified. For the bubble ensemble case, $V_b(0)$ and $V_b(H)$ in the volume expansion ratio refer respectively to the total volume of the bubble ensemble at the bottom of the supernatant and the total volume of the bubble ensemble upon its arrival at the waste surface. Therefore, to calculate the absolute bubble volume produced as a result of a gas injection and bubble ascent, we must estimate $V_b(0)$. The application of the bubble growth theory presented in the foregoing to the behavior of a cluster of bubbles is postponed until Section 5.0 where a tank bump consequence model is described and exercised.

An underlying assumption in the calculation is that the supernatant temperature is uniform; this is typically taken as obvious as mentioned above and in the discussion of Section 3.1. The point is proven here to illustrate how rigid the requirement is for the entire supernatant layer to be nearly saturated. For turbulent natural convection in a liquid layer with a free upper surface, the relationship between heat flux and core to surface temperature difference is (Katsaros et al. 1977):

$$Nu = 0.156\ Ra^{0.33} \tag{4-14}$$

where $Nu = h L / k$, and

$$Ra = g \beta \Delta T L^3 / \alpha \nu.$$

Heat flux is given by the product $h \Delta T$, and is equal to the amount of tank power Q_u lost upward divided by area A,

$$\frac{Q_u}{A} = 0.156\, k \left(\frac{g \beta}{\alpha \nu} \right)^{\frac{1}{3}} (\Delta T)^{4/3} \tag{4-15}$$

For a representative (and high) power of 10 kW, and typical values as follows, $A = 411\ m^2$, $k = 0.68$ W/m/K, $g = 9.81\ m/s^2$, $\beta = 6 \times 10^{-4}\ K^{-1}$, $\alpha = 3 \times 10^{-5}\ m^2/s$, $\nu = 3 \times 10^{-5}\ m^2/s$, the temperature difference is only $\Delta T = 0.29$ K. The total temperature difference between the bottom of the layer and the top of the layer would double this value, or about 0.6 K. For higher upward heat flux, typically required for the supernatant layer to be nearly saturated, the temperature difference would be even lower.

4.2 STEAM BUMP BY BUOYANT DISPLACEMENT

A buoyant displacement occurs when a gas (vapor)-generating and gas (vapor)-trapping non-convective layer is covered by a relatively thick layer of initially less dense supernatant. Eventually, gas (vapor) generation in the lower layer leads to a density inversion and the buoyant displacement event. The temperature T_{nc} in the non-convective layer usually exceeds the

temperature T_ℓ in the overlying supernatant. Using the physical properties of water it is possible for the non-convective layer to reach a temperature of 120 °C at a depth 10 m below the free surface of the waste. Owing to natural convection the supernatant temperature cannot exceed its boiling point of 100 °C at atmospheric pressure. During a buoyant displacement in a "hot tank", the bubbles trapped in the rising, hot non-convective layer material grow by converting the hot interstitial liquid (>100 °C) into steam while a bubble injected into the supernatant grows by accumulating vapor from the relatively low temperature supernatant (<100 °C). The model derived in the previous sub-section can be used to illustrate the effect of the temperature of the host liquid (supernatant or non-convective buoyant material) on the bubble volume expansion ratio $V_b(H) / V_b(0)$. The results are shown in Figure 4-5 where we see that the severity of a tank bump event increases dramatically once the non-convective layer temperature exceeds the maximum supernatant temperature T_{nc} = 100 °C.

The results in Figure 4-5 pertain only to representative cluster-bubble behavior beneath a constant pressure headspace. It will be seen later on that owing to the pressurization of the tank headspace and mixing between the buoyant parcel of initially non-convective material and the surrounding supernatant, the bubble volume expansion ratios achieved within the buoyant parcel during a tank bump are much smaller than those presented in Figure 4-5.

Most of the Hanford site tanks have little potential for a tank bump because either their heat loads are too low to heat the waste to its boiling point or the time required to self-heat to the boiling point is very long compared with the time required to repair the equipment failure. Possible exceptions are Tanks 241-AZ-101, 241-AZ-102, and 241-AY-102, which have rather large non-convective layer heat generation rates. The question remains as to whether these tanks will exhibit a buoyant displacement after their non-convective layer is heated to the boiling temperature.

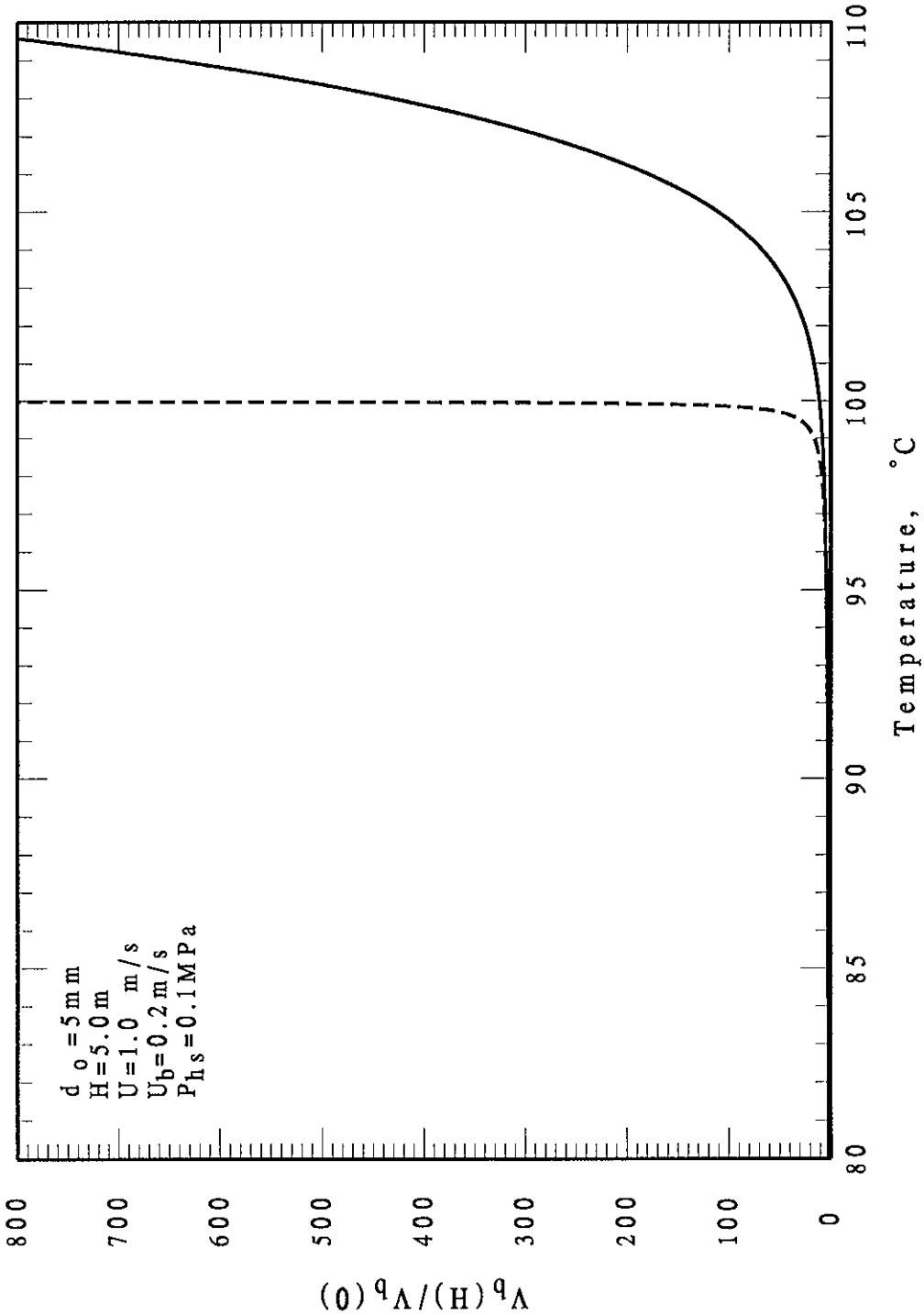
Meyer and Wells (2000) derived models that give criteria that must be satisfied in order for buoyant displacements to occur. Briefly, they developed an equation for the vertical void fraction profile within the non-convective layer based on a balance between internal gas generation and the rate at which gas is released at the top of the layer. The integrated average of this void fraction profile is compared with the neutral buoyant void fraction to determine whether a buoyant displacement may occur at some point during the transient (quasi-steady) void growth period. Two limiting case solutions were found for the void fraction profile and the corresponding criteria for a buoyant displacement are

$$\frac{C_1 \, h_{NCL}^2}{\rho_{NCL} - \rho_{CL}} \left(\frac{G\,T}{P_{NCL}} \right)^{1/3} > 1 \qquad (4\text{-}16)$$

for a uniform bubble nucleation rate and a zero initial void fraction, and

$$\frac{C_2}{\rho_{NCL} - \rho_{CL}} \left(\frac{\rho_{NCL}^2 \, h_{NCL}^2 \, G\,T}{P_{NCL}} \right)^{1/3} > 1 \qquad (4\text{-}17)$$

Figure 4-5. Bubble Expansion Ratio Versus Convective Layer Temperature (<100 °C) or Buoyant Parcel Temperature T_{nc} During Buoyant Displacement. Dashed curve refers to zero mass transfer resistance.



for an assumed bubble flux at the lower boundary and zero internal nucleation rate. In equations (4-16) and (4-17), ρ_{NCL} and ρ_{CL} are the density of the non-convective layer and the density of the convective layer (kg m^{-3}), respectively, G is the molar gas generation rate per unit volume of non-convective layer (g-mole m^{-3} day^{-1}), T is the average temperature of the non-convective layer (K), P_{NCL} is the average pressure of the non-convective layer (atm), and h_{NCL} is the depth of the non-convective layer (m). The constants C_1 and C_2, each with dimensional units, are empirically adjusted so that all the double-shell tanks with observed buoyant displacements obey the criteria given by equations (4-16) and (4-17). Equation (4-17) provides much more conservative results than equation (4-16). However, equation (4-16) yields a better representation of double-shell tank buoyant displacement behavior (Stewart 2000) and is chosen here for application to Tanks 241-AZ-101, 241-AZ-102, and 241-AY-102. The value of the constant in equation (4-16) based on the most recent tank data is $C_1 = 18.5$ (Stewart 2000).

The gas generation rate originally used in equation (4-16) is non-condensable gas generation by radiolysis and thermal decomposition. It is of interest to evaluate equation (4-16) when G is based on steam generation only, and then, when G is based on non-condensable gas generation only. In both evaluations, the non-convective layer is presumed to be at its boiling temperature at the local static pressure. The steam production rate G_v may be approximated by

$$G_v = \frac{\dot{Q}'''_{NCL}}{h_{fv} M_v} \tag{4-18}$$

where $\dot{Q}'''_{NCL}$ is the heat generation rate per unit volume of non-convective layer, h_{fv} is the latent heat of evaporation of water, and M_v is the molecular weight of water. The non-condensable gas generation rate at the boiling point T_{bp} (evaluated at the mid-plane of the non-convective layer) is obtained by using the Arrhenius equation to extrapolate the known gas generation rate at the prevailing non-convective layer temperature T_o to its value at T_{bp}:

$$G_g\left(T_{bp}\right) = G_g\left(T_o\right)\exp\left(-\frac{T_{act}}{T_{bp}} + \frac{T_{act}}{T_o}\right) \tag{4-19}$$

where the activation temperature T_{act} (= E / R) is 5,328(Hu and Barker2002).

Table 4-1 lists the predicted values of G_v and G_g for Tanks 241-AZ-101, 241-AZ-102, and 241-AY-102. It is obvious from the table that the steam production rate is much larger than the non-condensable gas generation rate. While the boiling temperature may be increased by a few degrees due to dissolved salt, this has only a minor effect.

Table 4-1. Gas and Steam Generation Rates in the Non-Convective Layer.

Tank, 241-	Prevailing Temp. T_o (K)	Boiling Temp. T_{bp} (K)	$\dot{Q}'''_{NCL}$ (W/m^3)	G_g (T_o) $\left(\frac{g-mole}{m^3\ day}\right)$	G_g (T_{bp}) $\left(\frac{g-mole}{m^3\ day}\right)$	G_v $\left(\frac{g-mole}{m^3\ day}\right)$
AZ-101	348	393	170.1	0.021	0.147	371
AZ-102	345	392	40.71	0.011	0.116	89
AY-102	345	385	56	0.069	0.173	122

The results of the buoyant displacement criterion calculations from equation (4-16) are listed in Table 4-2.

Table 4-2. Buoyant Displacement Model (equation (4-16)) Predictions for the High-Power Double-Shell Tanks.

Tank, 241-	ρ_{NCL} ($kg\ m^{-3}$)	ρ_{CL} ($kg\ m^{-3}$)	h_{NCL} (m)	P_{NCL} (atm)	LHS* Equation (4-16): $G = G_v$	LHS* Equation (4-16): $G = G_g$
AZ-101	1,620	1,240	0.48	2.02	0.47	0.03
AZ-102	1,380	1,140	0.97	1.96	1.89	0.21
AY-102	1,400	1,150	1.57	1.56	5.68	0.64

*LHS = left-hand side of equation (4-16).

An examination of the last column of Table 4-2 indicates that even in the presence of steam generation 241-AZ-101 fails to satisfy the buoyant displacement criterion (>1.0), owing to its shallow non-convective layer. It is recognized that the Meyer and Wells (2000) criterion is valid at non-convective layer boiling conditions only if the gas retention and gas migration properties of the non-convective layer remain the same during boiling of the layer. The criterion is probably valid during the period when the layer is heated from its initial, steady-state temperature to its boiling temperature and non-condensable gas generation is the dominant mode of void production. The last two columns of Table 4-2 show that buoyant displacement can occur only by steam generation for Tank 241-AZ-102, and Tank 241-AY-102. In no tank can non-condensable gas alone bring the NCL to buoyant conditions. As discussed below, steam condensation caused by mixing of the supernatant layer with the buoyant materials will prevent the buoyant displacement from becoming a tank bump.

A postulated buoyant displacement in Tanks 241-AZ-101, 241-AZ-102, or 241-AY-102 implies a weak (low yield strength) non-convective layer. In these tanks, the density difference between the non-convective layer and the overlying supernatant is large owing to the absence of significant quantities of dissolved salt. Consequently, the neutral buoyancy void fraction is high

(~0.3). The experimental evidence (Gauglitz et al. 1996) suggests that if the waste has a high yield strength, the gas bubbles will connect and form a continuous path at void fractions below the neutral buoyancy void fraction. If the waste in Tanks 241-AZ-101, 241-AZ-102, or 241-AY-102 is stiff, these tanks do not pose a buoyant-displacement-steam bump concern. Thus, a prerequisite for a steam bump, due to a non-condensable gas buoyant displacement gas release event, is a low non-convective-layer yield strength of the order of the known yield strengths of the non-convective layers in the six DSTs that exhibit buoyant displacement, say $\tau_y \approx$ 100 Pa. The available buoyant energy is more than sufficient to overcome the 100 Pa yield strength and rapidly transform the non-convective material in the rising parcel into a Newtonian fluid (Meyer et al. 1997). This transformation is immediately followed by the mixing of the buoyant parcel material with the surrounding sub-cooled supernatant.

Intense mixing of the structurally weak, steam-void containing buoyant parcel with the surrounding supernatant will begin just as the parcel rises from the non-convective layer (see Appendix C). Mixing is caused by a vertical buoyancy-dominated, turbulent diffusion mechanism (Epstein and Burelbach 2000a). The density difference between the buoyant parcel and the surrounding supernatant, combined with the very low initial momentum of the buoyant release, causes the inward flow of supernatant so that an unstable density gradient persists above the release area. Consequently, a density-gradient driven vertical mixing zone is quickly established between the rising parcel of previously non-convective material and the overlying supernatant. It is pertinent to note here that the top 10 to 50 cm of the parcel is sub-cooled and has a low void fraction. This parcel "cover" is non-buoyant and stiff with respect to the convective layer. However, it is reasonable to believe that the cover will move some distance to the side to allow the underlying, buoyant, and flowing portion of the parcel to rise into the supernatant. Thus, vertical mixing between the steam-bearing material and supernatant will still occur, although over an area that is smaller than the horizontal extent of the parcel.

The temperature at the top of the mixing layer T_{mix} as a function of the supernatant temperature T_{CL} and the temperature T_{bp} of the non-convective layer may be determined from Epstein and Burelbach's (2000b) formula for mixing above a circular source of buoyancy. For the miscible liquid-liquid (supernatant-non-convective layer) system of interest here, their formula takes the form

$$\frac{T_{CL} - T_{mix}}{T_{NCL} - T_{CL}} = 2.8\left[\frac{v_0^2\left(\frac{\rho_{CL}}{\rho'_{NCL}}\right)^2}{g\left(\frac{\rho_{CL}}{\rho'_{NCL}} - 1\right)R_0}\right]^{1/3} \tag{4-20}$$

where ρ'_{NCL} is the two-phase density of the void-containing non-convective layer $\left(\rho_{CL} > \rho'_{NCL}\right)$, R_0 is the effective horizontal extent of the mixing zone, and v_0 is the velocity (initial) of the buoyant parcel as it rises from and passes by the "surface" of the non-convective layer. Equation (4-20) is based on theoretical analysis and experimental data obtained specifically to address

fluid mixing in Hanford waste tanks (Epstein and Burelbach 1998), and it is currently applied in the flammable gas safety basis (Slezak et al. 1998).

The rise velocity v_0 of the buoyant parcel is proportional to the density difference $\rho_{CL} - \rho'_{NCL}$. The parcel cannot rise from the non-convective layer faster than the supernatant can flow into the region (cavity) vacated by the departing buoyant parcel. Thus, the velocity v_0 in equation (4-20) is less than or equal to the so-called exchange flow velocity v_0 across an opening of radius R_0; namely (see Brown [1962] or Epstein [1988]),

$$v_0 = 0.1\left[R_0\, g\left(\frac{\rho_{CL}}{\rho'_{NCL}} - 1\right)\right]^{1/2} \tag{4-21}$$

Eliminating v_0 between equations (4-20) and (4-21) and assuming $\rho_{CL} > \rho'_{NCL}$ in the numerator of equation (4-20), gives the following simple result for the temperature of the mixing zone above the buoyant release area:

$$T_{mix} = T_{CL} + 0.6\left(T_{NCL} - T_{CL}\right) \tag{4-22}$$

Inserting the typical values $T_{NCL} = 118$ °C and $T_{CL} = 100$ °C for the high self-heat tanks, gives $T_{mix} = 111$ °C or $T_{NCL} - T_{mix} = 7$ °C. Such a large and sudden drop in temperature will collapse the steam voids within the initially buoyant parcel. The void collapse results in the withdrawal of the released material's buoyancy and the material settles back into the non-convective layer.

As the parcel slumps and spreads out over the top of the non-convective layer, its residual energy relative to the surrounding supernatant is transported upward through the supernatant to the surface where it is "absorbed" by surface evaporation (boiling). It is of interest to estimate the pressure rise in the headspace due to the upward energy flux from the spreading and cooling parcel. Heat flows from the parcel by turbulent natural convection in accord with equation (4-15):

$$Q_u = 0.156\, k\, A\left(\frac{g\,\beta}{\alpha\,\nu}\right)^{\frac{1}{3}} (\Delta T)^{4/3} \tag{4-23}$$

where Q_u is the upward total heat flow, A is the heat transfer area, and ΔT is the temperature difference between the parcel and the overlying supernatant. The maximum possible upward heat flow occurs from a parcel that spreads out over the entire non-convective layer, i.e., to the tank wall, so that $A = 411\ m^2$. The mixing calculation presented in the foregoing indicates that $\Delta T \approx 10$°C. Inserting these estimates into equation (4-23), together with the physical properties of water given below equation (4-15), yields a maximum upward heat flow $Q_u = 1.12$ MW. The volumetric flow of steam $\dot{V}_v$ at the surface of the supernatant in response to the upward heat flow is

$$\dot{V}_v = \frac{Q_u}{\rho_v \, h_{fv}} \tag{4-24}$$

where ρ_v is the density of saturated steam at one atmosphere (0.6 kg m^{-3}). Assuming that the major resistance to steam flow from the tank headspace is exerted by the HEPA filters, the headspace pressure rise ΔP above ambient required to accommodate the heat flow from the aborted steam bump is

$$\Delta P = R \, \dot{V}_v = \frac{R \, Q_u}{\rho_v \, h_{fv}} \tag{4-25}$$

where R is an empirical (filter) resistance coefficient equal to 2.34×10^3 Pa s m^{-3}. The predicted pressure rise is $\Delta P = 2$ kPa (0.29 psi), which is negligible in comparison with the filter failure pressure of 36 kPa.

With regard to the historical bumping events, it is clear that the events occurred in tanks with deep supernatant layers and with sufficient powers to bring the non-convective layers to a boil and the supernatant layers up to their one-atmosphere boiling point. Many of the events were initiated by shutdown and restart of air lift circulators and may be classified as steam bumps by gas injection, as discussed in Section 4.1. Some of the events occurred naturally and periodically, most likely in tanks subject to episodic buoyant displacements driven by non-condensable gas generation.

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5.0 DESCRIPTION OF STEAM BUMP AND LIQUID WASTE RELEASE MODELS

5.1 STEAM BUMP SEQUENCE OF EVENTS

In this section, we consider a hypothetical tank with a non-convective layer that is capable of self-heating to its boiling point and within which non-condensable gas generation may lead to a buoyant displacement event. The major assumption underlying the models presented in this section is that the near-boiling buoyant displacement parcel becomes fluid as soon as it starts to move. In Appendix C, the Meyer et al. (1997) energy criterion is used to justify this assumption.

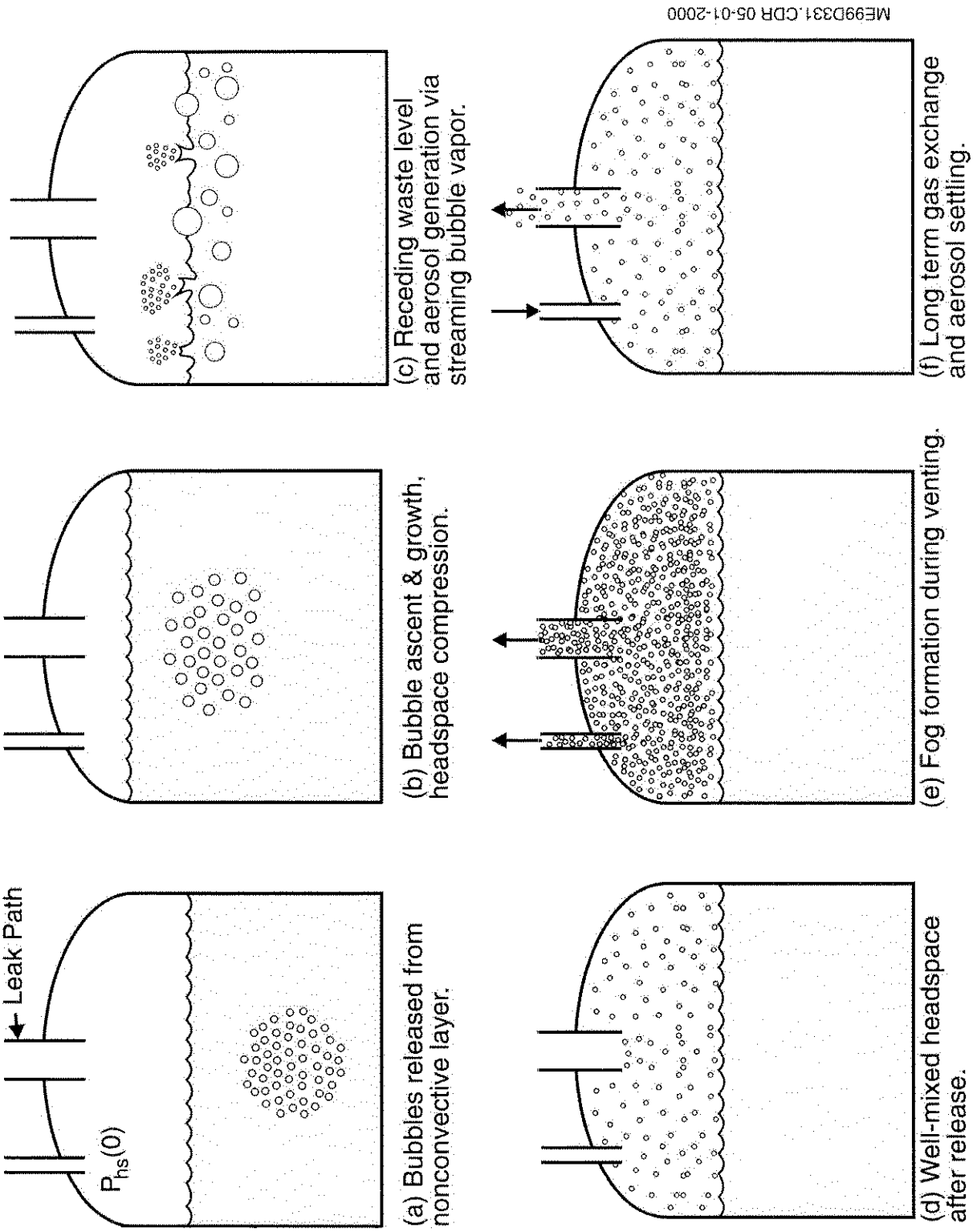
The envisioned sequence of events that result in liquid waste release from a tank during a steam bump is illustrated in Figure 5-1. Gas released from the non-convective layer forms a cluster of fine bubbles at the bottom of the convective layer or supernatant (Figure 5-1a). The cluster rises and grows due to the growth of the numerous individual bubbles that comprise the cluster. The bubbles' demand for volume causes the liquid surface to rise and the headspace gas to compress (Figure 5-1b). If the waste surface rises above the location of an open vent, the combination of a high waste level relative to the elevation of the vent opening and a pressurized headspace causes liquid to flow from the tank to the outside. Steam bump model results show that this mode of waste release to the outside does not occur because the vent openings are located close to the tank dome. Ultimately, the bubbles reach the surface of the waste. As the bubbles break through the surface, the release of bubble gas and vapor to the headspace is accompanied by the ejection of a spray of liquid waste (Figure 5-1c). Simultaneous bubble breakthrough and aerosol generation are assumed to occur instantaneously at the waste surface and result in a spatially uniform aerosol concentration within the headspace (Figure 5-1d). Finally, the venting pressurized headspace gas carries waste aerosol to the vent where it is released to the outside (Figure 5-1e). The addition of steam to the headspace via bubble breakthrough causes the headspace to expand to a saturated state before the depressurization process is over. Consequently, fog formation occurs during depressurization which contributes to the aerosol loading within the headspace. Subsequent aerosol transport to the outside may occur via natural ventilation flow over a relatively long time scale compared with the duration of the depressurization stage of the steam bump (Figure 5-1e).

5.2 BUBBLE AND WASTE ASCENT MODEL

The heart of the steam bump model are the equations for the rate at which the gas bubbles grow as they rise through the convective layer. Recall that equations (4-7) and (4-12) describe the bubble-interior diffusion-limited growth of a representative bubble. They are rewritten below in terms of the bubble volume normalized by the initial bubble volume and time t; that is,

$$\frac{d\left[P_v\, V_b\, /\, V_b\,(0)\right]}{dt} = \left[\frac{24\, D\, U_b}{V_b\,(0)} \cdot \frac{V_b}{V_b\,(0)}\right]^{1/2} P_{mix}\, \ln\left[1 + \frac{P_{eq}\left(T_\ell\right) - P_v}{P_{mix} - P_{eq}\left(T_\ell\right)}\right] \qquad (5\text{-}1)$$

Figure 5-1. Sequence of Events in Model of Steam Bump and Liquid Waste Release.



$$\frac{V_b}{V_b(0)} = \frac{P_{hs} + \rho_\ell \, g \, H - P_{eq}\left(T_\ell\right)}{P_{mix} - P_v} \tag{5-2}$$

where $P_{mix} = P_{hs} + \rho_\ell \, g \left(H - z_{bc}\right)$ (5-3)

The symbol $V_b(0)$ in the group 24DU / $V_b(0)$ is the volume of a representative bubble. As already mentioned, equations (5-1) and (5-2) are valid for both an isolated bubble and a cluster of bubbles, i.e., $V_{bc}(z) / V_{bc}(0) = V_b(z) / V_b(0)$ where V_{bc} is the bubble cluster volume and $V_{bc}(z) / V_{bc}(0)$ represents the volume expansion ratio of the bubble cluster at time t or at location z above the bottom of the convective layer (at z = 0). The instantaneous location z_{bc} of the center of the bubble cluster is related to time by the differential equation

$$\frac{d\, z_{bc}}{dt} = U \tag{5-4}$$

where U is given by equation (4-13) for the rise velocity of a bubble cluster. In terms of the total volume of the bubbles in the cluster, this equation becomes:

$$U = 0.76 \left(g^3 \, V_{bc}\right)^{1/6} \tag{5-5}$$

The value of $P_{eq}(T_\ell)$ in equations (5-1) and (5-2) depends on whether the bubbles are surrounded by supernatant liquid or, in the event of a buoyant displacement, by buoyant sludge (non-convective) interstitial liquid. In the former case, T_ℓ is limited by the boiling point of the supernatant at essentially atmospheric pressure; while in the latter case, T_ℓ may exceed this limit. For the buoyant displacement case, T_ℓ is a time-varying function which is determined by the mixing process which takes place between the buoyant parcel and the surrounding supernatant. This mixing process is different than the mixing process discussed at the end of Section 4.2, which occurs via a vertical buoyancy-dominated turbulent diffusion mechanism just as the parcel tries to emerge from the non-convective layer. In what follows, the mixing process is driven by the momentum carried by the buoyant parcel after it separates completely from the non-convective layer and while it rises to the surface of the waste.

To calculate the rate of mixing of the buoyant parcel with the supernatant, we adopt the now-classical entrainment assumption (Morton et al. 1956) which states that the mean supernatant inflow (entrainment) velocity v_{en} across the edge of the parcel is proportional to the instantaneous rise velocity U of the parcel; that is,

$$v_{en} = E_o \, U \tag{5-6}$$

where E_o is the so-called entrainment coefficient with an experimentally determined value of approximately 0.1. Equation (5-6) has proved enormously successful as an effective way of quantifying gas-phase and liquid-phase mixing problems involving jets, plumes, or buoyant puffs over a very wide range of scales (see, e.g., Briggs [1969] and Turner [1973]).

The instantaneous liquid mass m_ℓ within the buoyant parcel may be determined from the continuity equation

$$\frac{d\,m_\ell}{dt} = \rho_\ell\, v_{en}\, A_{bp} - \dot{m}_v \tag{5-7}$$

where ρ_ℓ is the liquid density, $\dot{m}_v$ is the mass rate at which liquid is converted to vapor by bubble growth within the buoyant parcel, and A_{bp} is the instantaneous area of the boundary through which supernatant is entrained by the buoyant parcel:

$$A_{bp} = 4\pi\left(\frac{3}{4\pi}\right)^{2/3}\left(V_b + \frac{m_\ell}{\rho_\ell}\right)^{2/3} \tag{5-8}$$

The instantaneous mean temperature T_ℓ of the liquid mass within the buoyant parcel is predicted with the energy equation

$$m_\ell\, c_\ell \frac{d\,T_\ell}{dt} = -\rho_\ell\, v_{en}\, A_{bp}\, c_\ell \left(T_\ell - T_{CL}\right) - \dot{m}_v\, h_{fv} \tag{5-9}$$

where T_{CL} is the constant temperature of the convective layer and c_ℓ is the specific heat of the liquid. Note that in integrating equations (5-7) and (5-9), the mass of the solid component of the material released from the non-convective layer is included in the initial volume of m_ℓ. For the sake of simplicity, the differences between the liquid and solid densities and specific heats are not included in equations (5-8) and (5-9).

The important initial conditions for the numerical simulation of a buoyant displacement-induced steam bump are the total volume $V_b(0)$ of the bubbles and the mass $m_\ell(0)$ of liquid that participates in the buoyant displacement. Meyer et al. (1997) recommend the following formula for the volume of gas released to the headspace during a buoyant displacement:

$$V_b(0) = 750\,\frac{\alpha_{NB}\, h_{NCL}\, \tau_y}{P_{NCL}\, \rho_{CL}} \tag{5-10}$$

where τ_y is the yield stress of the non-convective material in Pa and α_{NB} is the neutral buoyant void fraction $\left(1 - \rho_{CL}/\rho_{NCL}\right)$. Equation (5-10) is an approximate result that Meyer et al. (1997) derived from a more cumbersome set of equations; it is a dimensional equation that requires the units h_{NCL} in m, ρ_{CL} in kg m^{-3}, and P_{NCL} in atm. Actually equation (5-10) is the Meyer et al. (1997) expression divided by (P_{NCL} - 1) P_{NCL}, since it is the volume of the gas in the just released buoyant parcel that is of interest here rather than the volume of gas released to the headspace. The leading coefficient in equation (5-10) was chosen to best match the gas release volumes from the tank buoyant displacement data. Equation (5-10) is applicable only to the relatively weak non-convective layers in the double-shell tanks for which $\tau_y \sim 100$ Pa. Once

$V_b(0)$ is determined from equation (5-10), the initial void-free mass of the buoyant parcel is estimated using

$$m_\ell(0) = \rho_{NCL} V_b(0) \left(\frac{1}{\alpha_{NB}} - 1 \right) \tag{5-11}$$

Another parameter of interest to tank bump consequence analysis is the frequency of a buoyant displacement event. The average time t_{BD} between any two buoyant displacement events can be shown to be (Meyer et al. 1997):

$$t_{BD} = \frac{V_b(0)}{G_g A_T h_{NCL}} \tag{5-12}$$

where A_T is the tank cross-sectional area and G_g is in m^3/m^3-days. Equation (5-12) is based on the Meyer et al. (1997) formulation for a right circular cylindrical displacement parcel; it may be derived as follows. Referring to the equation numbers in the Meyer et al. (1997) report, divide equation (4.5.11) by equation (4.5.3) and use equation (4.5.5) to eliminate the waste level rise rate dh / dt from the result. Regardless of whether or not the non-convective layer is at its boiling point, G_g in equation (5-12) is the volume of non-condensable gas generated per unit volume of non-convective material per unit time, since the non-condensable gas is responsible for the buoyant displacement (see Section 4.2).

The headspace pressure P_{hs} in equation (5-2) is as yet an unknown quantity. Early on, the dynamic interaction between cluster bubble growth and the simultaneous compression of the headspace atmosphere determines the instantaneous value of P_{hs}. Later, fog formation and open ventilation paths determine the value of P_{hs}. The steam bump simulations are carried out by inserting equations (5-1) to (5-9) into the HADCRT waste tank source term computer model. The HADCRT model has been described by Plys et al. (2002) and will not be belabored here. Suffice it to say that the model is capable of tracking in-leakage and vent-path flows, simultaneous fog formation and deposition within the headspace, waste aerosol released from the headspace to the outside, and waste aerosol that enters the headspace from below. With respect to waste aerosol that enters the headspace from below, it remains to write the equations that describe the rate of generation of liquid aerosol by gas bubble breakthrough.

5.3 AEROSOL RELEASE MODEL

To simplify the calculation of droplet generation by the mechanism of gas bubble breakthrough at the liquid surface, all the bubbles are assumed to pass through the surface simultaneously and, correspondingly, the supernatant pool suddenly collapses to its initial depth H(0). The volume of liquid waste aerosol V_a that enters the headspace air (hereafter referred to as entrained liquid) is given by the definition of the entrainment coefficient E (see e.g., Ginsberg [1983]; or Kataoka and Ishii [1984]):

$$V_a = E \left(\frac{\rho_{hs}}{\rho_\ell} \right) V_b (H) \tag{5-13}$$

where ρ_{hs} is the density of the compressed headspace air and $V_b(H)$ is the volume of the bubble cluster, both evaluated at the instant the cluster arrives at the liquid surface, that is when $z_{bc} = H$. The mass m_a of aerosol entrained is

$$m_a = V_a \rho_\ell = E \rho_{hs} V_b (H) \tag{5-14}$$

The droplets produced just above the waste surface will not all be carried off into the core of the headspace atmosphere. Only those droplets whose terminal velocities are less than the gas velocity generated by bubble break through will be carried off. Kataoka and Ishii (1984) have developed the following correlation of the data of Golub (1970) and Garner et al. (1954) for the entrainment coefficient of stable aerosol production above a liquid pool with gas sparging:

$$E = 7.13 \times 10^{-4} \left[\frac{\mu_g^4 \rho_g^2 \left(\rho_\ell - \rho_g\right)^3}{\sigma^9 g^5} \right]^{1/8} j_g^3 \tag{5-15}$$

where j_g is the superficial velocity of the sparging gas, μ_g and ρ_g are the viscosity and density of the bubble gas, respectively, and σ is the interfacial tension of the waste liquid. For the present application, j_g must be related to the velocity U(H) of the bubble cluster when it arrives at the waste surface. The void fraction α of bubble clusters, estimated from slow motion photography (Marble 1983), appears to be about 0.5. Moody (1986) opines that a better estimate is $\alpha = 2/3$, a value which is more consistent with bubble cluster rise velocities. It follows that

$$j_g = \alpha U (H) = \frac{2}{3} U (H) \tag{5-16}$$

Once the bubble cluster velocity U(H) at the waste surface is calculated, the mass of the entrained liquid can be determined from equations (5-14) to (5-16). This is the theoretical maximum quantity that can enter the environment.

A portion of the entrained liquid (aerosol) will escape from the tank early on by flow of pressurized headspace air through vents and leakage paths. Subsequently, over a much longer time span, a portion of the remaining aerosol may be released by free-convection-driven exchange flow between the outside and the tank headspace. If unfiltered leak paths are small or have high flow resistance, substantial aerosol release can only occur if the headspace pressure exceeds the HEPA filter failure pressure. The major results of the steam bump simulations are postponed until Section 8.0. However, it is useful at this point to discuss the predicted buoyant parcel temperature versus time trends because of their potential importance to aerosol production at the waste surface.

5.4 EXAMPLE CALCULATION

Due to the mixing of the buoyant parcel with the supernatant, the liquid component of the parcel is predicted to remain sub-cooled during its rise to the surface of the waste. Figure 5-2 shows the calculated temperature history (solid curve) of the parcel for a buoyant release of initial liquid mass 4,000 kg, initial void volume 32 m^3, and initial near-saturation temperature 391.5 K into an 8.0-m deep supernatant at 373 K and density 1,210 kg m^{-3}. See Appendix E for computational details and other inputs. The headspace pressure is constant and equal to atmospheric pressure. That is, the tank is assumed to be wide open to the outside. The dashed curve in Figure 5-2 represents the boiling point of the liquid in the buoyant parcel at the instantaneous location of the parcel. Clearly, since the boiling point always exceeds the parcel temperature, the only mechanism of vapor generation is evaporation at the surface of the bubbles that were originally trapped in the non-convective layer.

Suppose that the vessel remains effectively sealed during the period of buoyant parcel rise, and the temperature of the supernatant is assumed to be at its one-atmosphere boiling point. In this case, the liquid component of the parcel is predicted to be slightly superheated by several degrees relative to the atmospheric boiling point 373 K when the parcel reaches the surface, but sub-cooled relative to the boiling point at the peak tank pressure (see Figure 5-3). As the tank gradually depressurizes, the warm parcel liquid will spread out beneath the surface and ultimately it will begin to boil and produce steam at a rate dictated by the depressurization rate of the tank. Additional mixing may occur between the parcel liquid and the supernatant as the parcel spreads. Even if no credit is given for the additional mixing and an adiabatic evaporation process is assumed for the stratified parcel liquid, the steam flux across the waste surface is found to be small (< 0.1 ms^{-1}). Thus, the liquid aerosol above the waste surface is created by the busting of bubbles and the volume of the aerosol is found to be small compared with that of the aerosol produced earlier by the breakthrough of the bubbles transported to the free surface within the buoyant parcel.

5.5 NUMERICAL EVALUATION NOTE

To couple integration of bubble volume and vapor pressure with other quantities, the P_v term of equation (5-1) is expanded as follows. State variables describing bubble rise are the bubble cluster volume expansion ratio $v = V_{bc}(z) / V_{bc}(0)$ and vapor pressure in the bubble P_v which appear in equations (5-1) and (5-2), are recast as:

$$P_v \frac{d\,v}{dt} + v \frac{d\,P_v}{dt} = \sqrt{\frac{24\,D\,U_b\,v}{V_{b0}}}\; P_{mix} \ln\left[1 + \frac{P_{eq}\left(T_\ell\right) - P_v}{P_{mix} - P_{eq}\left(T_\ell\right)}\right] \tag{5-17}$$

$$\frac{d\,v}{dt} = \frac{d}{dt}\left[\frac{P_{hs} + \rho_\ell\, g\, H - P_{eq}}{P_{hs} + \rho_\ell\, g\,(H - z) - P_v}\right] \tag{5-18)a}$$

$$\frac{d\,v}{dt} = \left(\frac{1 - v}{\Delta P_g}\right)\frac{d\,P_{hs}}{dt} + \rho_\ell\, g \left(\frac{1 - v}{\Delta P_g}\right)\frac{d\,H}{dt} + \frac{\rho_\ell\, g\, v\, U}{\Delta P_g} + \frac{v}{\Delta P_g}\,\frac{d\,P_v}{dt} \tag{5-18)b}$$

Figure 5-2. Temperature History of Buoyant Parcel Compared With its Boiling Temperature; Open Headspace.

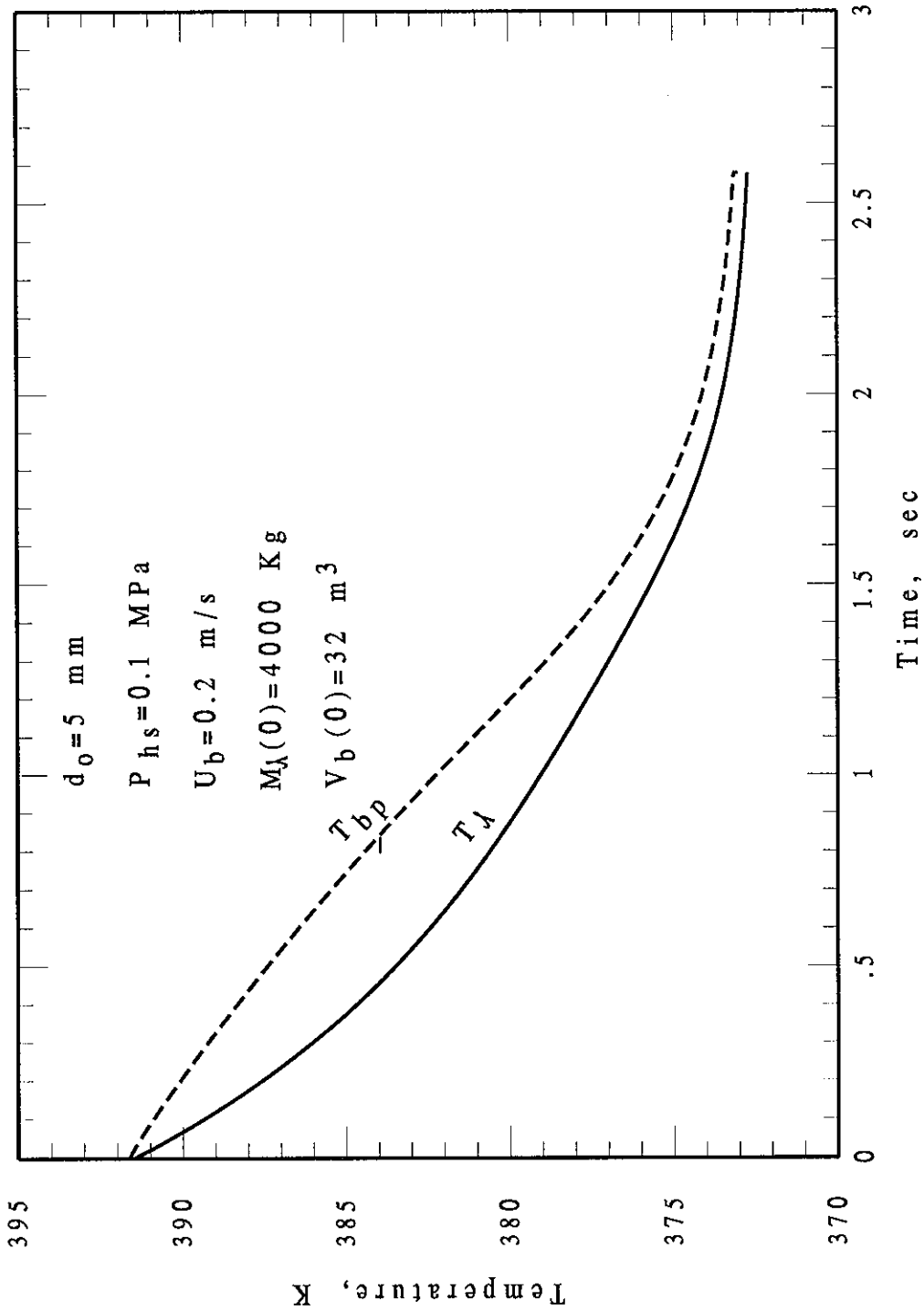
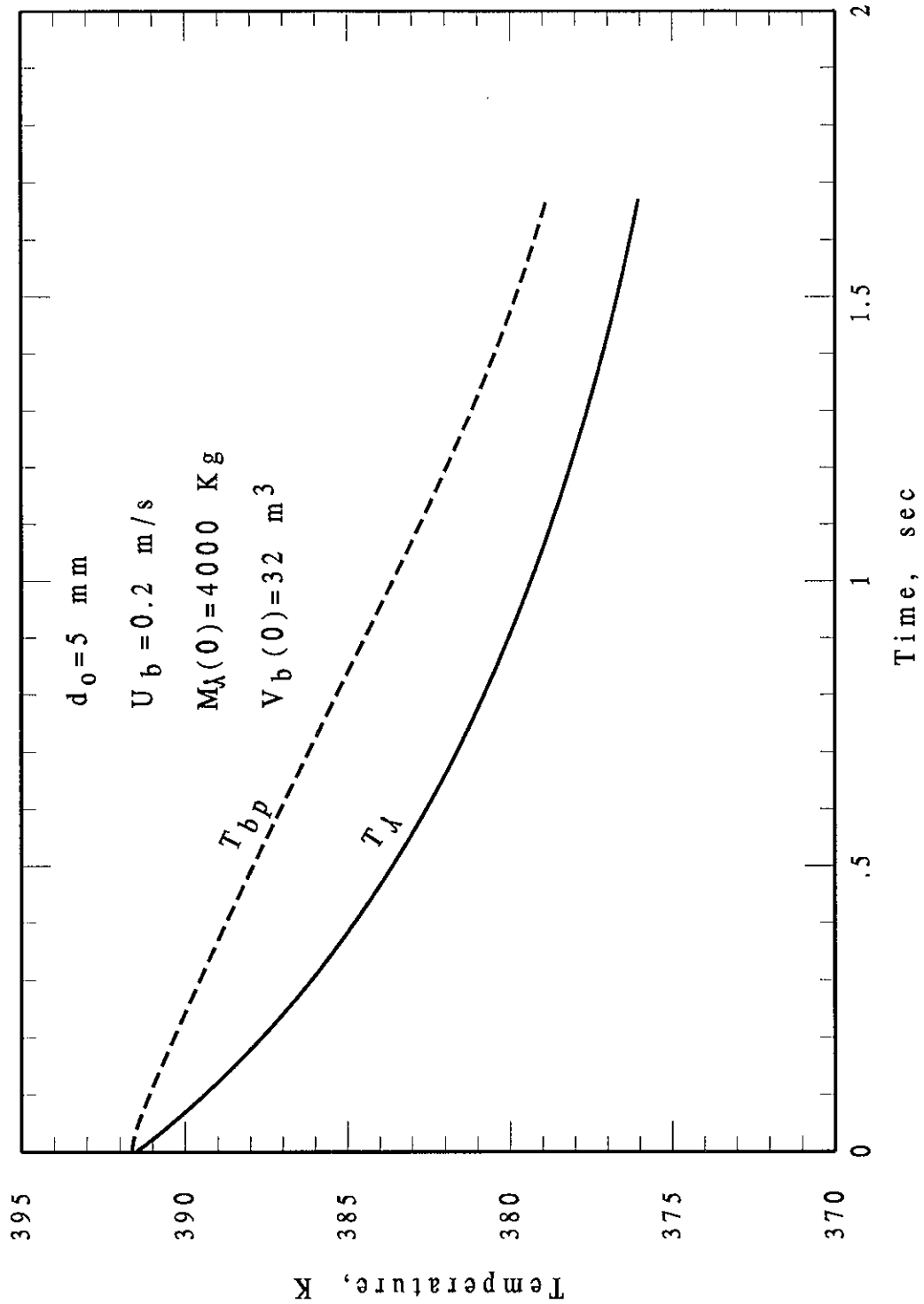


Figure 5-3. Temperature History of Buoyant Parcel Compared With its Boiling Temperature; Sealed Headspace.



where $\Delta P_g = P_{hs} + \rho_\ell \, g \, (H - z) - P_v$ (5-18)c

and $P_{mix} = P_{hs} + \rho_\ell \, g \, (H - z)$ (5-18)d

Derivatives other than dP_v / dt in equation (5-18) may be eliminated through auxiliary relations as follows. The headspace pressure derivative is given by

$$\frac{d\,P_{hs}}{dt} = \frac{P_{hs}}{m_{hs}} \frac{d\,m_{hs}}{dt} - \frac{P_{hs}}{V_{hs}} \frac{d\,V_{hs}}{dt} + \frac{P_{hs}}{T_{hs}} \frac{d\,T_{hs}}{dt} \tag{5-19}$$

The mass flowrate leaving the headspace is comprised of HEPA and leakage flow paths that can be quantified later:

$$\frac{d\,m_{hs}}{dt} = -W_{hs} \tag{5-20)a}$$

$$W_{hs} = W_{HEPA} + W_{leak} \tag{5-20)b}$$

$$W_{HEPA} = \rho_{hs} \left(\frac{P_{hs} - P_{amb}}{R_{HEPA}} \right) \tag{5-20)c}$$

The HEPA flowrate is directly proportional to pressure difference, and the standard compressible flow relation is used for leakage paths or in case of HEPA failure. The headspace volume derivative is simply

$$\frac{d\,V_{hs}}{dt} = -V_{bco} \frac{d\,v}{dt} \tag{5-21}$$

The headspace temperature derivative is found from the energy equation

$$m_{hs}\, c_{vhs} \frac{d\,T_{hs}}{dt} = -W_{hs} \left(c_{Phs} - c_{vhs} \right) T_{hs} + P_{hs}\, V_{bco} \frac{d\,v}{dt} \tag{5-22)a}$$

$$\frac{d\,T_{hs}}{dt} = -(\gamma - 1)\, T_{hs} \frac{W_{hs}}{m_{hs}} + (\gamma - 1)\, T_{hs} \frac{d\,v}{dt} \tag{5-22)b}$$

which allows the pressure derivative to be recast as

$$\frac{d\,P_{hs}}{dt} = -\frac{\gamma\, W_{hs}\, P_{hs}}{m_{hs}} + \frac{\gamma\, P_{hs}\, V_{bco}}{V_{hs}} \frac{d\,v}{dt} \tag{5-22)c}$$

Remaining derivatives required by equation (5-18) are

$$\frac{d\,z}{dt} = U \tag{5-23}$$

$$\frac{d\,H}{dt} = H_o \frac{V_{bco}}{V_\ell + V_{bco}} \frac{d\,v}{dt} \tag{5-24}$$

when equations (5-18) through (5-24) are combined, this yields an equation of the form

$$A_{12} \frac{d\,v}{dt} - \frac{v}{\Delta P_g} \frac{d\,P_v}{dt} = b_2 \tag{5-25)a}$$

$$A_{12} = 1 - \frac{1-v}{\Delta P_g} \left[P_{hs}\,\gamma_{hs} \frac{V_{bco}}{V_{hs}} + \rho_\ell\,g\,H_o \frac{V_{bco}}{V_{bco} + V_\ell} \right] \tag{5-25)b}$$

$$b_2 = \frac{\rho_\ell\,g\,U\,v}{\Delta P_g} - \left(\frac{1-v}{\Delta P_g} \right) \gamma_{hs}\,P_{hs} \frac{W_{hs}}{M_{hs}} \tag{5-25)c}$$

so that equations (5-17) and (5-25) may be solved simultaneously to calculate bubble cluster rise.

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6.0 BUMP CRITERIA MODEL APPLICATION

Current safe-storage conditions are first considered to find a short list of tanks that would be susceptible to bumps after a prolonged duration without active heat removal. In practice, this means that initial conditions for waste temperature are the Limiting Condition for Operation (LCO) rather than the current waste temperatures. The criteria developed in the previous sections are then applied to rationalize historic events shown in Table 3-1. Note that the criteria may be continually re-applied when reference tank conditions change.

6.1 APPLICATION OF TANK BUMP CRITERIA TO CURRENT TANK WASTE

This section applies the criteria developed in Section 4.0 to the Hanford SSTs and DSTs under a safe-storage off-normal scenario. This scenario assumes that the waste is undisturbed but there is no active system (ALCs, primary system ventilation or annular ventilation system) for heat removal.

Criteria are presented and ordered to create a graded approach from the easiest to most difficult to apply, and to leave successively fewer remaining tanks to screen. Individual tanks are excluded from further consideration if any of the following are true:

1. Supernatant depth does not exceed 1 m
2. There is an insignificant non-convective layer (<0.3 m)
3. Total tank heat load can be removed by steady-state conduction through the soil overburden (total tank heat load is less than 11,300 W)

The first criterion is obvious from the discussions of Section 3.0 and 4.0. The second and third criteria are derived here.

The second criterion states that to create bump conditions, the non-convective layer must exceed some minimum depth. Otherwise, the NCL simply follows the supernatant temperature and never reaches local saturation temperatures, as shown below. The third criterion states that tank bumps are not a concern if the tank heat load can be passively removed without nearing supernatant saturation temperature. Calculations below show that this occurs at or below 11,300 W.

An additional criterion has been proposed based on the analysis for Section 4.0. This criterion states that a steam bump from a quiescent state may not be possible without an initiating non-condensable gas, buoyant displacement gas release. This criterion is not applied at this time, however, because of its uncertainties.

To demonstrate the second criterion, consider the maximum temperature difference between the supernatant and the NCL:

$$\Delta T_{NCL} = \frac{Q'''_{NCL} X^2}{2k} \tag{6-1}$$

where Q''' is the volumetric heat generation rate, X is the NCL thickness, and k is the NCL thermal conductivity. This is the temperature rise across a heat-generating medium with fixed temperature on one side and adiabatic conditions on the other. In this instance, the top of the NCL will be very near the supernatant temperature, while in the absence of annulus ventilation the bottom may be regarded as adiabatic. If bounding volumetric heat generation rate $Q''' = 170$ W/m^3 (Tank 241-AZ-101 NCL), k = 0.7 W/m/K, and NCL thickness equals, say, 30 cm, the maximum temperature is 11 °C higher than the supernatant temperature. (Note the Tank 241-AX-104 NCL has a volumetric heat generation rate of over 500 W/m^3, but little inventory (7 cm)).

If the supernatant is 8 m deep and has pure water properties, saturation temperature increases to 117 °C at the NCL depth. Once the supernatant temperature reaches 100 °C, however, the maximum NCL temperature is constrained to 100 + 11 = 111 °C and buoyant displacement by vapor generation cannot occur. Equation (4-19) can be evaluated again using a temperature of 111 °C. This results in a gas generation rate about five times larger than that at the prevailing safe storage temperature of 75 °C. As seen in Tables 4-1 and 4-2, a five-fold increase in non-condensable gas generation is still way too low to bring the NCL to a buoyant condition.

Therefore, we adopt 30 cm as a screening criterion, based on the fact that for the bounding volumetric heat generation rate, the NCL cannot be made buoyant by either vapor generation or non-condensable gas generation. It is likely that 30 cm is a conservatively low value. Equation (4-16) suggests that relatively thick layers might not be able to achieve neutral buoyancy by non-condensable gas generation, but owing to model uncertainties, this likelihood is not considered further.

The third criterion is derived from the following steady-state conduction equation:

$$\dot{Q} = k_s A \Delta T \left(\frac{1}{\delta} + \frac{1}{R} \right) \tag{6-2}$$

where $\dot{Q}$ is the total heat removal in W, k_s is the soil thermal conductivity (1.0 W/m-K), A is the heat transfer area (411 m^2), ΔT is the difference between the maximum allowable tank dome temperature and the Hanford environment average temperature, and δ is the soil overburden, which has a nominal thickness of 4.0 m (Kummerer 1994). Assuming that the supernatant temperature and dome temperature are the same, the maximum allowable temperature is just a few degrees below the boiling point. With a site average temperature of 14 °C (Kummerer 1994), $\Delta T \approx 80$ °C is justifiable. Tank radius, R, is 11.0 m.

This expression describes upward and downward steady-state conduction, but neglects sideways heat conduction. Upward heat transfer rate is that for a planar slab held at the waste temperature, T, on one side and the average ambient temperature, T_i, on the other. Downward heat transfer rate is that for conduction through a circular region at temperature, T, in contact with a

semi-infinite medium at T_s (Carlslaw and Jaeger 1959). A simplifying assumption is that the soil temperature underneath the DST is equal to the average ambient temperature.

Considering SSTs, all but the two tanks listed in Table 3-5 fail Criterion #1, and are excluded on that basis. Table 6-1 lists DSTs with trivial non-convective layer depths, while Table 6-2 lists tanks that are excluded from further consideration based on a small heat load (< 11,300 W) and/or a small supernatant depth.

Table 6-1. Double-Shell Tanks With Negligible Non-Convective Layer.

241-AP-101
241-AP-102
241-AP-103
241-AP-104
241-AP-106
241-AP-107
241-AP-108
241-AN-101
241-AN-106
241-AW-102

Source:
Hu, T. A. and S. A. Barker, 2002, *Steady State Flammable Gas Release Rate Calculation and Lower Flammability Level Evaluation for Hanford Tank Waste*, RPP-5926, Rev. 2, CH2M HILL Hanford Group, Inc., Richland, WA.

Table 6-2. Single-Shell Tanks and Double-Shell Tanks With Small Heat Load and/or Small Supernatant Depth. (2 sheets)

Tank	Waste Depth (m)	Non-Convective Layer Depth (m)	Supernatant Depth (m)	Heat Load (W)
Single-Shell Tanks				
241-A-101	6.15	3.66	2.49	5,140
241-AX-101	6.18	3.31	2.87	5,210
Double-Shell Tanks				
241-AN-102	9.72	0.82	8.90	8,580
241-AN-103	8.32	3.73	4.58	9,030
241-AN-104	9.30	4.23	5.08	9,980
241-AN-105	10.18	4.31	5.86	6,980

Table 6-2. Single-Shell Tanks and Double-Shell Tanks With Small Heat Load and/or Small Supernatant Depth. (2 sheets)

Tank	Waste Depth (m)	Non-Convective Layer Depth (m)	Supernatant Depth (m)	Heat Load (W)
241-AN-107	9.60	2.28	7.32	10,000
241-AP-105	10.47	0.82	9.65	4,310
241-AW-101	10.17	3.35	6.82	8,760
241-AW-103	10.16	2.88	7.27	2,060
241-AW-104	2.91	2.05	0.86	1,080
241-AW-105	3.94	2.35	1.58	702
241-AW-106	2.76	2.20	0.55	1,500
241-AY-101	1.69	0.80	0.75	8,800
241-SY-101	8.80	2.40	6.40	4,690
241-SY-102	9.54	0.66	8.88	7,150
241-SY-103	6.72	2.96	3.76	6,050

Source:
Hu, T. A. and S. A. Barker, 2002, *Steady State Flammable Gas Release Rate Calculation and Lower Flammability Level Evaluation for Hanford Tank Waste*, RPP-5926, Rev. 2, CH2M HILL Hanford Group, Inc., Richland, WA.

Note that Tanks 241-AN-106 and 241-AW-102 fail on account of supernatant depth and total heat load (Criterion #3). From an operational standpoint, these DSTs can be excluded on the basis of total tank power alone, which means that a variable supernatant level is not a concern.

6.2 ANALYSIS OF TIME TO SATURATED CONDITIONS

For DSTs that fail the three simple screening criteria, tank bump conditions may be postulated. In this section we find the time required to reach saturated conditions for these DST, so as to judge the likelihood (frequency) of tank bumps conditions. If the time to saturated conditions is far in excess of the time needed to repair or restore active ventilation, the likelihood of a tank bump is very small. In Section 7.0, we consider repair times for the DST ventilation system.

AZ and AY DSTs require detailed calculation because there is a significant temperature difference between the convective and non-convective layers. An energy balance can be written for each layer:

$$\rho_{CL}\, V_{CL}\, c_{CL} \frac{d\,T_{CL}}{dt} = \dot{Q}_{CL} - \frac{k_s\, A}{\delta}\left(T_{CL} - T_{\infty}\right) + h_{ex}\, A\left(T_{NCL} - T_{CL}\right) \qquad (6\text{-}3)$$

$$\rho_{NCL}\ V_{NCL}\ c_{NCL}\ \frac{d\,T_{NCL}}{dt} = \dot{Q}_{NCL} - \frac{k_s\ A}{R}\left(T_{NCL} - T_s\right) - h_{cx}\ A\left(T_{NCL} - T_{CL}\right) \qquad (6\text{-}4)$$

where symbols and subscripts are defined as before (see Sections 3.5.1 and 6.1). A heat transfer coefficient, h_{cx}, is defined for exchange between the two layers. This heat transfer coefficient is sized so that in the quasi-steady approximation,

$$\frac{d\,T_{CL}}{dt} = \frac{d\,T_{NCL}}{dt} \qquad (6\text{-}5)$$

For DSTs 241-AZ-101 and -102, this system of equations was integrated using inputs from Hu and Barker (2002), which lists initial convective layer temperature, non-convective layer temperature, inventories, and heat loads for each layer. Use the site average air temperature of 14 °C for T_∞ and a soil temperature of 12 °C for T_s (Kummerer 1994).

Accounting for vapor pressure suppression by dissolved salts, bump conditions exist when supernatant temperature reaches 104 °C and the NCL reaches saturated conditions at mid-height. See Appendix H for details. We do not consider tank-specific data, but rather adopt a convenient expression stating that supernatant vapor pressure is 85% of the pure water vapor pressure (Crea et al. 2000). This means that boiling occurs when vapor pressure equal 119,235 Pa, rather than 101,350 Pa. Steam tables for pure water show that a vapor pressure of 119,235 Pa occurs when temperature equals at just over 104.5 °C; we round down to 104 °C here to define supernatant saturation temperature. In a similar vein, consider that for Tank 241-AZ-102, the supernatant height is 8.23 meters and hydrostatic pressure at the NCL is 193,389 Pa. After adjusting for 85% vapor suppression, vapor pressure is 227,516 Pa at boiling conditions. Steam tables show that this occurs at just over 397 K, so 124 °C is selected as the definition of saturated conditions in the NCL. Repeating the calculation for Tank 241-AZ-102, yields 125 °C. The slight difference in saturation temperatures can be explained by the Tank 241-AZ-102 supernatant density, which is slightly higher than that for Tank 241-AZ-101.

For Tanks 241-AZ-101 and 241-AZ-102, calculation inputs and the temperature rates of change are listed in Table 6-3. Calculational details are provided in Appendix G. This keeps the solution of equations (6-3) and (6-4) general and applicable for various combinations of total heat load and initial conditions. A parametric study for temperature rise as a function of heat load is performed to find heat-up rate (see Appendix G), considering Tank 241-AZ-101 first. Nominal total tank heat load is 60.4 kW, with a supernatant heat load of 26.7 kW, and NCL heat load of 33.7 kW. Starting from LCO conditions (supernatant temperature = 195 °F and NCL temperature = 215 °F), the resulting heat up rate is 0.31 °C/day. This calculation was repeated with heat loads of 40 kW and 80 kW. In each case, the heat load in the NCL was 60% of the total. The solution for heat up rate can be expressed by the following expression:

$$dT / dt = 0.00587\ Q - 0.06604\ °C/day$$

where Q is the DST heat load in kW. For the DST 241-AZ-101 waste inventory, this expression is valid down to 11.3 kW regardless of the heat load distribution between supernatant and NCL; note setting (dT / dt) to zero results in Q equal to 11.3 kW, as expected. The heat up rate actually

has a slight dependence on waste temperature, but the equation is based on the initial heat up rate and is conservative with respect to heat losses because waste temperature is at a minimum. Heat up rate decreases over time because heat losses increase with increasing waste temperature.

Table 6-3. Heat-up Rates for AZ Double-Shell Tanks.

DST	CL Density, (kg/m^3)	NCL Density, (kg/m^3)	T_{NCL}, (K)	T_{CL}, (K)	CL Volume, (m^3)	NCL Volume, (m^3)	Heat-up Rate[1], (°C/day)
241-AZ-101	1,240	1,620	375	364	3,377	197	0.0058 Q – 0.066
241-AZ-102	1,140	1,380	375	364	3,377	397	0.006 Q – 0.068

[1]Calculations assume Q (total heat load) is in kW, soil conductivity = 1.0 W/m-K, heat transfer area = 411 m^2, tank radius = 11.0 m, CL specific heat = 3,300 J/kg/K, and NCL specific heat = 2,850 J/kg/K.

CL = convective layer.
DST = double-shell tank.
NCL = non-convective layer.

Knowing the heat-up rate, it is simply a matter of determining initial temperatures and bump condition temperatures (saturated conditions) to determine the time to bump conditions. With the quasi-steady approximation, the two layers have the same heat-up rate. If applied to initial conditions below the LCO, the heat up rate given by this equation is a good approximation to the average heat up rate between initial and saturated conditions.

The process can be repeated for Tank 241-AZ-102 and the resulting heat-up rate equation is found to be 0.0060 Q - 0.068 °C/day, where Q is in kW (see Appendix G). This equation was derived for heat loads between 20 kW and 40 kW. Heat up rates for Tanks 241-AZ-101 and 241-AZ-102 are very close, which demonstrates that if the quasi-steady approximation is satisfied, only the total tank heat load and inventory (heat capacity) are needed to compute heat up rate. These equations should not be applied to DST with inventories that differ from 241-AZ-101 and 241-AZ-102 – tanks that have a thin NCL layer and very deep supernatant. The quasi-steady approximation is satisfied when NCL thickness is less than a meter.

As an example of time to bump calculation, consider the Hu and Barker (2002) heat loads for Tanks 241-AZ-101 and 241-AZ-102, which are 60.4 kW and 32.4 kW, respectively, and the safe storage condition temperatures. For Tank 241-AZ-101, waste temperatures are 75 °C for the NCL and 64 °C for the supernatant. With a heat up rate of 0.31 °C/day, it would take 130 days for the Tank 241-AZ-101 supernatant to reach the saturation condition of 104 °C.
Hu and Barker (2002) report 72 °C as temperature for both the Tank 241-AZ-102 supernatant and NCL. With the heat up rate of 0.13 °C/day, it would take 246 days for the supernatant to reach saturated conditions.

We repeat calculations for Tank 241-AZ-101, but start from LCO conditions, which are 90 °C in the supernatant and 101.7 in the NCL. It would take 45 days [(104 – 90) °C / 0.31 °C/day] to reach saturated conditions in the supernatant.

6.3 APPLICATION TO HISTORIC EVENTS

The historic events shown in Table 3-1 can be better understood in light of the discussion in this section. The most important aspect of Table 3-1 is that the tank heat rates greatly exceed even the highest current tank heat loads. For the historic tanks, the time to bump conditions would have been much less than the 100 days or so predicted for the present AZ DSTs, and without a sufficient ventilation flowrate, bumping could have been expected shortly after the tank was filled, even without an initiator. For example, Tank 241-S-104 was filled in July 1953, and began bumping in October of 1953, despite the installation of auxiliary water-cooled condensers (Tomlinson 1955). In Tank 241-S-101, bumping began in January 1954. In both cases, the waste temperature at the bottom probably exceeded the saturation temperature at the bottom hydrostatic pressure. This was definitely the case in the other events, where the temperature at the bottom was anywhere between 260°F and 357°F. This can be compared to the value used in this section as the bump criterion for, say, Tank 241-AZ-101, which is 398 K, or 257°F.

Finally, we note that a number of later bump events were initiated by ALC restart after shutdown, and observed behavior is in qualitative according to expectations based on Section 4.1.

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7.0 CONTROL STRATEGY EVALUATION

A tank bump requires loss of active waste cooling functions for an extended period, given the requisite conditions of waste volumetric heat generation, supernatant depth, etc., described in the previous section. The control strategy is to monitor waste temperature and require actions to restore cooling when the temperature exceeds a specified limit. This control strategy works if there is sufficient time available to discover the increasing temperature event and restore cooling prior to the waste reaching accident conditions (i.e., saturation temperature). The results of Section 6.0 show that the main active waste cooling function of interest is the AZ/AY ventilation system. Control strategy evaluation consists of two parts. First, find the minimum ventilation flow rates needed to prevent bump conditions. Then, given that ventilation is lost, find the probability that it can (or cannot) be recovered before the supernatant reaches bump conditions.

7.1 MINIMUM VENTILATION FLOW RATE REQUIREMENTS

In this section, we determine the minimum ventilation flow rate requirements for Tank 241-AZ-101 and then parametrically study a range of DST heat loads.

7.1.1 Minimum Primary Ventilation Flow Rate for DST 241-AZ-101

An approximate analytical solution for the steady-state, minimum primary ventilation flow rate can be found using the following assumptions:

- There is no conduction heat transfer to surrounding soil,
- Primary ventilation flow rate is constant,
- Incoming air is dry,
- Thermal properties are constant, and
- Supernatant is replenished to match evaporative losses.

The first assumption also means that annulus ventilation is conservatively ignored. This is appropriate because we have demonstrated that if the supernatant is sufficiently sub-cooled, bump potential is negligible regardless of NCL conditions. The fourth assumption is needed to assure a true steady-state. For large DST heat loads, annual evaporative losses could reduce level by many centimeters. For this analysis, it does not matter if the supernatant is replenished by recirculation of condensate or water addition, as long as losses are matched.

Analysis proceeds much like that in Epstein (1988), except that the water mass fraction in the headspace is computed. As shown in Section 3.2.1, Epstein (1988) computed heat removal due to evaporative cooling under the assumption that headspace water mass fraction is zero. Here we

relax that assumption, but assume that the incoming air has no water. This is appropriate because the DST headspace will be hot and humid for the minimum ventilation rate, which makes any incoming moisture a negligible part of the overall water mass balance.

Using the analogy between heat and mass transfer, the latent heat transfer from the pool surface is given by Epstein (1988):

$$Q = 0.156 \frac{h_{fg}\, D\, \rho\, A}{(\alpha\, \nu / g)^{1/3}} (Y_s - Y_\infty) \left[\frac{T_s - T_\infty}{T_\infty} + (Y_s - Y_\infty) \left(\frac{M_a}{M_w} - 1 \right) \right]^{1/3} \tag{7-1}$$

where λ is latent heat of water (2.2 MJ/kg), D is the diffusion coefficient of water vapor into air $\left(2 \times 10^{-5}\ m^2/s\right)$, ρ is gas density, ν is the kinematic viscosity of air/water vapor $\left(2 \times 10^{-5}\ m^2/s\right)$, α is the thermal diffusivity of air/water vapor $\left(2.5 \times 10^{-5}\ m^2/s\right)$, g is the acceleration of gravity, Y is water vapor mass fraction, T is temperature, M_a is the molecular weight of air (28.9 kg/kg-mole), M_w is the molecular weight of water (18 kg/kg-mole), subscript "s" refers to the supernatant surface, and the infinity subscript refers to the tank headspace conditions.

In equation (7-1) above, Q, T_s, and T_∞ are either known or selected. The total heat load for Tank 241-AZ-101 is 60.4 kW. Select the maximum supernatant temperature, T_s, to be 90.0 °C (~ 195 °F). A good assumption for the DST is that the headspace temperature is close to the supernatant temperature; i.e., $T_s \approx T_\infty$. This means that the term $(T_s - T_\infty) / T_\infty$ in brackets can be ignored.

Water vapor mass fraction at the surface Y_s is calculated from the vapor pressure of water at T_s, PP_s:

$$Y_s = \frac{1}{1 + \left(\frac{101350}{\chi\, PP_s} - 1 \right) \frac{M_a}{M_w}} \tag{7-2}$$

where PP_s is known from the steam tables or vapor pressure correlation and χ is the activity coefficient that accounts for vapor suppression by salts dissolved in the supernatant. Water vapor in the gas headspace can be determined from a mass balance, knowing the ventilation flow rate, W_{air}, and the evaporation rate, W_v:

$$Y_\infty = \frac{W_v}{W_v + W_{air}} \tag{7-3}$$

with W_v known from Q / h_{fg}. The first equation can be re-written as:

$$W_v = 0.156 \frac{D\, \rho\, A}{(\alpha\, \nu / g)^{1/3}} (Y_s - Y_\infty) \left[(Y_s - Y_\infty) \left(\frac{M_a}{M_w} - 1 \right) \right]^{1/3} \tag{7-4}$$

The end result is a system of two equations and two unknowns (W_v and Y_∞) that can be solved iteratively. Assuming $\chi = 85\%$, W_{air} equals 0.034 kg/s (64 cfm), and Y_∞ equals 0.43. Results are shown in Table 7-1.

Table 7-1. Results for Tank 214-AZ-101
Minimum Primary Ventilation Flow Rate

Symbol	Definition	Value
T_s	*liquid surface temperature, °C*	90.0
Y_∞	*water vapor mass fraction in the gas space*	0.4367
Eq. (7-3)	$W_v / (W_{air} + W_v)$	0.4367
W_{air}	*ventilation flow rate, kg/s*	0.034
PP_s	*partial pressure of steam at the surface, Pa*	59235.00
Y_s	*water vapor mass fraction at surface*	0.467
W_v	*evaporation flow rate, kg/s*	0.0264
Q_v	*heat removal, W*	60400

Repeating the calculation with 100 kW, 175 kW, and 250 kW, produces values of 112, 217 and 337 cfm, respectively. Again, these values are predicated on condensate reflux or inventory makeup. If supernatant temperature is allowed to increase to 90 °C, tank bump potential is negligible, but evaporative losses are very significant and can be measured in meters of level per year.

7.1.2 Validation of Minimum Primary Ventilation Flow Rate Calculations

These calculations can be easily validated by showing that the model predicts the current conditions. Set the heat load to 49,100 W (60,400 minus the amount removed by conduction, which is 11,300 W) and the ventilation rate to the actual value, which is roughly 300 cfm. Note that we ignored conduction in the calculations above, but consider it here to obtain a best-estimate answer. Then find the corresponding liquid surface temperature and confirm that it matches the measured value. Calculation results are shown in Table 7-2. For the inputs shown, the calculated liquid surface temperature of 64.9 °C (PP_s = 20991 Pa) is in good agreement with the measured supernatant temperature (64 °C), thereby demonstrating that the calculation is sufficient to predict temperature given ventilation flow rate, or vice versa. To estimate conditions in Tank 241-AZ-102, calculations were repeated with ventilation flow rate equal to 300 cfm and heat load equal to 21,100 W (32,400 – 11,300 W). This results in a liquid

temperature of 49.6 °C, which is in good agreement with the observed dome temperature of 46 °C.

Table 7-2: Results for Tank 214-AZ-101
Primary Ventilation Flow Rate Validation

Symbol	Definition	Value
T_s	*liquid surface temperature, °C*	64.9
Y_∞	*water vapor mass fraction in the gas space*	0.1181
W_{air}	*ventilation flow rate, kg/s*	0.1600
W_{air}	*ventilation flow rate, cfm*	301.3137
PP_s	*partial pressure of steam at the surface, Pa*	20991.37
Y_s	*water vapor mass fraction at surface*	0.140
W_v	*evaporation flow rate, kg/s*	0.0214
Q_v	*heat removal, W*	49100

7.2 FAILURE TO RECOVER PROBABILITY

In a study that presents the probability of schedule delays for delivery of high-level waste feed batches, the reliabilities of the primary heating, ventilation, and air conditioning (HVAC) system, the annulus HVAC system, ancillary HVAC systems, the ALCs, and miscellaneous support systems have been considered for Tank 241-AZ-101 waste transfer operations (Carlson 1999a and 1999b). Schedule delays were estimated by creating individual reliability, availability, and maintainability (RAM) models for each of the following contributors: primary HVAC, annulus HVAC, service air, transfer system, monitoring system, recirculation condenser, human errors, ventilation condenser system, and external events. In the RAM, the ALC system is modeled within the service air system. The primary HVAC system consists of individual air inlets, filters, an exhaust condenser, a high-efficiency mist eliminator, redundant exhaust fans and filter banks, and an exhaust stack with radiological sampling equipment. Individual RAM models were built for the annulus HVAC, ventilation condenser cooling, and recirculation condenser cooling.

By using 10,000 simulated waste transfer operations, Carlson's (1999b) studies found the number of "off-normal" events that occurred and the delay due to each event. In summary, out of 10,000 simulated batch transfer events, 8 delay events can be expected on average, with a mean delay per event of 43 hours. The breakdown by system contribution is shown in Table 7-3. The results of this study will be adapted to find recovery times for loss of ventilation under LCO conditions. A key assumption is that the individual recovery times for restoration and/or corrective maintenance as determined by the waste feed delivery RAM can be applied to the safe storage scenario.

Table 7-3. Critical Items List for the High-Level Waste Transfer RAM B, Ranked by the Contribution of System Type to Expected Schedule.

System Type	Expected No. of Delay Events	Expected Delay per Event (hrs)	Total Expected Delay Time (hrs)	Percent Contribution to No. of Events	Percent Contribution to Total Delay
Total	8.0	43	341	100%	100%
HVAC Primary	2.32	37	85	29.0%	25.0%
HVAC Annulus	1.22	52	64	15.3%	18.7%
Transfer	2.23	28	62	28.0%	18.2%
Service Air	0.61	88	54	7.7%	15.9%
Monitoring	0.22	167	37	2.8%	10.9%
Vent Cond. Cooling System	0.38	27	10	4.8%	3.0%
Raw Water	0.10	31	3	1.2%	0.9%
Dilution/Flush	0.01	168	2	0.1%	0.6%
Nitrogen	0.00	1006	2	0.02%	0.6%
Instrument Air	0.06	30	2	0.7%	0.5%
Process Air	0.04	29	1	0.5%	0.4%
Service Water	0.003	131	0.4	0.04%	0.1%
Instrumentation	0.01	34	0.3	0.1%	0.1%
Electric Power	0.01	6	0.03	0.1%	0.01%

Source:

Carlson, A. B., 1999b, *Waste Feed Delivery System Phase 1 Preliminary Reliability, Availability, Maintainability Analysis*, HNF-2863, Rev. 1, Numatec Hanford Corporation, Richland, Washington.

HVAC = heating, ventilation, and air conditioning.

Failure to recover probability consists of two components: failure to restore ventilation within the available time and failure to enact corrective maintenance within the available time. Restoration considers that ventilation system functions can be recovered without repair in many instances by manual switchover for functions with redundant hardware. This was recognized and accounted for in the waste transfer RAM by developing probability density functions for restoration times and determining whether recovery from an off-normal event required a restoration function or a corrective maintenance function. A key assumption was that if the first component failed, the backup component would run with negligible failure rate until the main component could be repaired. For the most part, restoration functions inside a tank farm fence required an expected value (mode) of one day, with a maximum time of one week.

From Table 7-3, it is clear that most, but not all, recoveries involved restoration actions rather than corrective maintenance actions. This is because expected delays were on the order of two days, which is much less than the expected corrective maintenance times. A description of corrective maintenance activities is given in Table 7-4, and log-normal distributions (low = 5th percentile and high = 95th percentile) for clock hours to complete these activities are shown in Table 7-5. From Table 7-4, activities requiring tank farm radiological access are considered to

estimate corrective maintenance times; in response to ventilation system failures, activities requiring pit or tanks access are not expected, as are activities not requiring radiological access. Activities requiring tank farm radiological access have identifiers TRISA, TRIEL, TCIEL, TCNSA, and TCNEL. For these activities, 200 hours is representative of a mean time for corrective maintenance. An estimate of the fraction of recovery activities that are restoration functions rather than corrective maintenance activities is calculated using the following expression:

$$t_d = x_{rs}\, t_{rs} + \left(1 - x_{rs}\right) t_{CM} \tag{7-5}$$

where t_d is the mean delay time, x_{rs} is the fraction of events that requires restoration rather than corrective maintenance, t_{rs} is the mean restoration time, and t_{CM} is the mean corrective maintenance time. Assuming the mean delay time is 37 hours, the mean restoration time is 24 hours and the mean corrective maintenance time is 200 hours, x_{rs} equals 93%. Assuming the mean restoration time is very small, but the mean corrective maintenance time is still 200 hours, x_{rs} equals 82%. In application, x_{rs}, is taken to be 85% as a point-estimate.

Table 7-4. Component Types and Recovery Conditions. (2 sheets)

Recovery ID	Basic Description	Component Repair Effort Category								
		1	2	3	4	5	6	7	8	9
PRIML	Definition: Pit or Tank Access, Remote Handled, Moderate Planning, Long Lead Spares. Examples: new or a replacement jumper, initial installation of a mixer pump.					X				
PRIEL	Definition: Pit or Tank Access, Remote Handled, Extensive Planning, Long Lead Spares. Examples: Pump removal /replacement, thermocouple tree removal/replacement.	X				X			X	
PCIML	Definition: Pit or Tank Access, Contact Handled, Moderate Planning, Long Lead Spares. Example: Replace valve/piping components (waste contacted surfaces) on an existing jumper that has been removed and is intended to be reinstalled.					X			X	
PCIEL	Definition: Pit Access Only (no tank access), Contact Handled, Extensive Planning, Long Lead Spares. Examples. This includes, for example, the investigation and repair of frozen or non-rotating pump impellers, the replacement of valve actuator components.	X		X		X			X	
TRISA	Definition: Tank Farm Rad area access, Remote Handled /Intrusive, Simple Planning, Spares Available. Examples: pre-approved maintenance procedure, semi-routine actions.									

Table 7-4. Component Types and Recovery Conditions. (2 sheets)

Recovery ID	Basic Description	Component Repair Effort Category								
		1	2	3	4	5	6	7	8	9
TRIEL	Definition: Tank Farm Rad area access, Remote Handled, Moderator to Extensive Planning, Long Lead Spares. Examples: Removal/replacement of vent system de-entrainer or mist eliminator elements.					X				
TCISA	Definition: Tank Farm Rad area access, Contact Handled /Intrusive, Simple Planning, Spares Available. Examples: Routine removal/replacement of consumable components, process instrument (pressure, temperature, and flow device) calibrations.	X				X	X			
TCIEL	Definition: Tank Farm Rad area access, Contact Handled/Intrusive, Mod to Extensive Planning, Long Lead Spares. Examples: Remove/replace ENRAF, contaminated piping/ducting weld repairs, primary vent heater element replacement.			X		X				
TCNSA	Definition: Tank Farm Rad area access, Non-intrusive (non-Contact), Simple Planning, Spares Available. Examples: replacing roughing (pre) filters, CAM vacuum pump replacement.	X	X	X		X	X	X		X
TCNEL	Definition: Tank Farm Rad area access, Non-intrusive, Mod to Extensive Planning, Long Lead Spares. Examples: Non-routine maintenance on electrical feeds/motor control centers, primary vent system fan wheel replacement.	X	X	X		X				
NCNNA	Definition: Non-Radiological area access, Minimum Planning, Spares Available. Examples: Infrastructure repairs, site utility, and Refrigeration and Equipment Services (RES) team support.	X	X	X	X	X	X			X
NCNEL	Definition: Non-Radiological area access, Moderate to Extensive Planning, Long Lead Spares. Examples: major component rebuilds/replacements.	X		X	X	X		X		

Source:

Carlson, A. B., 1999a, *Waste Feed Delivery Technical Basis, Volume IV: Waste Feed Delivery Operations and Maintenance Concept*, HNF-1939-Vol. IV, Rev. 0, Numatec Hanford Corporation, Richland, Washington.

Component Repair Effort Categories:

1 = I&C General
2 = I&C Special
3 = Electrical Onsite
4 = Electrical Offsite
5 = Mechanical General
6 = HVAC Special
7 = Computer
8 = Mechanical Major
9 = Support Facilities

Table 7-5. Summary of Corrective Maintenance Requirements (Clock Hours and Effort). (2 sheets)

Recovery Time Description	Recovery Time ID	Range Factor	Clock Hours Required to Complete a Corrective Maintenance		
			Low	Mean	High
I&C COMP, NCNEL	1NCNEL	2	44	96	176
I&C COMP, NCNNA	1NCNNA	1.5	23	36	52
I&C COMP, PCIEL	1PCIEL	3.5	185	865	2,266
I&C COMP, PRIEL	1PRIEL	3	158	592	1,422
I&C COMP, TCISA	1TCISA	2	46	101	184
I&C COMP, TCNEL	1TCNEL	2.5	54	158	338
I&C COMP, TCNSA	1TCNSA	2	31	68	124
I&C SPECIAL, NCNNA	2NCNNA	1.5	26	40	59
I&C SPECIAL, TCNEL	2TCNEL	2.5	56	163	350
I&C SPECIAL, TCNSA	2TCNSA	2	34	74	136
ELEC ONSITE, NCNEL	3NCNEL	2	52	114	208
ELEC ONSITE, NCNNA	3NCNNA	1.5	25	39	56
ELEC ONSITE, PCIEL	3PCIEL	3.5	155	725	1,899
ELEC ONSITE, TCIEL	3TCIEL	2.5	123	359	769
ELEC ONSITE, TCNEL	3TCNEL	2.5	64	187	400
ELEC ONSITE, TCNSA	3TCNSA	2	30	66	120
ELEC OFFSITE, NCNEL	4NCNEL	2	8	17	32
ELEC OFFSITE, NCNNA	4NCNNA	1.5	6	9	14
MECH COMP, NCNEL	5NCNEL	2	41	90	164
MECH COMP, NCNNA	5NCNNA	1.5	26	40	59
MECH COMP, PCIEL	5PCIEL	3.5	223	1,043	2,732
MECH COMP, PCIML	5PCIML	3.5	212	992	2,597
MECH COMP, PRIEL	5PRIEL	3	207	776	1,863
MECH COMP, PRIML	5PRIML	3	186	697	1,674
MECH COMP, TCIEL	5TCIEL	2.5	102	298	638
MECH COMP, TCISA	5TCISA`	2	71	155	284
MECH COMP, TCNEL	5TCNEL	2.5	53	155	331
MECH COMP, TCNSA	5TCNSA	2	30	66	120
MECH COMP, TRIEL	5TRIEL	2	74	162	296
HVAC SPECIAL, NCNNA	6NCNNA	1.5	28	43	63
HVAC SPECIAL, TCISA	6TCISA	2	45	98	180
HVAC SPECIAL, TCNSA	6TCNSA	2	35	76	140
COMPUTER, NCNEL	7NCNEL	2	47	103	188
COMPUTER, TNTSA	7TCNSA	2	38	83	152
MECH MAJOR, PCIEL	8PCIEL	3.5	660	3,087	8,085

Table 7-5. Summary of Corrective Maintenance Requirements (Clock Hours and Effort). (2 sheets)

Recovery Time Description	Recovery Time ID	Range Factor	Clock Hours Required to Complete a Corrective Maintenance		
			Low	Mean	High
MECH MAJOR, PCIML	8PCIML	3.5	441	2,063	5,402
MECH MAJOR, PRIEL	8PRIEL	3	532	1,995	4,788
SUP FACILITY, NCNNA	9NCNNA	1.5	16	25	36
SUP FACILITY, TCNSA	9TCNSA	2	33	72	132

Source:
Carlson, A. B., 1999a, *Waste Feed Delivery Technical Basis, Volume IV: Waste Feed Delivery Operations and Maintenance Concept*, HNF-1939-Vol. IV, Rev. 0, Numatec Hanford Corporation, Richland, Washington.

The probability that ventilation is not recovered in the available time is then:

$$P_{nrR} = \left(1 - x_{rs}\right) \sum_{n=1}^{N} x_n \left[1 - \text{log-normal}\left(t_a, \alpha_n, \beta_n\right)\right] \tag{7-6}$$

where N is the number of corrective maintenance activities, x is the fraction of all corrective maintenance activities for the nth corrective maintenance activity (the relative frequency such that the sum of all x_n values is equal to one), log-normal is the cumulative log-normal distribution function evaluated at the available time, t_a, for the log-mean α_n and log-standard deviation, β_n, of the nth corrective maintenance activity. This expression assumes that restoration activities succeed during the available time, which is a crude approximation made justifiable because timeframes on the order of a day are unimportant. This expression states that the probability that corrective maintenance fails is the sum of the probabilities that individual corrective maintenance activities fail. The probability that an individual corrective maintenance activity will fail in the available time is just the exceedance probability for the log-normal distribution of repair time. Exceedance probability for each individual corrective maintenance activity is weighted by the relative frequency of each corrective maintenance activity.

Based on Table H-6 of the Carlson (1999a) reference, only the 3TCNEL, 5TCISA, and 5TCIEL corrective maintenance activities are relevant and log-normal distribution for these repair times have the following input values (see Table 7-6).

Table 7-6. Corrective Maintenance Activity Clock Time Distributions.

Corrective Maintenance Activity	Relative Frequency (Mean Value) (x_n)	Log-Mean α	Log-S. D. β	5th Percentile (hrs)	95th Percentile (hrs)
3TCNEL (n =1)	48.5%	5.08	0.56	64	400
5TCISA (n = 2)	48.5%	4.89	0.56	71	284
5TCIEL (n = 3)	3%	5.56	0.56	102	638

7.3 RESULTS FOR LIMITING CONDITIONS FOR OPERATION CONDITIONS

Equation (7-6) is evaluated with the following input:

- The relative frequency of the corrective maintenance activity 5TCIEL is 3.0 % and the other two corrective maintenance activities are equally likely
- Available time varies between 1 day and 30 days
- The fraction of events that require corrective maintenance rather than restoration is 15%.

Figures 7-1 and 7-2 illustrate results. Figure 7-1 expresses results in terms of the probability of recovering the ventilation system. To make results clear as time available approaches 30 days, Figure 7-2 shows the failure probability, which is just one minus the success probability, on a log scale. Figure 7-1 starts at 85% because the assumption is that restoration actions take one day and 85% of recovery actions are restoration actions. This assumption is not important, however, because we would never expect such a small available time. In a similar vein, the calculation ends at a probability of failure of just under 0.1% at 30 days.

7.4 CONCLUSIONS

Figure 7-1 or 7-2 show that there is high confidence that ventilation cooling can be restored in less than about 1 week. One week is short compared to the time available to reach waste saturation temperatures. Therefore, the strategy of monitoring waste temperature and requiring restoration actions is viable.

Figure 7-1. Probability of Recovering Ventilation as a Function of Days Available.

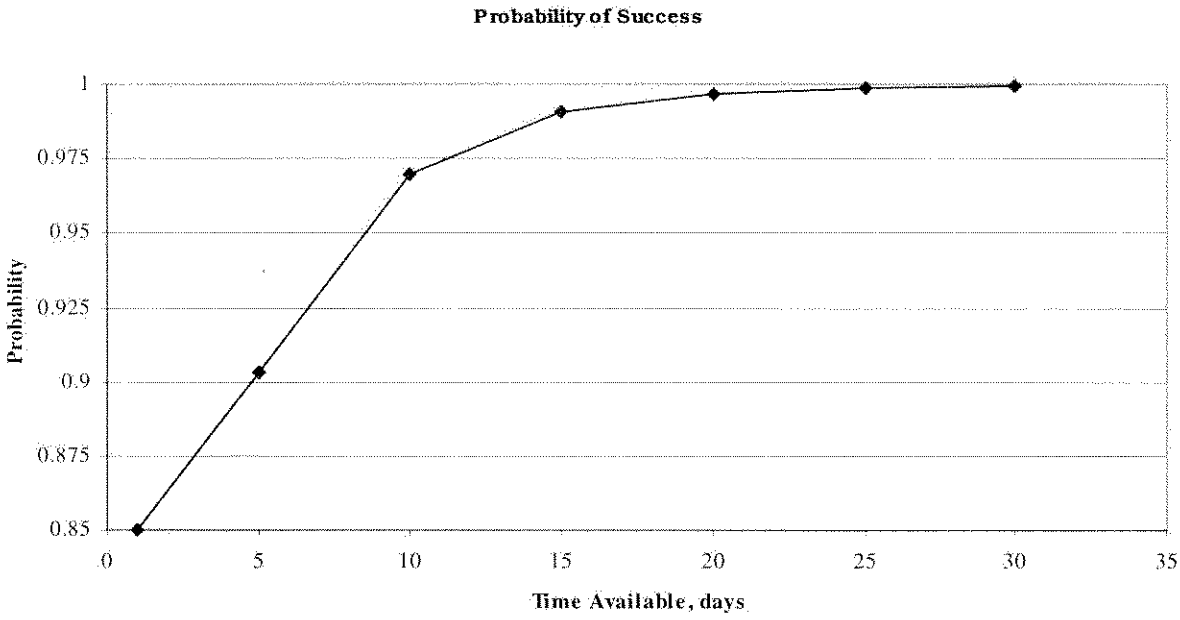
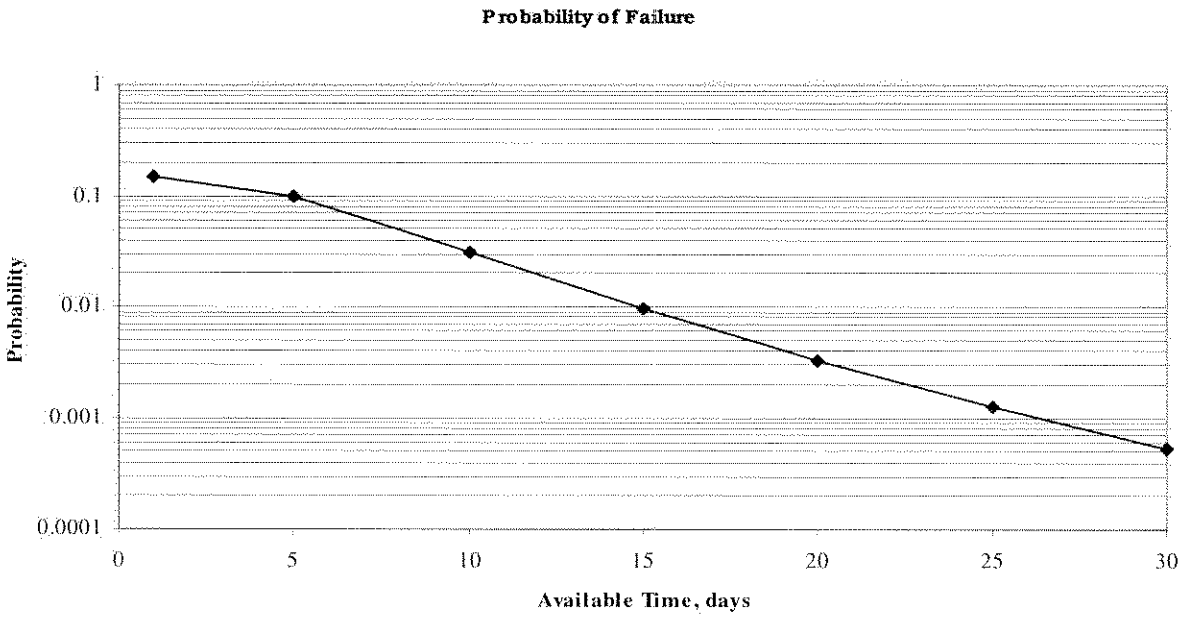


Figure 7-2. Probability of Not Recovering the Ventilation System as a Function of Available Time.



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8.0 CONSEQUENCE EVALUATION

Here we consider consequences of a tank bump that occurs during off-normal conditions of storage, i.e., without retrieval actions. Due to the long time for waste heat-up after loss of power in such circumstances, such events are evaluated against evaluation criteria for accidents with an "unlikely" frequency.

The consequence model employed is essentially that of Section 5.0 with modification to consider gas flows from the tank headspace. This allows the conservative adiabatic headspace compression assumption to be relaxed, and ultimately allows attenuation in the headspace to be considered. Also, aerosol models are added, as are representations of pump and sluice pit regions. This is accomplished by incorporating the model from Section 5.0 into the HADCRT code, as described next.

Releases from DSTs 241-AZ-101, 241-AZ-102, and 241-AY-102 are calculated here. Each DST presents unique considerations and it is difficult to select one as representative. Tank 241-AZ-101 has the highest heat load and the greatest likelihood of attaining saturated conditions, given a prolonged loss of ventilation. But because of its NCL depth of only 48 cm, Tank 241-AZ-101 appears least likely to achieve buoyant displacement and large initial gas release volume. Tank 241-AZ-102 has a much smaller heat load than does Tank 241-AZ-101, but has a thick NCL (97 cm) and deep supernatant, which would suggest a greater likelihood of buoyant conditions and larger gas release volumes. Tank 241-AY-102 satisfies buoyancy criteria and has a deep NCL (157 cm), but relatively low heat load and shallow supernatant.

Analysis proceeds by assuming that gas generation in each NCL is just large enough to create buoyant condition as defined by equation (4-16). We have noted that Tanks 241-AZ-101 and 241-AZ-102 are unlikely to satisfy this criterion, but include these DSTs for analysis based on total heat load and/or waste levels.

8.1 THE HADCRT CODE

The HADCRT code (Plys et al. 2002) is an integrated model for considering storage tank thermal-hydraulic and accident phenomena, such as deflagration, detonation, and the potential for fission product release. HADCRT accounts for generic phenomena such as gas and aerosol transport between regions, and heat transfer to structures, including evaporation/condensation. Generic phenomenological capabilities include:

- Multiple compartment representation
- Pressure-driven and counter-current gas flows
- Gas and aerosol transport between compartments
- Vapor-aerosol equilibrium
- Aerosol deposition due to gravitational sedimentation, impaction, etc.
- Heat transfer to structures.

Routines containing phenomenology specific to an accident or thermal-hydraulic scenario are used to provide rates-of-change for the generic routines listed above, for example, vapor-phase

combustion followed by blowdown and entrainment of aerosols. Accident-specific routines provide sources of mass, such as products of combustion or entrained aerosols from liquid surfaces and deposited solid particulate, or energy, as in the heat of reaction by hydrogen combustion.

The tank bump phenomena described in this section were coded and added to the HADCRT 1.46 code. HADCRT integrates the rates-of-change over the course of the bubble cluster rise to obtain position, volume of gas and liquid, vapor pressure, and temperature as a function of time, as described in equations (5-1) through (5-9) and (5-17) and (5-25). Temperature and pressure in the headspace are tracked by generic models during bubble cluster rise, so as to capture the feedback between bubble cluster dynamics and the headspace conditions during compression.

Vapor and entrained aerosols passing through the top of the supernatant are a source of mass and energy to the headspace. When the bubble cluster center reaches the supernatant surface, which has swollen per equation (5-6), the aerosol release equations (5-12) through (5-14) define the mass of material released to the headspace. These sources are used in turn to determine pressure, temperature, and airborne aerosol mass as a function of time. Coding details are left for Appendix F.

8.2 HADCRT INPUT FOR CONSEQUENCE EVALUATION

Table 8-1 is a listing of waste inputs required for the model of Section 5.0. Fundamental inputs are as follows: supernatant volume, NCL height, supernatant depth, NCL density, supernatant density, and shear strength, which is 100 Pa as a best-estimate. Layer heights, volumes, and densities are given by Hu and Barker (2002). Headspace volume is found by subtracting waste volume from the total DST volume of 5338 m^3.

Table 8-1. Waste Parameter Inputs for DST Consequence Analysis (2 sheets)

	AZ-102	**AZ-101**	**AY-102**
NCL Height, m	0.97	0.48	1.57
Shear Strength, Pa	100	100	100
Supernatant Depth, m	8.23	8.23	4.28
Supernatant Density, kg/m^3	1140	1240	1150
NCL Density, kg/m^3	1380	1620	1400
Supernatant Volume, m^3	3377.00	3377.00	1757.00
Neutral Buoyancy	0.17	0.23	0.18
Hydrostatic Pressure, atm	1.96	2.02	1.56
Saturation Temperature, K	392.05	392.87	385.44
Initial Total Bubble Volume, m^3	10.67	6.92	10.31
Headspace Volume, m^3	1564.00	1764.00	2935.00

Table 8-1. Waste Parameter Inputs for DST Consequence Analysis (2 sheets)

	AZ-102	AZ-101	AY-102
NCL Parcel Mass, kg	69960	36598	66387
Required Gg, gmole/m^3/day	13.11	3637.2	0.6685
Gas Generation Rate, m^3/m^3/day	0.42	117.2	0.0211
Seconds Between Bumps	5484	26	65297
Number of bumps	6.50	6.68	11.18

Other values in the table are derived from these inputs in accord with the model described by Section 5.0. Neutral buoyancy is given by $1 - \rho_{sup} / \rho_{NCL}$, where ρ_{sup} is supernatant density and ρ_{NCL} is NCL density. Hydrostatic pressure is reported in atmospheres at the mid-plane of the NCL and saturation temperature is that for pure water at the computed hydrostatic pressure. Initial total bubble volume and parcel mass are evaluated per equations (5-10) and (5-11), respectively. To find the required gas generation rate for neutral buoyancy, the left-hand side of equation (4-16) is set to 1.0 and G is calculated in units of molar gas generation per unit volume NCL. Equation (5-12) gives the time between bumps. The number of bumps is the total volume of NCL gas at neutral buoyancy (NCL volume multiplied by neutral buoyancy fraction) divided by the initial total bubble volume. The analysis does not consider fractions of a bump; i.e., the resulting value for the number of bumps is rounded down to the nearest integer.

Tank heat load is not an input to the model and is immaterial to the analysis, provided we have assumed bump conditions exist. Tank heat load is vital to the likelihood of bump conditions and the plausibility of these accident scenarios, but in this section we do not give regard to these concerns.

The HADCRT model for this case contains four volumes or regions: the tank headspace, a region representing four sluice pits, the center pump pit, and the environment. Normal flow paths between the environment and the headspace are the filtered 8 in. diameter inlet and the filtered 20 in. diameter. Tank configuration is given in Section 3.4. Other inputs are shown in Table 8-2.

Table 8-2. Other Parameter Values for Consequence Analysis Example for Tank 241-AZ-102 (2 sheets)

A. Headspace Parameters	
$P_{hs}(0) = 1.012 \times 10^5$ Pa	Initial headspace pressure; (Assumption).
$T_{hs}(0) = 100°C$	Headspace initial temperature; (Saturated Conditions).
$X_{st}(0) = 95\%$	Headspace steam mole fraction; (Near Saturation).

Table 8-2. Other Parameter Values for Consequence Analysis Example for Tank 241-AZ-102 (2 sheets)

A. Headspace Parameters	
B. Flow Path Parameters	
A_{in} = 0.03 m^2	8 in. inlet line; Section 3.4.
A_{out} = 0.20 m^2	20 in. outlet line; Section 3.4.
A_{leak} = 5 x 0.00133 m^2	Leakage around 42 in. risers; Section 3.4.
C_e = 0.5	Flow coefficient for inlet and outlet paths.
V_{pit} = 4 x 10 m^3 + 1 x 20 m^3	Sluice pit and center pit volumes; Section 3.4.
T_{pit} (0) = 75°C	Pit initial temperature.
P_{pit} (0) = 1.012 x 10^5 Pa	Pit initial pressure.
C. Property Values	
μ_g = 1.2 x 10^{-5} kg m^{-1} s^{-1}	Viscosity of bubble gas (vapor).
ρ_g = 0.6 kg m^{-3}	Density of bubble gas (vapor).
σ = 0.059 kg s^{-2}	Surface tension of supernatant.
D = 9.2 x 10^{-5} m^2 s^{-1}	Bubble gas/water vapor diffusion coefficient.

HEPA = high-efficiency particulate air (filter).

8.3 241-AZ-102 TANK BUMP RELEASE CALCULATION RESULTS

Results of the 241-AZ-102 tank bump calculation are shown in Figure 8-1, which provides long-term histories for headspace temperature and pressure, and the aerosol distribution. The pressure attained during a bump is about 3.6 psig, which is sufficiently large to not credit the HEPA filters as assumed. Temperature and pressure decay immediately following a bump due to forced flow and natural circulation flow to the environment. The natural circulation flow path is down through the damaged inlet line and up through the damaged outlet line.

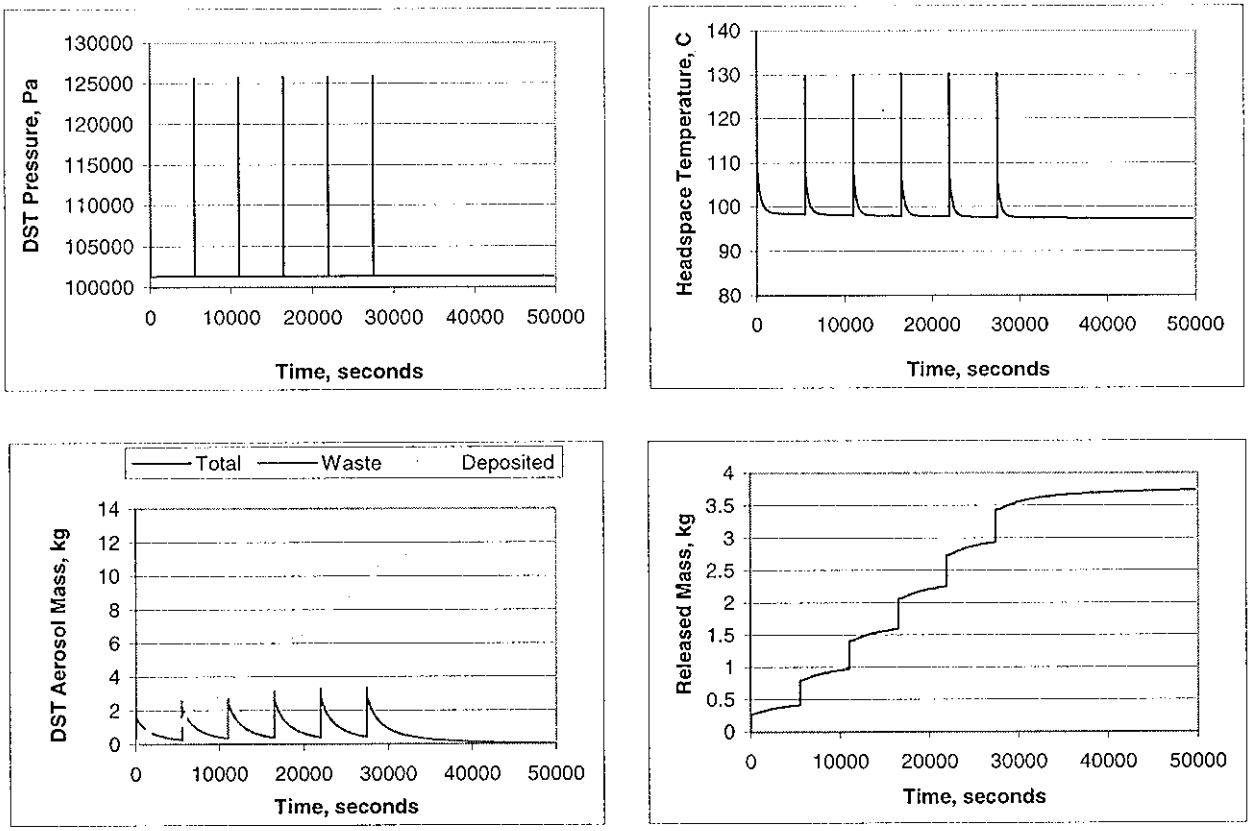
In the first bump, about 1.9 kg of aerosol are released, of which somewhat more than 20%, about 0.4 kg, is forced into the environment, so that 1.5 kg are retained. During the interval between bumps, sedimentation in the tank accounts for about 1.2 kg depletion from the headspace and natural circulation flow removes about 0.05 kg, so that about 0.25 kg aerosol remain when the second bump occurs.

After 6 bumps in this calculation, the entire non-convective layer has undergone buoyant displacement. Immediately following this last bump, the aerosol inventory is as follows: about

Figure 8-1. 241-AZ-102 Tank Bump Results.

In the DST Aerosol Mass plot, "Total" denotes all airborne aerosol mass, "Waste" is airborne supernatant and NCL material, and "Deposited" shows settled aerosol mass.

"Total" and "Waste" are nearly the same.



9.0 kg are settled in the tank, 3.4 kg are airborne in the headspace, and 2.9 kg are released to the environment, from a total source of about 15.3 kg. Long-term natural circulation competes with settling, but only an additional 0.7 kg are released while the remainder of the 2.1 kg airborne settle. Overall, 3.7 kg are released to the environment and 11.6 kg are retained in the tank. The present calculation considers one sequence of bumps that eventually displaces all non-convective material. Sedimentation, non-condensable gas retention, and attainment of neutral buoyancy are required for a subsequent bump sequence. Another sequence of successive bumps can therefore repeat later in time after neutral buoyancy is again achieved, on a timescale consistent with buoyant displacement events.

Solids volume fraction, or the liters of solids released, is important for radiological and toxicological consequence calculations. The volume fraction of solids released can be estimated assuming the tank mixed-mean solids fraction applies. This is conservative because it really applies only to the last bump and implies that the DST is well-mixed, which maximizes amounts of solids in the final parcel volume. First, find the volume fraction of solids in the NCL as:

$$\alpha_{s,NCL} = \frac{\rho_{NCL} - \rho_{CL}}{\rho_s - \rho_{CL}} \tag{8-1}$$

where the subscript "s" refers to the solids density, which is 3.8 g/cc (Crea et al. 2000). For Tank 241-AZ-102, appropriate values are: ρ_{NCL} = 1.38 g/cc and ρ_{CL} = 1.1 g/cc; this leads to a NCL solids fraction 10%. This value is somewhat lower than the 17% reported by (Crea et al. 2000), but this is to be expected because the most recent NCL density is lower than that used by Crea, et al. (1.49 g/cc). Mixed-mean solids fraction is then found from the NCL solids fraction, the supernatant volume, and NCL volume, and is

$$\bar{x} = \frac{V_{NCL} \cdot x_{NCL}}{V_{NCL} + V_{CL}} \tag{8-2}$$

where x is solids volume fraction and V is volume. This expression states that the DST mean solids fraction is the volume of solids in NCL divided by the total volume. Values for NCL and CL volumes are just area (411 m^2) times height listed in Table 8-1. Substituting in numerical values yields the following:

$$\frac{0.97 \times 411 \times 10\%}{(0.97 \times 411) + 3377} = 1.1\% \tag{8-3}$$

Now the initial NCL parcel volume is the initial NCL parcel mass (~ 70,000 kg) divided by the NCL density, and is 50.72 m^3. Code results show that 128 m^3 of liquid are added to the initial parcel. Overall solids fraction for releases is the volume of solids in the parcel divided by the total volume of the parcel. Total volume of the parcel is the initial parcel volume, V_{P0}, plus the added entrained mass, V_{Pe}. So overall solids volume fraction, x_s, can be written:

$$x_s = \frac{V_{P0} \cdot x_{NCL} + V_{Pe} \cdot \bar{x}}{V_{P0} + V_{Pe}} \tag{8-4}$$

$$\frac{(50.72 \times 10\%) + (128 \times 1.1\%)}{50.72 + 128} = 4\% \tag{8-5}$$

If 3.7 kg of waste are released and the waste is nearly all liquid, then 3.4 liters (3700 grams divided by 1100 g/l) of material are released. By volume, 4% (0.14 l) is solid and 96% (3.26 l) is liquid.

8.4 241-AZ-101 TANK BUMP RELEASE CALCULATION RESULTS

As shown in Figure 8-2, the series of tank bumps for Tank 241-AZ-101 is so rapid that they can be considered as a single event for evaluation of releases. Peak pressure is 2.5 psig and temperature piles to 148°C. During the first 200 seconds, 2.6 kilograms of waste are released, with another 0.3 kg released over the next several hours. A total of 5.1 kilograms of waste are retained.

The solids fraction for releases can be repeated in the same manner as for Tank 241-AZ-102, knowing that the final parcel mass is 144,982 kg; this is an additional 108,384 kg of supernatant. NCL solids fraction is 13.7%, but mixed-mean solids fraction is only 0.7% because Tank 241-AZ-101 has a thin NCL and a deep supernatant layer. Using the inputs in Table 8-1 gives 3.4% for the solids release fraction. By volume, 2.3 liters (2900 g divided by 1260 g/l) are released, with 3.4% (0.08 l) as solid and 96.6% (2.22 l) as liquid.

8.5 241-AY-102 TANK BUMP RELEASE CALCULATION RESULTS

Figure 8-3 shows that results for only one bump, but this suffices because for this DST, the bumps are distinct from each other. The aerosol mass plot shows that there is no airborne aerosol in the DST when the second bump occurs at 65,000 seconds; all aerosol mass is deposited or released by that time. The cumulative effect of the eleven bumps is just eleven times the value for one bump, or 0.6 kg.

The final parcel mass is 160,500 kg; this is an additional 94,100 kg (82 m^3) of supernatant. NCL solids fraction is 10.0%, but mixed-mean solids fraction is 2.7% because Tank 241-AY-102 has a thick NCL and a relatively thin supernatant layer. Using the inputs in Table 8-1 gives 5.3% for the solids release fraction. By volume 0.52 liters (600 g divided by 1150 g/l) are released for each bump, with 5.3% (0.03 l) as solid and 94.7% (0.49 l) as liquid.

8.6 SENSITIVITY ANALYSIS FOR PEAK PRESSURE

To consider the possible peak over-pressure created by tank bumps, Tank 241-AZ-102 was re-run with no flow path to the environment. Heat sinks were retained. Isolating the DST had little effect on the pressure and temperature after the first bump, which remained close to the values reported in the original run (see Figure 8-1). Peak pressure after six bumps was 4.3 psig, owing

Figure 8-2. 241-AZ-101 Tank Bump Results.

In the DST Aerosol Mass plot, "Total" denotes all airborne aerosol mass, "Waste" is airborne supernatant and NCL material, and "Deposited" shows settled aerosol mass.

"Total" and "Waste" are nearly the same.

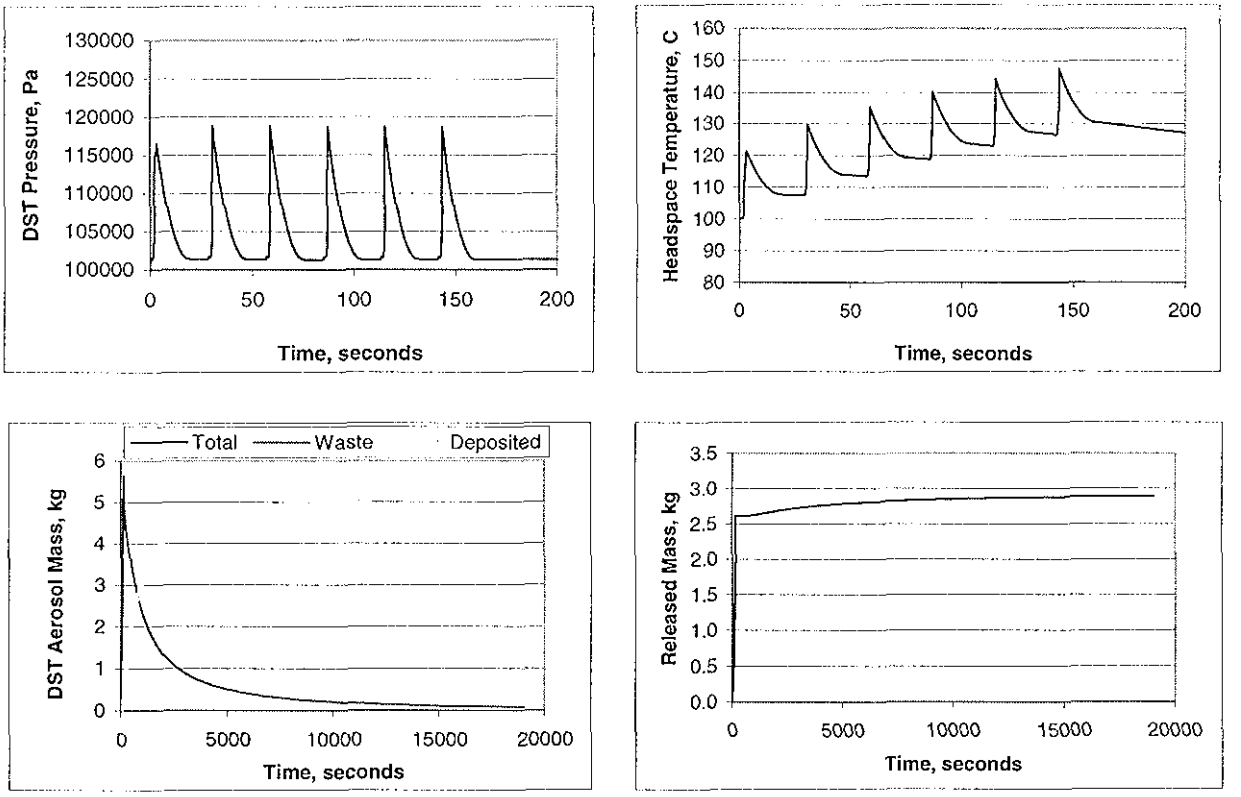
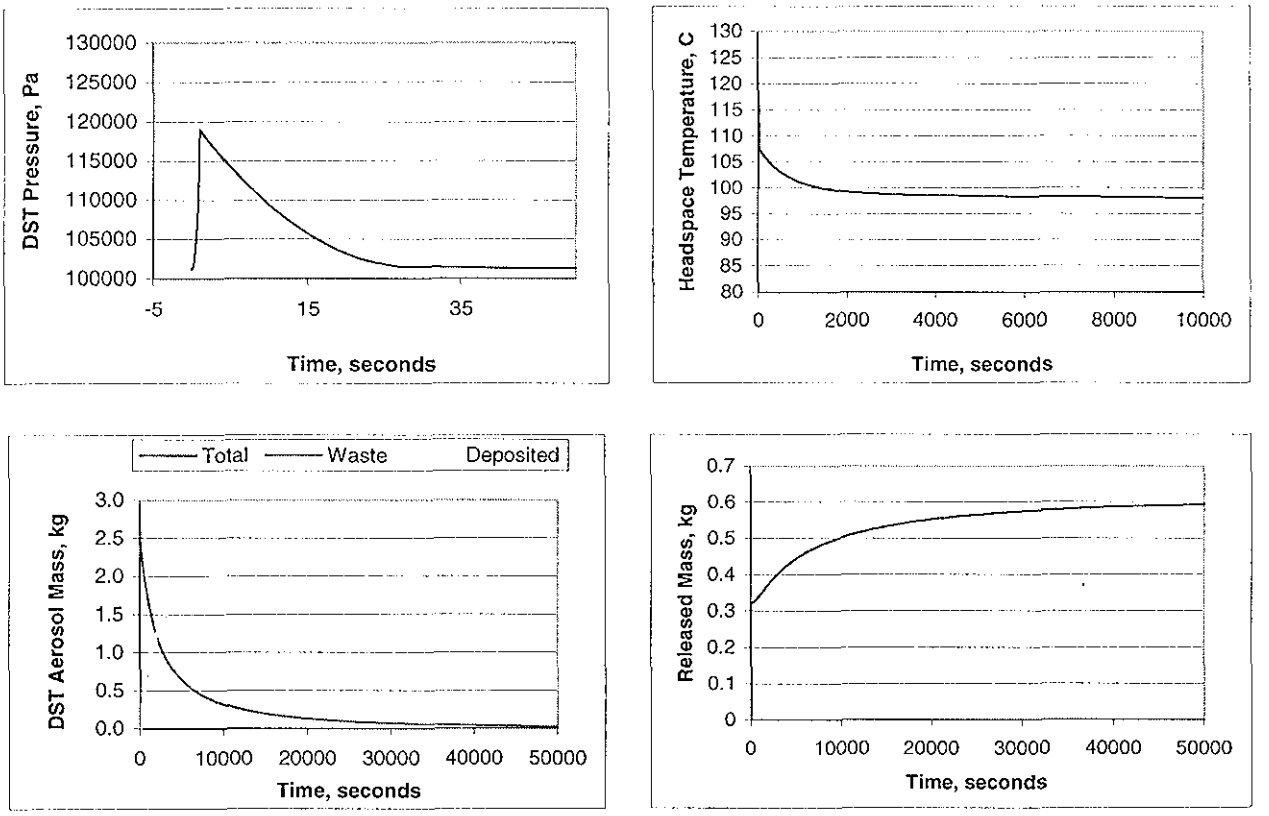


Figure 8-3. 241-AY-102 Tank Bump Results for One Bump.

In the DST Aerosol Mass plot, "Total" denotes all airborne aerosol mass, "Waste" is airborne supernatant and NCL material, and "Deposited" shows settled aerosol mass.

"Total" and "Waste" are nearly the same.



to pressure piling in the isolated case. These results demonstrate that the DST has little vent area in relation to the mass and energy addition posed by a single bump. Peak pressure is limited, however, to 3.6 psig for Tank 241-AZ-102, and 2.5 psig for Tank 241-AZ-101.

The overpressure calculated for the Tank 241-AZ-102 case (3.6 psig) is a reasonable upper bound for structural response analysis. Note that the predicted values are somewhat higher than the dome pressures listed in the history of events (Table 3-1). Without detailed knowledge of the initial and boundary conditions that precipitated the historical events, it is difficult to benchmark or validate the HADCRT results. It is reasonable, however, to state that HADCRT calculations are conservative in this respect, because the historic events occurred at heat loadings and temperatures that greatly exceed any conceivable conditions.

8.7 SENSITIVITY ANALYSIS FOR SUPERNATANT LEVEL

Because supernatant level measurements have some uncertainty, sensitivity to supernatant level (and headspace volume) was considered by re-running the Tank 241-AZ-102 case with supernatant level decreased by 0.1 m. Supernatant level measurement error is 10 cm at most. If results are unchanged by a 10 cm variation in supernatant level, then the current measurements are accurate enough for tank bump concerns.

With respect to the base case Tank 241-AZ-102 results, peak pressure, and temperature are scarcely changed by a 10 cm reduction in supernatant level. Total waste release increases to 3.8 kg from 3.7 kg, and peak pressure decreases from 125,900 Pa to 125,700 Pa. These differences are immaterial, which means that for input to tank bump release calculations, an accuracy of ± 10 cm is sufficient.

8.8 SENSITIVITY ANALYSIS TO WASTE YIELD STRENGTH

Waste yield strength is an uncertain input that we have assigned a value of 100 Pa, based on the discussion of Section 3.4. A value of 100 Pa is a best-estimate (mean, median, or mode) of a range that starts at 50 Pa and ends at 200 Pa. An average is entirely appropriate because yield strength is a linear function of depth, with minimum values (~ 50 Pa) at the top of the NCL and maximum values (~ 200 Pa) at the bottom. Here we repeat calculations with both ends of this range.

New inputs are shown in Table 8-3. If yield strength is reduced to 50 Pa, the main effect is to cut the initial NCL parcel size in half, but double the number of bumps. If the yield strength is increased to 200 Pa, the number of bumps is reduced from six to three, but the size of the bump is doubled. In summary, a weaker sludge leads to many small bumps in rapid succession, while a strong sludge leads to a few big bumps with long intervals in between.

Table 8-3. Inputs for the Shear Strength Sensitivity Analysis

	AZ-102: Base Case	**AZ-102: Weak NCL**	**AZ-102: Strong NCL**
NCL Height, m	0.97	0.97	0.97
Shear Strength, Pa	100	50	200
Supernatant Depth, m	8.23	8.23	8.23
Supernatant Density, kg/m^3	1140	1140	1140
NCL Density, kg/m^3	1380	1380	1380
Supernatant Volume, m^3	3377.0	3377.0	3377.0
Neutral Buoyancy	0.174	0.174	0.174
Hydrostatic Pressure, atm	1.96	1.96	1.96
Saturation Temperatue, K	392.05	392.05	392.05
Initial Total Bubble Volume, m^3	10.67	5.34	21.35
Headspace Volume, m^3	1564.00	1564.00	1564.00
NCL Parcel Mass, kg	69960	34980	139920
Required Gg, gmole/m^3/day	13.12	13.12	13.12
Gas Generation Rate, m^3/m^3/day	0.42	0.42	0.42
Seconds Between Bumps	5484	2742	10968
Number of bumps	6.50	12.99	3.25

Results are shown in Table 8-4. In terms of both total release mass at 50,000 seconds and peak pressure, the base case (100 Pa NCL) results fall right between the weak case (50 Pa NCL) and strong case (200 Pa NCL) results. Changes with respective to the base case are noticeable but not marked. Decreasing yield strength by 50% increases mass release by 20% and decreases peak pressure by 30%. Increasing yield strength by 100% increases peak pressure by 27% and decreases releases by about 20%. The weak sludge cases leads to larger releases because the bumps occur in rapid succession and there is less settling time between bumps; each new bump occurs when there is a significant airborne aerosol mass in DST headspace. The strong sludge case leads to a larger overpressure because each bump is large, but also leads to smaller releases because there is adequate settling time between bumps. Note that the peak overpressure of 4.7 psig is far greater than that in any of the historic events, where 2.6 psig appears to be an upper bound.

Table 8-4. Results of the Shear Strength Sensitivity Analysis

	AZ-102 Base Case	Weak NCL	Strong NCL
Peak Overpressure, psig	3.7	2.6	4.7
Waste Released at 50,000 seconds, kg	3.7	4.4	3.0

Sensitivity analysis demonstrates that the shear strength value of 100 Pa is a good choice and that results are not especially sensitive to the choice of shear strength. The base case is somewhat conservative with respect to the historic peak overpressures and falls right in the middle of the possible release range for variation in yield strength.

8.9 SENSITIVITY TO WASTE INVENTORY

Current waste storage conditions are subject to change, and waste transfers can create new configurations that have not been analyzed. In this sensitivity analysis, we concoct the hypothetical tank that would create the worst tank bump consequences by selecting supernatant depth, NCL depth, supernatant density, and NCL density. Clearly, although mass released increases with both NCL depth and supernatant depth, the bump size is constrained because the sum of NCL depth and supernatant depth is limited. A deep supernatant and thin NCL do not result in the worst bump because the initial total bubble volume is limited. A very deep NCL and thin supernatant layer do not result in the largest bump because bubble expansion ratio increases with supernatant depth.

A series of tank bumps can be optimized by selecting the time between bumps. The time between bumps should be less than the aerosol settling time so that each bump after the first occurs with an existing airborne aerosol load.

The hypothetical tank has the inputs shown in Table 8-5. NCL shear strength was kept at the best-estimate, or average, value. Supernatant and NCL depths were set to 5.0 m to maximize the size of the bump. Supernatant and NCL densities are representative values, but also result in a large neutral buoyancy fraction and large initial bubble volume. Time between the seven bumps is arbitrarily set to one hour, which is less than the aerosol settling time in the DST, to facilitate releases.

Table 8-5.
Inputs for the Maximum Tank Bump Case and Comparison with the Base Case (2 sheets)

	AZ-102: Base Case	Maximum Bump Tank
NCL Height, m	0.97	5

Table 8-5.
Inputs for the Maximum Tank Bump Case and Comparison with the Base Case (2 sheets)

	AZ-102: Base Case	**Maximum Bump Tank**
Shear Strength, Pa	100	100
Supernatant Depth, m	8.23	5.00
Supernatant Density, kg/m^3	1140	1100
NCL Density, kg/m^3	1380	1500
Supernatant Volume, m^3	3377.0	2055.0
Neutral Buoyancy	0.174	0.267
Hydrostatic Pressure, atm	1.96	1.80
Saturation Temperature, K	392.05	389.49
Initial Total Bubble Volume, m^3	10.67	72.59
Headspace Volume, m^3	1564.00	1564.00
NCL Parcel Mass, kg	69960	299454
Required Gg, gmole/m^3/day	13.12	--
Gas Generation Rate, m^3/m^3/day	0.42	--
Seconds Between Bumps	5484	3600
Number of bumps	6.50	7.55

Results show that peak pressure is 5.4 psig and releases are 9 kg after 50,000 seconds. Again, calculated peak pressure suggests that the hypothetical bumps are much larger than any of the historical events. These results show that the base case calculations for the current aging waste tanks are fairly robust. Base case results of 3.7 psig and 3.7 kg after 50,000 seconds are comparable to the hypothetical tank results. It is unlikely that any combination of waste transfer would create tank bump consequences that exceed the existing ones.

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9.0 SUMMARY AND DISCUSSION OF ASSUMPTIONS AND APPROXIMATIONS

9.1 TANK BUMP PHYSICAL MODELS

The steam bump model is subject to a number of simplifying, realistic, and conservative assumptions. The important assumptions are listed below together with their estimated degree of conservatism.

A1.1 Bubble growth is limited by steam transport within the bubble.

Degree of Conservatism: This assumption is believed to be moderately conservative in that the resistance to growth imposed by the thermal boundary layer on the liquid side of the bubble surface is at least as important as the diffusional resistance to growth on the vapor side.

A1.2 The flow field within the bubble is approximated by a Hill's vortex for the purpose of estimating the resistance to steam mass transfer within the bubble.

Degree of Conservatism: This assumption is regarded as realistic since it has been supported by bubble growth data available in the literature.

A1.3 The rise velocity of the buoyant parcel is estimated by appealing to an available correlation for the rise velocity of gas-bubble ensembles.

Degree of Conservatism: This assumption is realistic as the quasi-steady application of the correlation to growing, but essentially inertialess bubbles is valid.

A1.4 The mixing of the rising buoyant parcel with the surrounding supernatant is well described by the Morton-Taylor-Turner entrainment equation.

Degree of Conservatism: This very realistic assumption is supported by numerous experiments on mixing of jets, plumes, or buoyant parcels with the ambient fluid.

A1.5 The mass of aerosol produced by steam bubble breakthrough is estimated with the Kataoka and Ishii (1984) correlation.

Degree of Conservatism: The use of this correlation is regarded as realistic since it is consistent with the available data in the high gas-flow regime.

A1.6 The Meyer et al. (1997) semi-empirical expressions are used to assess the total void volume and the total mass of non-convective material that are assumed to suddenly appear and participate in the buoyant displacement.

Degree of Conservatism: This assumption is probably very conservative for several reasons. The evidence from the six DSTs that exhibit buoyant displacements suggests that the buoyant release occurs gradually over time (~ 1 min) as opposed to the sudden release of the single, large parcel assumed in the model. The tanks believed to be most susceptible to a bump and chosen for tank bump model evaluation are sludge tanks. It is doubtful that neutral buoyancy can be attained in the non-convective layers in these tanks through buildup of non-condensible gases. The Meyer et al. (1997) energy criterion for gas release indicates that non-condensable gas generation cannot bring the non-convective layers to a buoyant condition, even at their boiling points. Also, there are some reasons to believe that gas-solid or steam-solid attachment is difficult in sludge-like materials so that gas or vapor retention is limited in these materials (Kovach 2000).

9.2 TANK BUMP CONSEQUENCE EVALUATION

A2.1 Initially released gas volume and time between bumps are found using the Meyer et al. (1997) expressions.

Degree of Conservatism: These are best-estimate models for tanks observed to undergo buoyant displacements today, but per (A1.6) and (A3.1), this is conservative for application to Tank 241-AZ-102.

A2.2 Leakage paths from the tank headspace are gaps around the 42 in. riser shield plugs, and inlet/outlet HEPA filters are assumed not present.

Degree of Conservatism: Leakage path values follow the Barton and Bingham (1999) methodology, and are best-estimate, although it is unclear whether or not other leakage paths may exist for any given tank. Neglect of HEPA filters is slightly conservative because the headspace pressure attained during a bump is at the threshold for failure, and this is a simplifying assumption. The actual effect of filters would be difficult to justify.

A2.3 Aerosol retention in sluice and pump pits is not credited.

Degree of Conservatism: This is somewhat conservative, but most aerosols are released via the normal inlet and outlet paths, so the contribution to release from the pits is small.

A2.4 Approximate solid fractions are used to convert released mass to solid and liquid volumes.

Degree of Conservatism: The mass of solids entrained per bump varies throughout the sequence of bumps, so a somewhat conservative approach was taken, whose impact is deemed small.

A2.5 Onsite and offsite doses assume an 8-hour release duration.

Degree of Conservatism: 90% of the waste is released over 6 hours (12 bumps at 30 minute intervals), so the worker shift assumption is reasonable, and the offsite conservatism is small.

A2.6 The effect of further bumps after settling of waste from the original sequence of bumps is not quantified.

Degree of Conservatism: Further sets of bumps would result in the same sources as predicted for the original sequence described here, and this is mentioned in Section 8.3. However, considerable time would elapse for sufficient non-condensible gas generation and accumulation to trigger a new set of bumps. Even though not considering further sets of bumps is non-conservative, this is judged to be an unlikely event following an originally unlikely event.

9.3 VENTILATION FLOW RATE CALCULATIONS

A3.1 Conduction is neglected to calculate minimum ventilation flow rates.

Degree of Conservatism: This is a significant conservatism for the aging waste tanks in the current state, but as the postulated heat load increases, it becomes unimportant. As calculated in Section 6.0, upward and downward conduction alone can remove 11.3 kW. This is neglected for the sake of simplicity when computing the minimum ventilation flow rate. Now for Tank 241-AZ-101, which has 60.4 kW, ignoring 11.3 kW is a noticeable conservatism. But for other calculations, where tanks are postulated with 100 to 150 kW heat loads, ignoring 11.3 kW is immaterial.

A3.2 Ambient relative humidity is neglected to calculate minimum ventilation flow rates.

Degree of Conservatism: This is a slight non-conservatism which is more than offset by Assumption A3.1. The mass balance for steam in the headspace assumes that the relative humidity (water vapor mass fraction) of the incoming air is zero. This is acceptable if water vapor mass fraction in the DST headspace is much larger than water vapor mass fraction in the ambient environment, which can be written:

$$Y_{amb} = \frac{1}{1 + \left(\frac{101{,}350}{RH \times PPS} - 1 \right) \frac{M_a}{M_w}} \qquad (9\text{-}1)$$

where PPS is the partial pressure of steam at the ambient temperature, M is molecular weight, and subscripts "a" and "w" refer to air and water, respectively.

Evaluating this equation shows that the assumption is acceptable. If the ambient temperature is, say 15°C (close to the site annual average) and relative humidity (RH) is 50%, PPS is 1.7051 kPa and the water mass fraction in the ambient air is 1.0%. Even in the extreme case of 25°C and 100% RH, the water vapor mass fraction in the environment is 5%. This can be compared to the water vapor fraction in the gas headspace, which is 43% in Table 7-1 for the Tank 241-AZ-101 case.

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APPENDIX A

TANK WASTE CHARACTERIZATION DATA

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APPENDIX A

TANK WASTE CHARACTERIZATION DATA

A.1 E-MAIL CORRESPONDENCE

From: Blaine_A_Crea@RL.gov
Sent: Tuesday, April 04, 2000 6:38 PM
To: plys@Fauske.com
Cc: Thomas_G_Tom_Goetz@apimc01.rl.gov; David_R_Bratzel@apimc01.rl.gov
Subject: RE: DST Inlet Information Needs

The following explanation of the ventilation systems in the aging waste facility hopefully will clarify item 8 for you: I'll dig up appropriate reference material for you later.

There are four tanks in this facility. Two in AY tank farm (AY-101 and AY-102). Two in AZ tank farm (AZ-101 and AZ-102)

First each tank has both a primary (Dome space) and secondary (Annulus) ventilation system.

I'll discuss the annulus vent systems first. They are in general capable of drawing about 1000 CFM of air through the tank annulus when they're operating this is true for the current configuration of all the systems.

Each tank in the AY tank farm has a similar but totally separate annulus vent system. The two tanks in the AZ farm, however, share a common exhauster i.e. fans filters, stack, monitors.

All four tanks share elements of a common primary vent system. Each tank has, however, a separate recirculation cooling system. The included simplified sketch of the primary system may help the show the component arrangement.

The components in the lower right corner of the sketch are housed in a separate building outside of the farms. This provides tank vacuum and discharge cleanup. It also can provide some cooling, but the original design basis for the chiller driven condenser was to cool the off gas to slightly above 0 centigrade and so remove almost all the moisture and the associated tritium. It also is service by dedicated UPS's and a backup diesel generator with an automatic start/transfer switch.

The components of the recirculation modules shown next to each tank are designed to remove most of the heat over the long run. There is one of these recirculation modules with associated condensers, fans, cooling towers, coolant loops etc for each tank.

From: Sathyanarayana, K
Sent: Wednesday, April 05, 2000 4:36 PM
To: 'plys@fauske.com,'; Bratzel, David R; Crea, Blaine A
Cc: Sathyanarayana, K
Subject: Pumps and Sluice Pits Information

Marty and Dave,

Blaine was looking for information on details of Pump and Sluice Pits for Tank 241-AZ-101. I donot have drawings but I could find the following information in old SAR document (SD-HS-SAR-010, Rev.1).

Above each of the 241-AZ tanks is a Pump Pit, located in the center of the tank, and two Sluice Pits located opposite to each other. The Pump Pits have approximate inside dimensions of 8 ft by 12 ft by 7 ft deep with 2.5 ft thick concrete cover blocks. The walls are 1 ft thick concrete. The Sluice Pits have approximate inside dimensions of 6 ft by 8 ft by 7 ft deep with 2 ft thick concrete cover blocks. The walls are 1 ft thick concrete.

The pump and sluice pit covers are purposely not air tight to permit some air leakage into the tank. The pits have drains and base plate openings for a pump or sluice nozzle, going directly into the vapor space of the tanks. Air can leak in through the cracks between cover blocks and the penetrations in the blocks (i.e., holes for mechanisms to operate the sluice nozzle, valves, etc.).

I hope this information is correct and represen present conditions. Hope this is the information that you are looking for and to make sure Blaine can verify this.

Thanks
Sathya

From: Blaine_A_Crea@RL.gov
Sent: Monday, April 10, 2000 9:44 AM
To: plys@Fauske.com
Cc: Thomas_G_Tom_Goetz@APIMC01.RL.GOV; David_R_Bratzel@APIMC01.RL.GOV
Subject: RE: DST Inlet Information Needs

The only information that I have been able to come up with on filter failure threshold is from ASME AGA-1. This is the standard that all HEPA filters must meet.

The performance test requires that they withstand a differential pressure of 10 inches of water while subjected to an air stream that contains 1 lbm water droplets /1000 cubic feet of air for an hour. The airflow rate during this test is adjusted to maintain the 10 inches of water differential pressure throughout the test.

The filter is a 500 SCFM rated filter. That means that it has an initial (clean) pressure drop of 1 inch of water at 500 SCFM. Since the pressurization of the dome will be a back flow it would seem reasonable that this would be the filter characteristic at the initiation of the backflow sequence.

From: K_Sathyanarayana@RL.gov
Sent: Monday, April 10, 2000 12:32 PM
To: plys@Fauske.com
Cc: David_R_Bratzel@apimc01.rl.gov; Blaine_A_Crea@apimc01.rl.gov; K_Sathyanarayana@apimc01.rl.gov
Subject: RE: Pumps and Sluice Pits Information

Marty-

The primary Tank Ventilation System contains individual controlled air inlets and a common off-gas exhaust for the four AY and AZ Tank Farm waste tanks. The individual tank air inlet consists of a heater, pre-filter, high-efficiency particulate air (HEPA) filter, flow control valve and a vaccum relief valve.

Inlet Equipment: Heater, Pre-filter and HEPA filter

1. The ouside air inlet has an electric 3-phase heater to protect the filters from excessive humidity or frost. Heaters are sized for an air flow of 100 to 500 cfm.

2. The pre-filter protects the HEPA filter from unnecessary particulate loading which would shorten its life. The pre-filter efficiency is about 25 to 30% per ASHRAE Standard 52-68. It is 12" by 24" by 2", UL Class 1, fiber glass media with nonflammable frame. The filter surface area is atleast 8.5 ft2.

3. The HEPA filter is necessary to protect the environment against potential backflow from the waste tank inlet. The filter is nuclear grade, 12" by 24" by 11 1/2" with a nominal rating of 500 cfm. The operating pressure drop of 3" of water for the nominal flow rate. The maximum pressure for leak is 10" of wate gauge (I need to get confirmation of this value).

The inlet pipe is 6 inches diameter schedule 40.

Thanks
Sathya

A.2 DRAWINGS

Figure A-1. System Schematic Diagram.

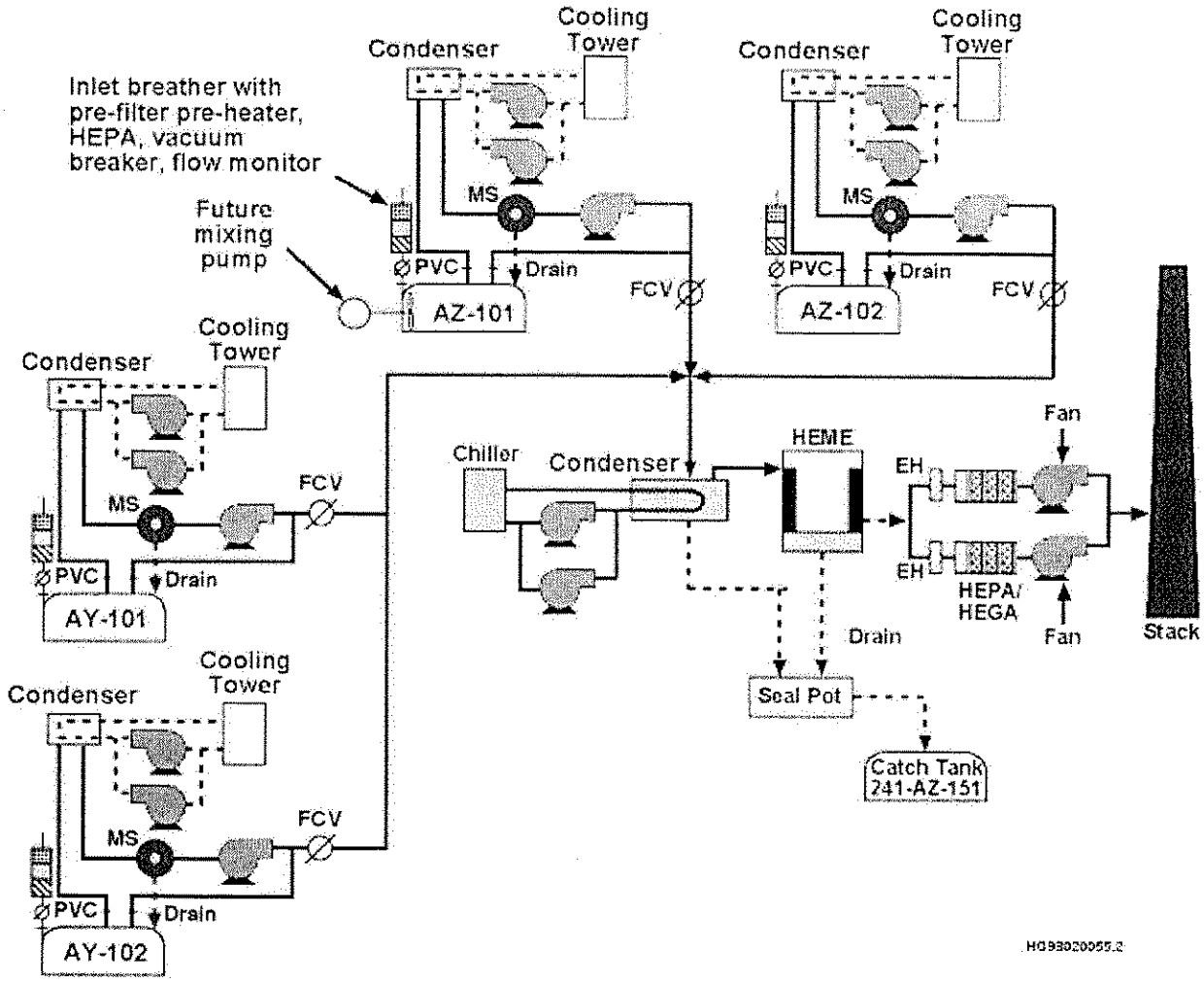

Figure A-2. Structural Concrete Sluicing Pit Plans - Part 1 of 2.

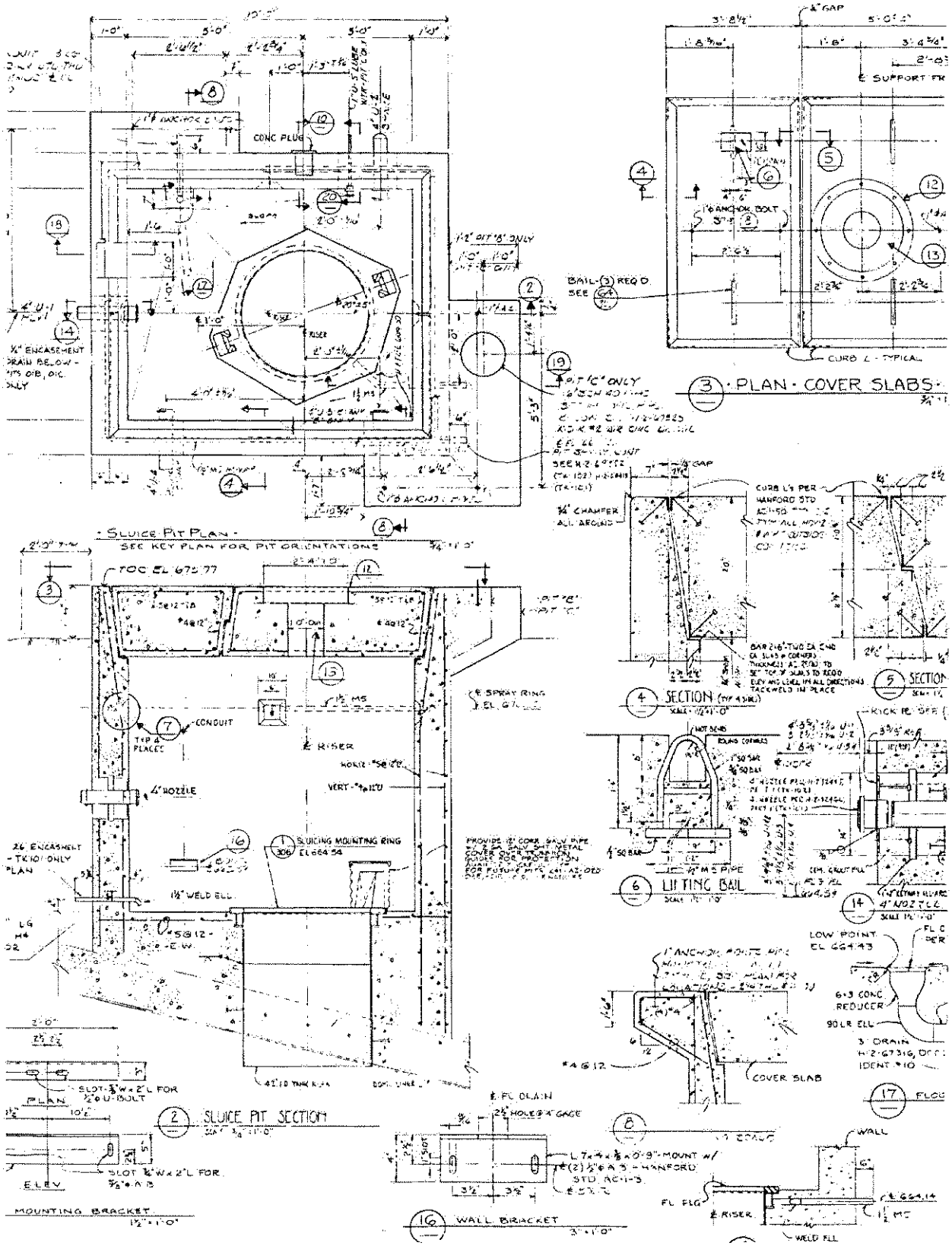

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Figure A-3. Structural Concrete Sluicing Pit Plans - Part 2 of 2.

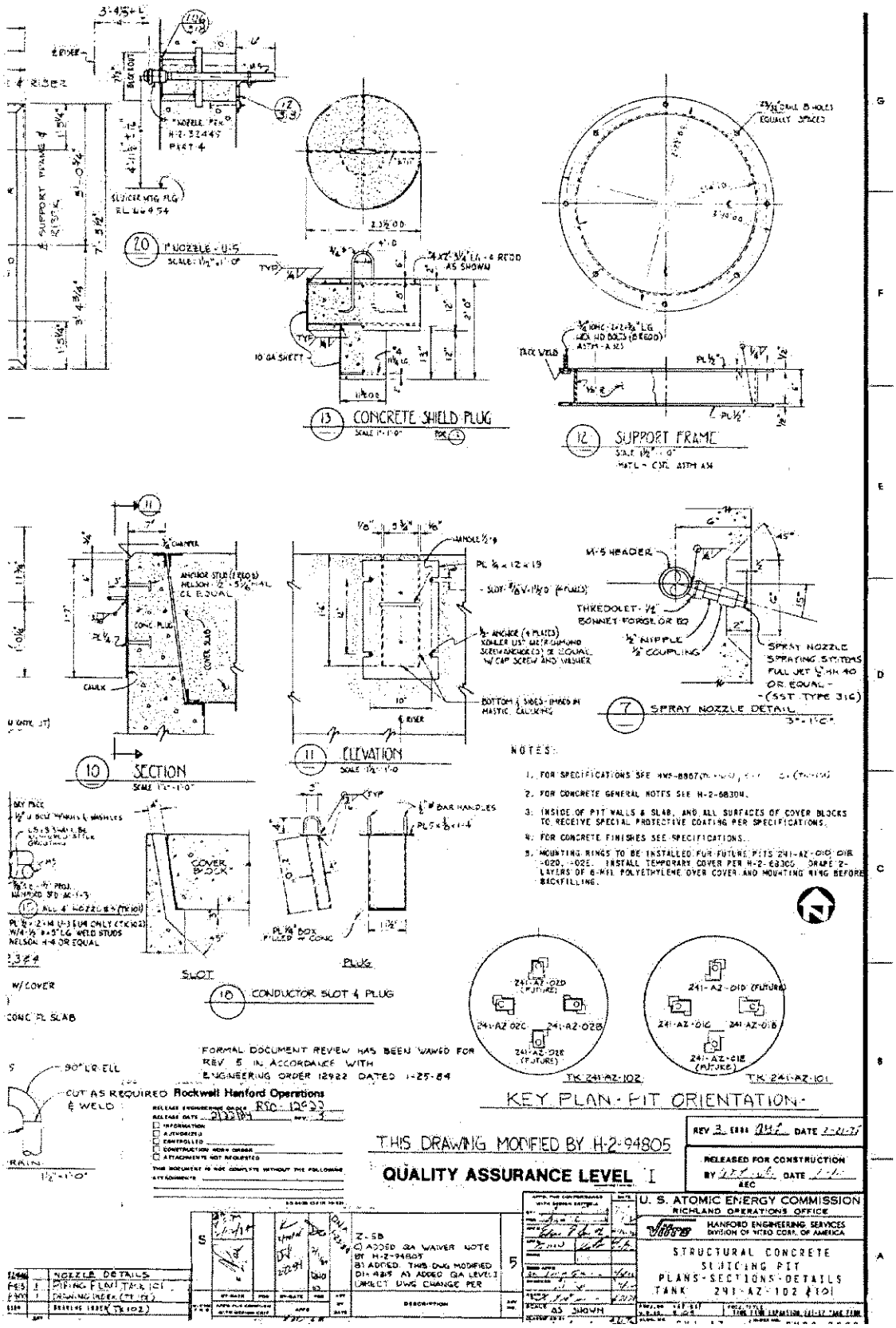

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Figure A-4. Structural Concrete Pump Pit Plans - Part 1 of 2.

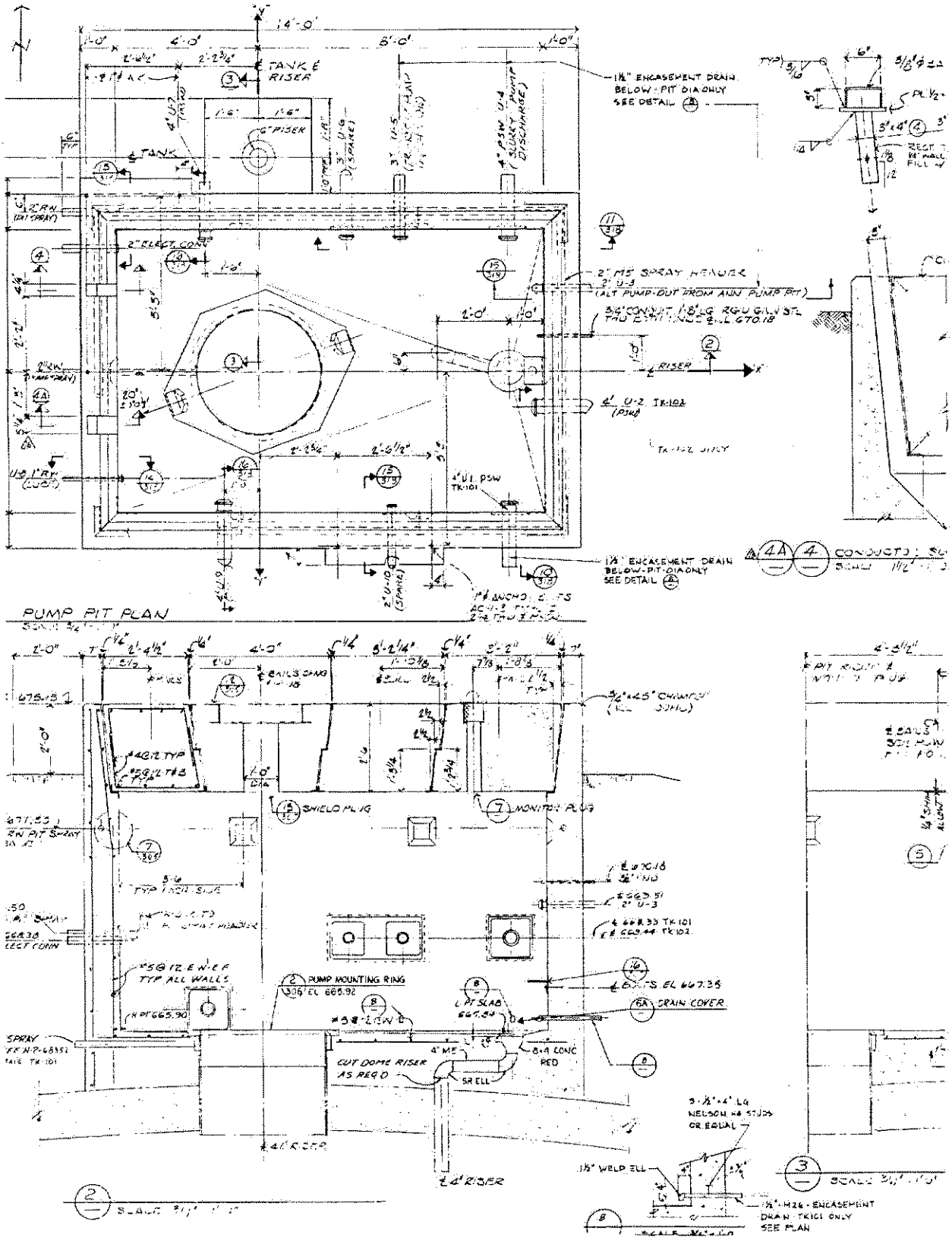

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Figure A-5. Structural Concrete Pump Pit Plans - Part 2 of 2.

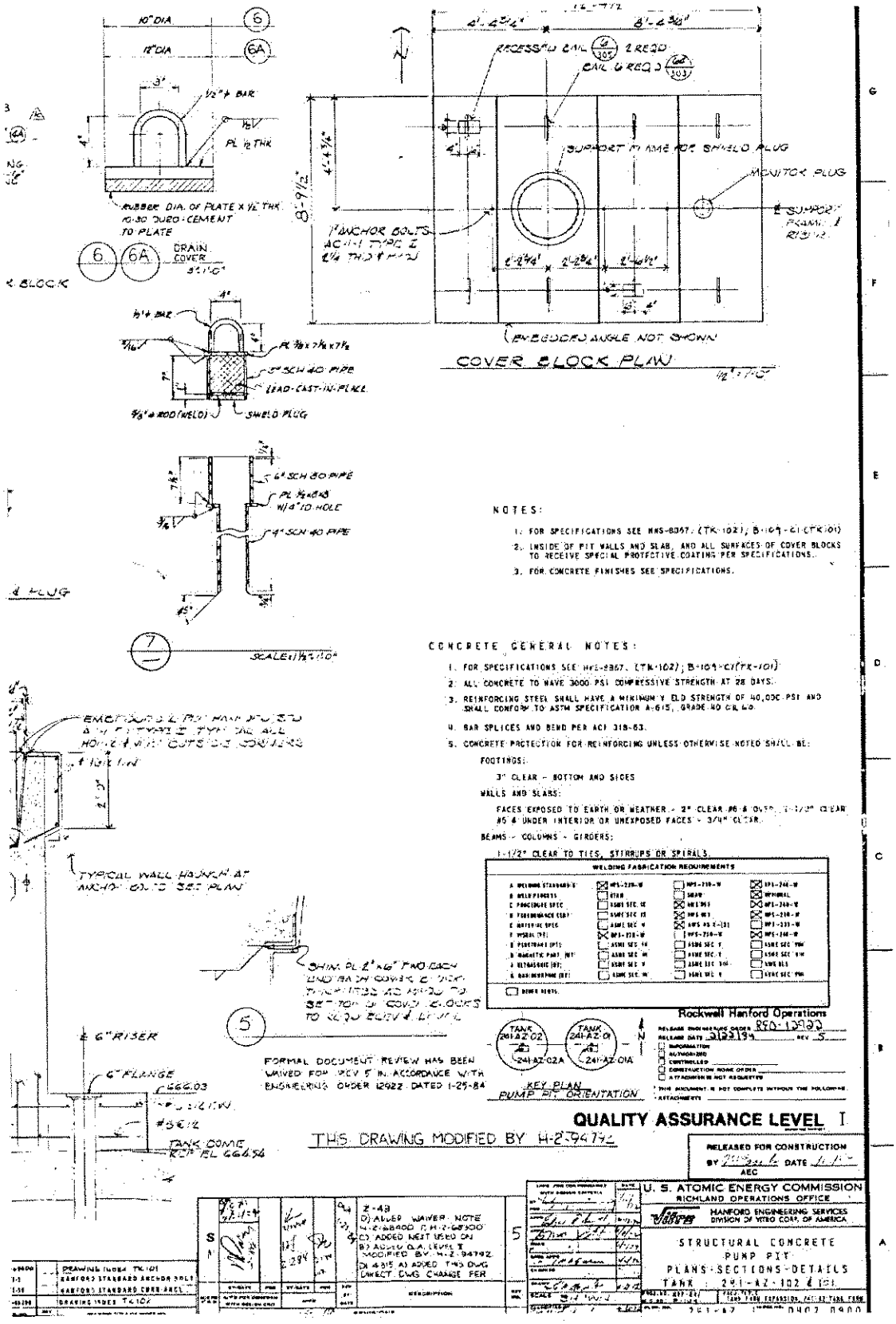

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Figure A-6. Air Lift Circulator and Riser Extension Details - Part 1 of 2.

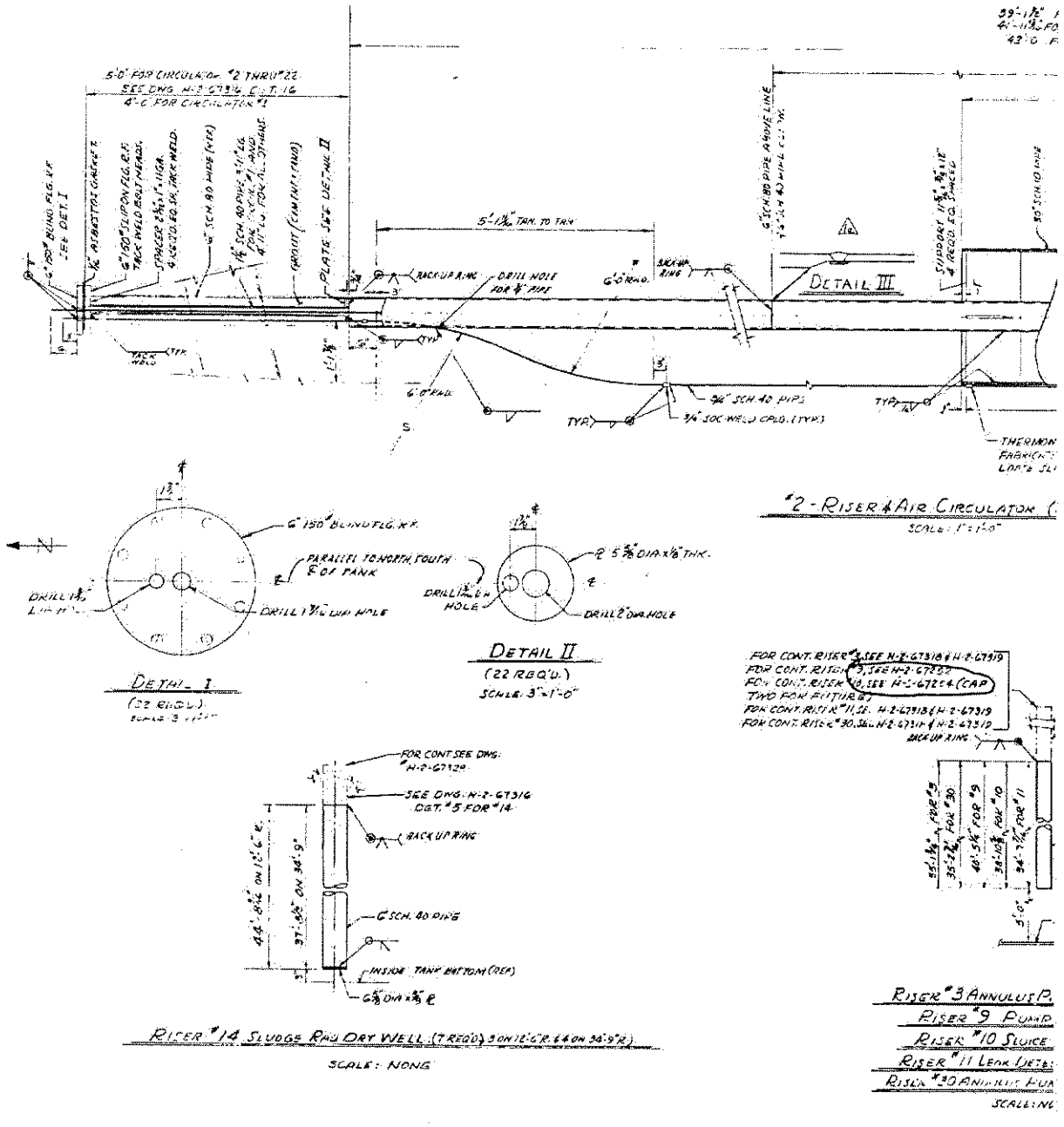

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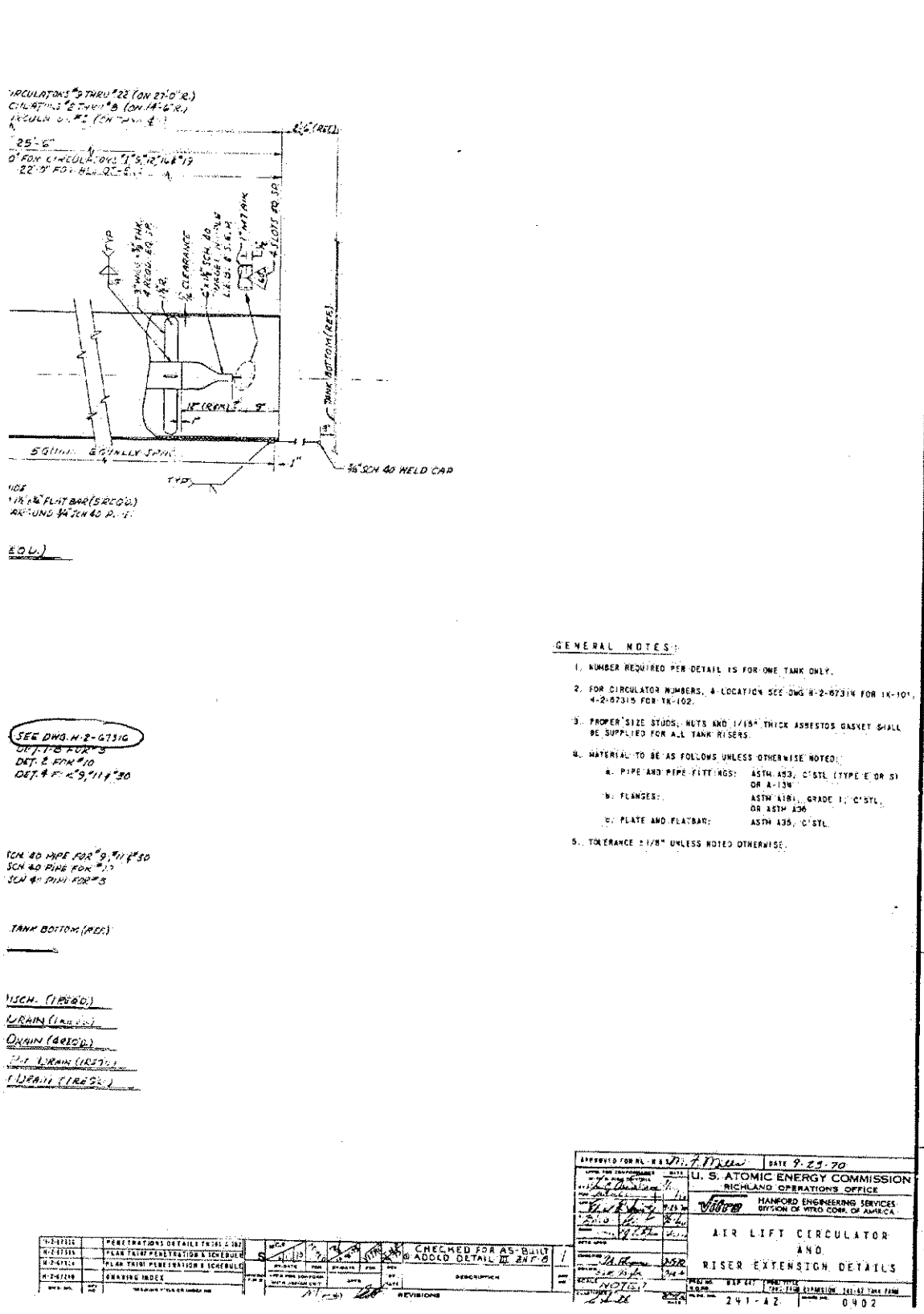
Figure A-7. Air Lift Circulator and Riser Extension Details - Part 2 of 2.



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APPENDIX B

POSTULATED BUMP SCENARIOS DEEMED NOT PLAUSIBLE

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APPENDIX B

POSTULATED BUMP SCENARIOS DEEMED NOT PLAUSIBLE

B.1 STEAM BUMP BY INTERSTITIAL SLUDGE SUPERHEAT

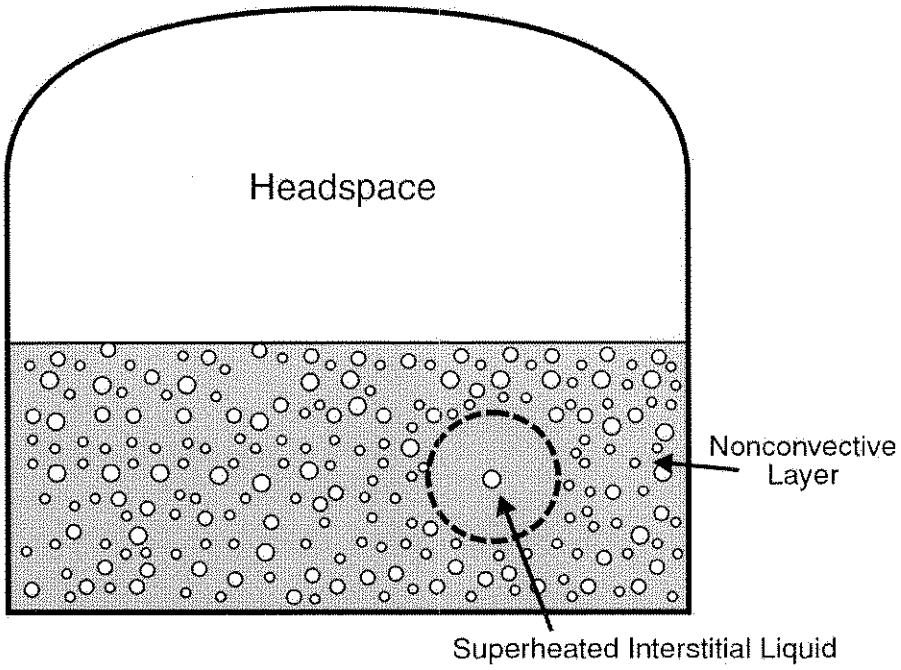
In Section 4.0, we demonstrated the importance of a deep supernatant layer as a necessary condition for a tank bump. Here we examine the potential for a steam bump within a non-convective layer during dryout (see Figure B-1). Steam bumps are known to occur in pure water that is rapidly brought to boiling in a vessel with smooth walls. In this case, boiling is started with large liquid water superheatings. The few bubbles that form at large superheats grow very rapidly at a rate controlled largely by heat conduction in the surrounding liquid just outside the bubbles. The process is rather unstable and could result in the ejection of liquid from the vessel (i.e., "bumping"). To prevent the occurrence of bumping, the water is usually seeded with solid particles or gas bubbles that act as nucleation sites and promote boiling at low superheats. In this case, numerous slowly growing bubbles are formed and a more uniform (smooth) boiling activity is realized. Thus, steam bumps in boiling water derive mainly from high liquid superheats. As we shall see below, significant liquid superheating is precluded in sludge by the presence of the solid phase particulate and pre-existing gas bubbles that serve as vapor-bubble nuclei.

In the analysis that follows, it is assumed that the non-convective layer evaporation process is one of bubble production by volumetric (decay) heating. This picture is believed to be conservative because water loss from the overheated layer is likely a dryout phenomenon in which an evaporation front propagates up from the bottom toward the surface of the layer. In this regard, it should be recognized that the effective upward heat flux in the sludge is very low ($\leq$ 100 W m^{-2}, see Section 3.6) and about two-to-four orders of magnitude less than typical nucleate boiling heat fluxes (10^4 to 10^6 W m^{-2}).

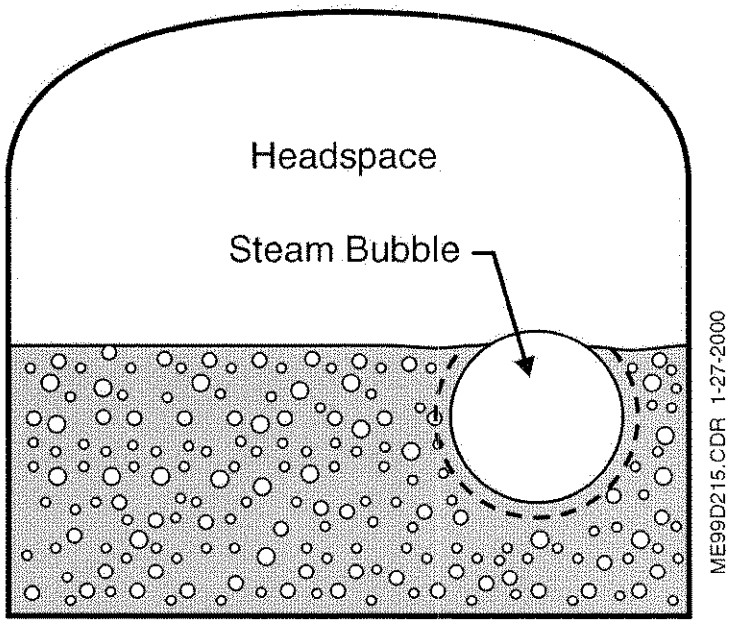
Bubble growth occurs when the internal pressure (vapor pressure plus partial pressure of any additional gas) is large enough to overcome the external bubble pressure due to surface tension and yield stress ($2\sigma / R + 2 / \sqrt{3}\, \tau_0$, where R is the bubble radius, σ is the surface tension, and τ_0 is the yield stress in the Bingham model of the non-convective layer). The bubble is then unstable and grows at a rate governed by the inertia of the surrounding liquid and conduction heat transfer from the surrounding liquid to the bubble "surface". The initial period of inertially-limited growth is important only in cases involving very high liquid superheats and/or low (sub-atmospheric) ambient pressures. This gives rise to a "waiting time" before a period of thermally-dominated bubble growth. After the waiting time, which is practically non-existent for the conditions of interest here, bubbles grow by the thermally-limited process and the bubble radius after time t is (see, e.g., Scriven [1959]):

$$R = Ja\ (\pi\, \alpha_\ell\, t)^{1/2} \qquad \text{(B-1)}$$

Figure B-1. Steam Bump Due to Interstitial Superheat in Non-Convective Layer (Hypothetical).



(a) Sludge with region of interstitial liquid heated above its boiling point



(b) Rapid bubble growth following nucleation of bubble in superheated region

with the Jakob number, Ja, defined as

$$\mathrm{Ja} = \frac{\rho_\ell \, c_{p,\ell} \left(T - T_{bp}\right)}{\rho_g \, h_{\ell g}} \tag{B-2}$$

In equations (B-1) and (B-2) T_{bp}, ρ_ℓ, $c_{p,\ell}$, α_ℓ, and $h_{\ell g}$ are, respectively, the boiling point, density, specific heat, thermal diffusivity, and latent heat of evaporation of the liquid (interstitial water), T is the instantaneous temperature of the volumetrically heated waste, and ρ_g is the density of the vapor in the bubble. In writing equation (B-1) it is assumed that the bubble displaces both the precipitate particles and the liquid as it grows, so that the bubble only contains water vapor. If, instead, the precipitate particles are locked in place so that the bubble must push the surrounding liquid through channels in a stationary precipitate matrix, then a different bubble growth equation is required (see Epstein [1994]). For the double-shell tanks of interest, bubbles growing between stationary particles is not possible (Gauglitz et al. 1996; and Stewart et al. 1996a).

As the liquid temperature T rises above the liquid boiling point owing to volumetric decay, heating new bubbles will form from the nuclei present in the liquid if the rate of energy input is higher than that removed by the bubbles nucleated previously at lower superheats. Thus, at any particular time there will be a distribution of bubble sizes within the waste. We will ignore this complication and assume that all the bubble nuclei in the system are activated as soon as the waste is heated to its boiling temperature T_{bp}. Subject to this assumption, the distribution of bubble sizes is a uniform one and given by R in equation (B-1).

By considering an energy balance for the boiling waste, we may write

$$Q = \rho_\ell \, c_{p,\ell} \frac{dT}{dt} + N \, h_{\ell g} \, \rho_g \, 4 \pi R^2 \frac{dR}{dt} \tag{B-3}$$

where N is the number of active nuclei (precipitate + gas bubbles) per unit volume of non-convective layer and Q is the volumetric decay heating rate (in W m^{-3}). Equation (B-3) simply states that the rate of energy input is equal to the rate of increase in liquid waste sensible heat plus the heat removed volumetrically by the growing bubbles. For small temperature increases, equation (B-3) may be integrated from $T = T_{bp}$ and $R = 0$ at $t = 0$ to get

$$T - T_{bp} = \frac{Q \, t}{\rho_\ell \, c_{p,\ell}} - \frac{h_{\ell g} \, N \, \rho_g}{\rho_\ell \, c_{p,\ell}} \frac{4}{3} \pi R^3 \tag{B-4}$$

Eliminating R between equations (B-1) and (B-4) gives

$$T - T_{bp} = \frac{Q \, t}{\rho_\ell \, c_{p,\ell}} - \frac{4 \pi \, h_{\ell g} \, N \, \rho_g}{3 \, \rho_\ell \, c_{p,\ell}} \left(\frac{\rho_\ell \, c_{p,\ell}}{\rho_g \, h_{\ell g}}\right)^3 \left(\pi \, \alpha_\ell \, t\right)^{\frac{3}{2}} \left(T - T_{bp}\right)^3 \tag{B-5}$$

Equation (B-5) is an implicit relationship between the instantaneous liquid superheat ($T - T_{bp}$) and time (t). A careful examination of equation (B-5) reveals the important behavior that $T - T_{bp}$ achieves a maximum value. This value can be determined by differentiating equation (B-5) with respect to time and setting the derivatives equal to zero. To facilitate this mathematical operation, it is convenient to introduce the following dimensionless variables:

$$\tau = \left(\frac{16\,\pi^5\,Q^4\,\alpha_\ell^3\,N^2}{9\,\rho_g^4\,h_{\ell g}^4} \right)^{\frac{1}{7}} t \tag{B-6}$$

$$\theta = \left(\frac{16\,\pi^5\,k_\ell^3\,N^2}{9\,Q^3} \right)^{\frac{1}{7}} \left(\frac{\rho_\ell\,c_{p,\ell}}{\rho_g\,h_{\ell g}} \right)^{\frac{4}{7}} \left(T - T_{bp} \right) \tag{B-7}$$

Then, equation (B-5) reduces to the compact and universal form

$$\theta = \tau - \tau^{\frac{3}{2}}\,\theta^3 \tag{B-8}$$

For any chosen value of dimensionless time τ, the dimensionless superheat is readily seen to be the solution of a cubic equation. Equation (B-8) is plotted in Figure B-2.

Figure B-2. Dimensionless Liquid Superheat Versus Dimensionless Time.

DIMENSIONLESS SUPERHEAT

To obtain the peak superheat value θ_{max}, we seek the condition $d\,\theta / d\,\tau = 0$. From equation (B-8), we find that this condition is satisfied at all points (θ_{max}, τ_{max}) that lie along the curve

$$\frac{3}{2}\,\theta_{max}^{3}\,\tau_{max}^{\frac{1}{2}} = 1.0 \tag{B-9}$$

Finally, solving equations (B-8) and (B-9) gives the maximum dimensionless superheat

$$\theta_{max} = \left(\frac{4}{27}\right)^{\frac{1}{7}} = 0.761 \tag{B-10}$$

which occurs at the dimensionless time

$$\tau_{max} = (324)^{\frac{1}{7}} = 2.28 \tag{B-11}$$

Using equations (B-6) and (B-7) to convert back to physical variables, we find that the liquid superheat attains its peak value after an elapsed time

$$t_{max} = \left(\frac{182\,\rho_g^4\,h_{\ell g}^4}{\pi^5\,Q^4\,\alpha_\ell^3\,N^2}\right)^{\frac{1}{7}} \tag{B-12}$$

and the peak liquid superheat is

$$T_{max} - T_{bp} = \left(\frac{Q^3}{12\,\pi^5\,k_\ell^3\,N^2}\right)^{\frac{1}{7}} \left(\frac{\rho_g\,h_{\ell g}}{\rho_\ell\,c_{p,\ell}}\right)^{\frac{4}{7}} \tag{B-13}$$

We note from equation (B-13) that the maximum liquid superheat increases with increasing decay power Q and decreases with increasing bubble nucleation site density N. All the parameters in equation (B-13) are known, except for the nucleation site density N. The potential number density of nucleation sites in waste can be bounded from above by assuming that each precipitate particle of radius r_p is an active site. This results in the estimate

$$N = \frac{\varepsilon_s}{\left(\frac{4}{3}\right)\pi\,r_p^3} \tag{B-14}$$

where ε_s is the volume fraction occupied by the solid precipitate ($\varepsilon_s \approx 0.5$) and r_p is the effective (average) radius of the precipitate particles ($r_p \approx 1.0\ \mu m$). Equation (B-14) results in $N \approx 10^{17}/m^3$, an estimate which is probably unrealistically high. The value of N for pre-existing gas bubbles is obtained from the relation

$$N = \frac{\alpha}{\left(\frac{4}{3}\pi r_b^3\right)} \tag{B-15}$$

where α is the volume fraction occupied by the gas bubbles (α Á 0.2) and r_b is the average bubble radius (r_b Á 1.0 mm). Equation (B-15) yields N Á 5 x $10^7/m^3$ for the number density of pre-existing gas-bubbles. Coincidentally, this value of N falls within the range of values for ordinary water (no precipitate particles) containing natural impurities (dust, etc.), namely 10^6 to $10^{11}/m^3$ (Richter 1981; Abdollahian et al. 1982; Ardon 1978; and Rivard and Travis 1980).

Some indication of the validity of equation (B-13) can be given by considering the Lipkis et al. (1956) experimental study of boiling in a volumetrically-heated aqueous KOH solution pool. In order to prevent bumpiness, a sheet of teflon™ with embedded aluminum chips was placed on the bottom of the test vessel. The aluminum/KOH reaction produced very many tiny hydrogen bubbles which acted as vapor-bubble nuclei. The volumetric power applied to the pool was nominally 1.5 x 10^7 W m^{-3}. The corresponding measured superheat was $\Delta T = 0.5°C$. Substituting these measured values into equation (B-13), together with the water physical properties $h_{\ell g} = 2.3 \times 10^6$ J kg^{-1}, $k_\ell = 0.68$ W m^{-1} K^{-1}, $c_{p,\ell} = 4200$ J kg^{-1} K^{-1}, $\rho_g = 0.6$ kg m^{-3}, and $\rho_\ell = 960$ kg m^{-3}, and solving for N gives

$$N = 2.3 \times 10^9 / m^3 \tag{B-16}$$

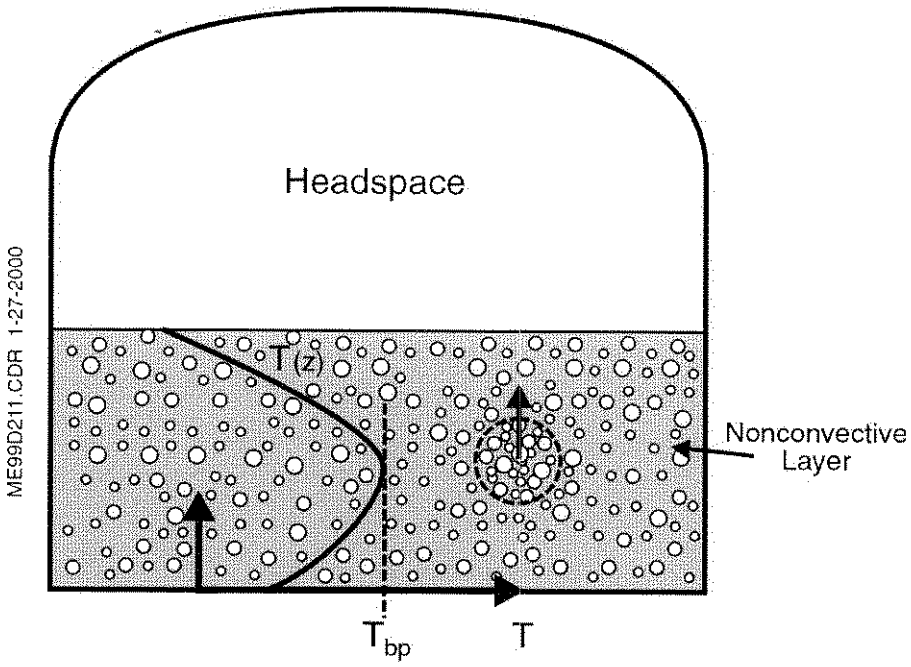
This is an encouraging result because it falls in the middle of the expected range of site densities 10^6 to $10^{11}/m^3$.

Inserting our previous estimate N Á 5 x $10^7/m^3$ for 1.0 mm pre-existing gas bubbles together with the decay heat rate Q = 200 W m^{-3} into equation (B-13) gives a maximum waste-liquid superheat of only $T_{max} - T_{bp} = 1.2 \times 10^{-2}$°C. Even if one adopts the lower end of the site density range for gas bubble, namely N = 4 x $10^5/m^3$ for r_b = 5 mm, the liquid superheat in boiling waste is still small and equal to $T_{max} - T_{bp} = 4.8 \times 10^{-2}$°C. Laboratory experience with boiling liquids indicate that these superheats are far too small to produce bumpy boiling action. For example, smooth volumetric boiling activity was achieved in the experiments of Lipkis et al. (1956) with measured water superheats as high as 0.5°C. We conclude by stating that the volume-heating rate in the non-convective layer is too low to produce a steam bump.

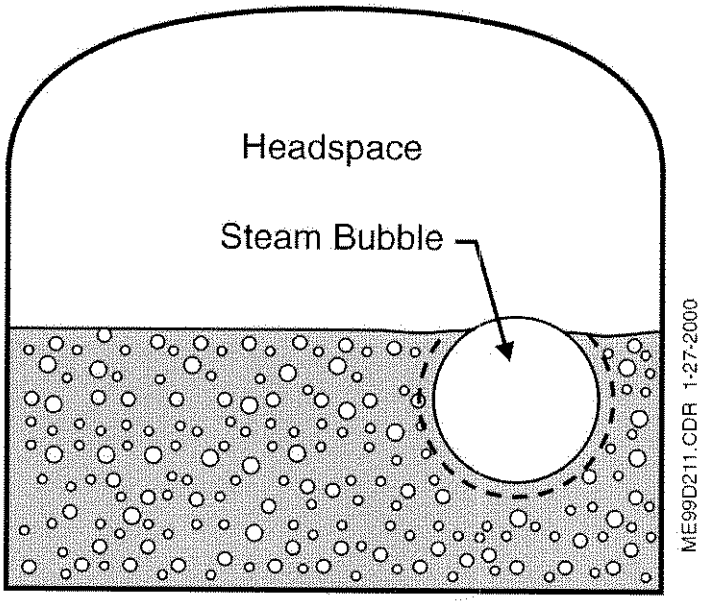
B.2 STEAM BUMP BY LOCAL CONVECTION IN SLUDGE (FUMAROLES)

Tank bumps have been postulated to occur via a buoyant displacement <u>within</u> a hot, otherwise non-convective layer (see Figure B-3). The mechanism that might cause a buoyant displacement within the non-convective layer is as follows. Generally, the waste material near the mid-plane of the non-convective layer retains more gas than the overlying layer that extends to the surface. A Taylor instability develops in which the central waste material is presumed buoyant enough with respect to the overlying layer to rise and mix with the overlying layer. During an overheated condition, the temperature of the sludge near the mid-plane of the non-convective

Figure B-3. Steam Bump Due to Local Convection in Non-Convective Layer (Hypothetical, "Fumarole").



(a) Hot sludge parcel begins to rise and superheat.



(b) Steam bubble growth within hot sludge parcel

layer is close to the boiling point of the interstitial liquid. As the initially, centrally located hot sludge rises through the non-convective layer, it experiences a reduction in hydrostatic pressure and its interstitial liquid may boil and produce steam. We emphasize that this mechanism differs from the rollover mechanism for steam production in that an overlying convective layer is not required - the buoyant displacement is postulated to occur within the non-convective layer itself. However, in the absence of a convective layer, it is difficult to envision significant waste release from the tank.

In order to rigorously apply the Taylor instability theory to Hanford sludge, it is necessary to take into account the viscoplastic nature of the sludge material. Construction of the equations and their solution for this case would be very difficult and no analysis of this problem is available. Here, we content ourselves with an analysis that considers the waste material to be a viscous Newtonian material. That is, the waste gel is assumed to be shocked into a liquefied state. The same waste rheology was assumed by Meyer et al. (1997) in their Taylor-instability model of buoyant displacements in DSTs. We are concerned with the waste tank situation in which a central horizontal waste layer of thickness h and low density lies below a relatively thick, dense layer that extends to the surface of the waste. The lower layer is less dense than the upper layer owing to a higher degree of gas retention in the lower layer. The two layers are assumed to have the same kinematic viscosity.

An approximate dispersion relation for the problem described above has been derived by Plesset and Whipple (1974) and is

$$h = \nu k^2 \left[1 + \frac{g\, k\, \Delta\rho / \rho}{\left[1 + \coth(kh)\right]\left(\nu k^2\right)^2} \right]^{1/2} - \nu k^2 \qquad \text{(B-17)}$$

where ν and ρ are the kinematic viscosity and the density of the waste material, respectively, $\Delta\rho$ is the density difference between the upper and lower layers, g is the gravitational constant, k is the wave number, and n is the growth rate of the unstable waves that develop at the boundary that separates the two layers. The wave number is related to the disturbance wavelength by the definition

$$k = \frac{2\pi}{\lambda} \qquad \text{(B-18)}$$

and the characteristic time for the waves to grow to an amplitude of the order of the wavelength is

$$\tau \cong \frac{1}{n} \qquad \text{(B-19)}$$

A typical in situ measurement in DSTs shows a void fraction increment in the lower layer over the upper layer of 10% (Stewart et al. 1996b). The void fraction in a hypothetical tank without a supernate layer could be much higher than 10%. Assuming 30% for the void fraction,

$\Delta\rho / \rho$ Á 0.3. The waste viscosity μ is assigned the value 10^4 Pa•s which is the peak measured value at the bottom of undisturbed DST waste, that is first-pass ball rheometer measurements reported by Stewart et al. (1996b) and Stewart (1998). The waste material density is approximately ρ Á 1600 kg m^{-3} so that $\nu = 6.25$ m^2 s^{-1}. Figure B-4 shows the characteristic time for the buoyant displacement to develop as a function of the wavelength of the disturbance that caused the instability for several relevant values of the thickness h of the central layer. The minimums in the curves correspond to the most unstable disturbance wavelengths. These waves cannot materialize within the Hanford waste tanks because they exceed the lateral dimensions of the tanks (~ 20 m). However, smaller wavelengths are also unstable and may occur with lower probability. The most probable wavelength coincides with the tank diameter. Despite the high viscosity assigned to the material, seven orders of magnitude larger than the viscosity of water, these waves will develop and reach the surface of the waste less than about 10 s.

Obviously, the Taylor instability has the potential of producing significant quantities of steam by transporting massive quantities of waste material from the hot mid-plane region to the surface in a relatively short period of time compared with, say, bubble rise times in the assumed Newtonian waste layer. When the sludge temperature is low and not conducive to steam production, the Taylor instability should still be operative and result in very efficient and dangerous gas release events. However, this has not been observed in waste tanks that lack a convective layer (e.g., SSTs). Field measurements indicate gas release times of at least 1.0 hour in duration. The release efficiencies are less than 10% with most of the releases in the 0.1 to 1.0% range. The actual small, lethargic releases are consistent with a mechanism of gas percolation to the surface through bubble inter-connectivity. Apparently, the strength of the material, which enables it to accumulate gas, stabilizes the waste layer against an internal buoyant displacement. If the Taylor stability analysis were performed for the viscoplastic case (a difficult analysis), one would most likely find a cutoff wavelength that exceeds the tank diameter.

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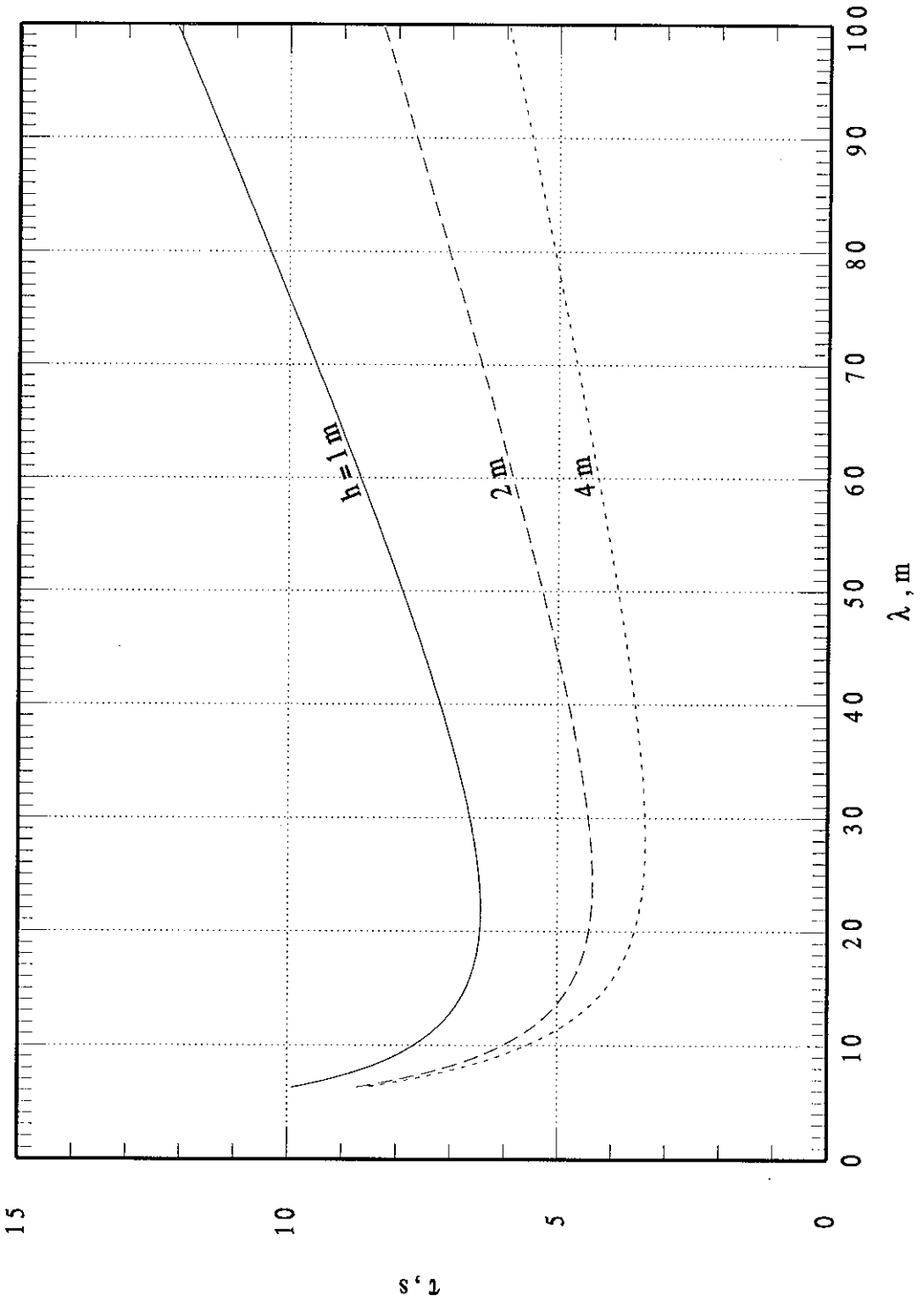
Figure B-4. Wave Growth Time Versus Disturbance Wave Length; Depth of Less-Dense Layer as a Parameter. ($\Delta\rho / \rho = 0.3, \mu / \rho = 6.3$ K g m^{-3})



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APPENDIX C

RISE DISTANCE TO YIELDING OF VOID-BEARING PARCEL

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APPENDIX C

RISE DISTANCE TO YIELDING OF VOID-BEARING PARCEL

In this appendix the assumption that the buoyant displacement parcel becomes fluid after rising only a short distance z is examined. Meyer et al. (1997) presented a model that describes the energy requirements to yield the gas-retaining material and transform it into a liquid state. According to the model, the material within the buoyant parcel will yield and start to flow when the available buoyant energy,

$$E_b = \int_0^z g\left[\rho_\ell V(z) - \rho_s V_s\right] dz \tag{C-1}$$

equals or exceeds the energy required to yield the parcel,

$$E_y = V_0 \varepsilon_y \tau_y \left(1 - \alpha_0\right) \tag{C-2}$$

In the above equations ρ_ℓ is the density of the convective layer, g is the gravitational constant, ε_y is the strain at failure (Á 1.0), τ_y is the yield stress of the non-convective layer material, α_0 is the initial void fraction within the non-convective layer which should be nearly equal to the neutral buoyancy void fraction (α_{NB}), V_0 and V (z) are, respectively, the initial volume of the parcel and the volume of the parcel at elevation z above the mid-plane of the non-convective layer, and ρ_s and V_s are, respectively, the density and volume of the void-free material within the non-convective layer.

The ratio of the two energies given by equations (C-1) and (C-2) is

$$\frac{E_b}{E_y} = \frac{\int_0^z g\left[\rho_\ell V(z) - \rho_s V_s\right] dz}{V_0 \varepsilon_y \tau_y \left(1 - \alpha_0\right)} \tag{C-3}$$

Meyer et al. (1997) compared equation (C-3) with scaled experimental results (Stewart et al. 1996) and concluded that most of the buoyant parcel will yield when $E_b / E_y \gtrsim 5.0$. They concluded that for current tank conditions the buoyant parcel must rise several meters before the buoyant parcel yields and flows. It should be recognized, however, that the increase in buoyant energy of the parcel at the current, relatively low waste temperatures is due mainly to bubble growth via hydrostatic pressure reduction with distance z. As the temperature of the non-convective layer increases and approaches the boiling point of the layer, bubble expansion by evaporation becomes increasingly important and the Meyer et al. (1997) criterion must be modified to account for this.

Assuming that the steam/non-condensible gas mixture that fills the void is always in equilibrium with the interstitial liquid at temperature T_{NC} (see equation (4-12) with $P_v = P_{eq}$), we have

$$\frac{V_b\,(z)}{V_b\,(0)} = \frac{P_{hs} + \rho_\ell\, g\, H - P_{eq}\left(T_{NCL}\right)}{P_{hs} + \rho_\ell\, g\,(H - z) - P_{eq}\left(T_{NCL}\right)} \tag{C-4}$$

where $V_b\,(0)$ is the initial void volume in the buoyant parcel before its ascent (i.e., at $z = 0$), $V_b\,(z)$ is the void volume at elevation z, and H is the distance from the mid-plane of the non-convective layer to the surface of the waste. The equilibrium assumption underlying equation (C-4) is justified because it gives results in good agreement with the non-equilibrium model when the temperature is low (see Figure 4-3) and when the temperature is high because the rise distances to yielding are small and the rise velocities through these distances are low. Note that in the low-temperature limit $P_{eq}\,(T_{NCL}) << P_{hs}$ and equation (C-4) reduces to the void expansion equation used by Meyer et al. (1997).

The total volume of the parcel at elevation z is

$$V\,(z) = V_s + V_b\,(z) \tag{C-5}$$

The density of the void-free material is related to ρ_ℓ and the neutral buoyancy void fraction α_{NB} by

$$\rho_s = \frac{\rho_\ell}{1 - \alpha_{NB}} \tag{C-6}$$

The volume of the void-free material and the initial void volume in the buoyant parcel may be expressed as

$$V_s = V_0\left(1 - \alpha_0\right) \tag{C-7}$$

$$V_b\,(0) = \alpha_0\, V_0 \tag{C-8}$$

Combining equations (C-1) and (C-5) to equation (C-8) gives

$$E_b = g\,\rho_\ell\,\alpha_0\,V_0 \int_0^z \left[\frac{V_b\,(z)}{V_b\,(0)} - k\right] d\,z \tag{C-9}$$

$$\text{where } k = \frac{\alpha_{NB}\left(1 - \alpha_0\right)}{\alpha_0\left(1 - \alpha_{NB}\right)} \tag{C-10}$$

Substituting equation (C-4) into equation (C-9) and carrying out the indicated integration yields

$$E_b = -g\,\rho_\ell\,\alpha_0\,V_0\,H\left[\frac{1+\gamma}{\gamma}\ln\left(1-\frac{\gamma}{1+\gamma}\,\frac{z}{H}\right)+k\,\frac{z}{H}\right] \tag{C-11}$$

where $$\gamma = \frac{\rho_\ell\,g\,H}{P_{hs}-P_{eq}\left(T_{NCL}\right)} \tag{C-12}$$

Dividing equation (C-11) by equation (C-2) leads to the criterion for the yielding of the parcel:

$$\frac{E_b\,\varepsilon_y\,\tau_y\left(1-\alpha_0\right)}{E_y\,g\,\rho_\ell\,\alpha_0\,H} = -\frac{1+\gamma}{\gamma}\ln\left(1-\frac{\gamma}{1+\gamma}\,\frac{z}{H}\right)-k\,\frac{z}{H} \tag{C-13}$$

which is an implicit expression for the rise distance z where failure of the parcel occurs. If the initial void fraction α_0 is equal to the neutral buoyancy void fraction, then k = 1 in equation (C-13).

Before solving equation (C-13), it is important to point out that the equation becomes invalid as T_{NCL} approaches the boiling point T_{bp} of the non-convective layer at the mid-plane static pressure, as defined by the equation

$$P_{eq}\left(T_{bp}\right) = P_{hs}+\rho_\ell\,g\,H = P_{NCL} \tag{C-14}$$

This is because as T_{bp} is approached equation (C-4) predicts more vapor production than is thermodynamically possible by converting the available sensible energy in the buoyant parcel to steam. Indeed the minimum rise distance z_{min} to yielding the parcel may be determined by replacing equation (C-4) with a void growth or "flashing" expression that accounts for the finite thermal energy stored in the void-free non-convective layer material.

If the sensible heat available in the buoyant parcel is adiabatically delivered to the surfaces of the bubbles, the mass m_v of steam produced as the parcel rises to elevation z is

$$m_v\,(z) = m_v\,(0) + \frac{m_s\,c_s\left[T_{NCL}-T\,(z)\right]}{h_{fv}} \tag{C-15}$$

where m_v (0) is the initial mass of steam in the parcel, c_s and m_s are, respectively, the specific heat and mass of the void-free material, h_{fv} is the latent heat of evaporation of the parcel's interstitial liquid, and T (z) is the temperature of the parcel at elevation z. Using the ideal gas law, m_v (z) and m_v (0) can be expressed as

$$m_v\,(z) = \frac{P\,(z)\,V_b\,(z)}{R\,T\,(z)} \tag{C-16}$$

$$m_v(0) = \frac{P_{NCL}\, V_b(0)}{R\, T_{NCL}} \tag{C-17}$$

where R is the ideal gas constant for water, P (z) is the static pressure at elevation z, and P_{NCL} is the pressure in the non-convective layer (see equation (C-14)). Also, m_s is given by

$$m_s = \rho_s V_s = \rho_s V_0 \left(1 - \alpha_0\right) \tag{C-18}$$

where again ρ_s is the density of the void-free non-convective material.

Substituting equations (C-16) to (C-18) into equation (C-15) results in

$$V_b(z) = \frac{T(z)}{T_{NCL}} \frac{P_{NCL}}{P(z)} V_b(0) + \frac{R\, T(z)\, \rho_s\, V_0 \left(1 - \alpha_0\right) c_s}{h_{fv}\, P(z)} \left[T_{NCL} - T(z)\right] \tag{C-19}$$

It will be seen below that the parcel rises only a short distance before it yields; consequently it is permissible to exploit the following approximations in equation (C-19):

$$T(z) \cong T_{NCL} \tag{C-20}$$

$$P(z) \cong P_{NCL} \tag{C-21}$$

except, of course, for the temperature difference term T_{NCL} - T (z). This term may be approximated by the linearized form of the Clausius-Clapeyron equation

$$T_{NCL} - T(z) = \frac{T_{NCL}^2\, R}{h_{fv}} \left[\frac{P_{NCL} - P(z)}{P_{NCL}}\right] = \frac{T_{NCL}^2\, R}{h_{fv}} \left[1 - \frac{P_{hs} + \rho_\ell\, g\, (H - z)}{P_{hs} + \rho_\ell\, H}\right] \tag{C-22}$$

Combining equations (C-19) to (C-22) gives the desired expression for the void volume enhancement in the rising and "flashing" buoyant parcel:

$$\frac{V_b(z)}{V_b(0)} = 1 + \frac{J\, \rho_\ell\, g\, z}{P_{NCL}} \tag{C-23}$$

$$\text{where} \quad J = \frac{R^2\, T_{NCL}^3\, \rho_s\, (1 - \alpha_0)\, c_s}{h_{fv}^2\, P_{NCL}\, \alpha_0} \tag{C-24}$$

Inserting equation (C-23) into equation (C-9) yields

$$E_b = g\, \rho_\ell\, \alpha_0\, V_0 \left[\frac{J\, \rho_\ell\, g\, z^2}{2\, P_{NCL}} + (1 - k)\, z\right] \tag{C-25}$$

Forming the ratio E_b / E_y and solving the result for z in the practical limit k = 1 gives the following expression for the minimum rise distance to yielding of the buoyant parcel:

$$z_{min} = \left[\frac{2\, E_b\, P_{NCL}\, \varepsilon_y\, \tau_y\, (1 - \alpha_0)}{E_y\, g^2\, \rho_\ell^2\, \alpha_0\, J} \right]^{1/2} \tag{C-26}$$

The solution to equation (C-13) for parameter values that correspond to conditions in tank 241-AZ-102 is presented in Figure C-1. The parameter values used in the calculations are listed in Table C-1. At low non-convective layer temperatures the parcel maintains a yield stress during its first 2 meters of travel. However, the vertical distance required to turn the parcel into a fluid decreases rapidly as its boiling point is approached. For all practical purposes, the boiling or near-boiling parcel can be assumed to liquefy as soon as it begins to move (z_{min} = 13 cm).

Figure C-1. Rise Distance to Yielding of Void-Bearing Parcel Versus Temperature of Non-Convective Layer; Input Parameters Pertain to Tank 241-AZ-102.

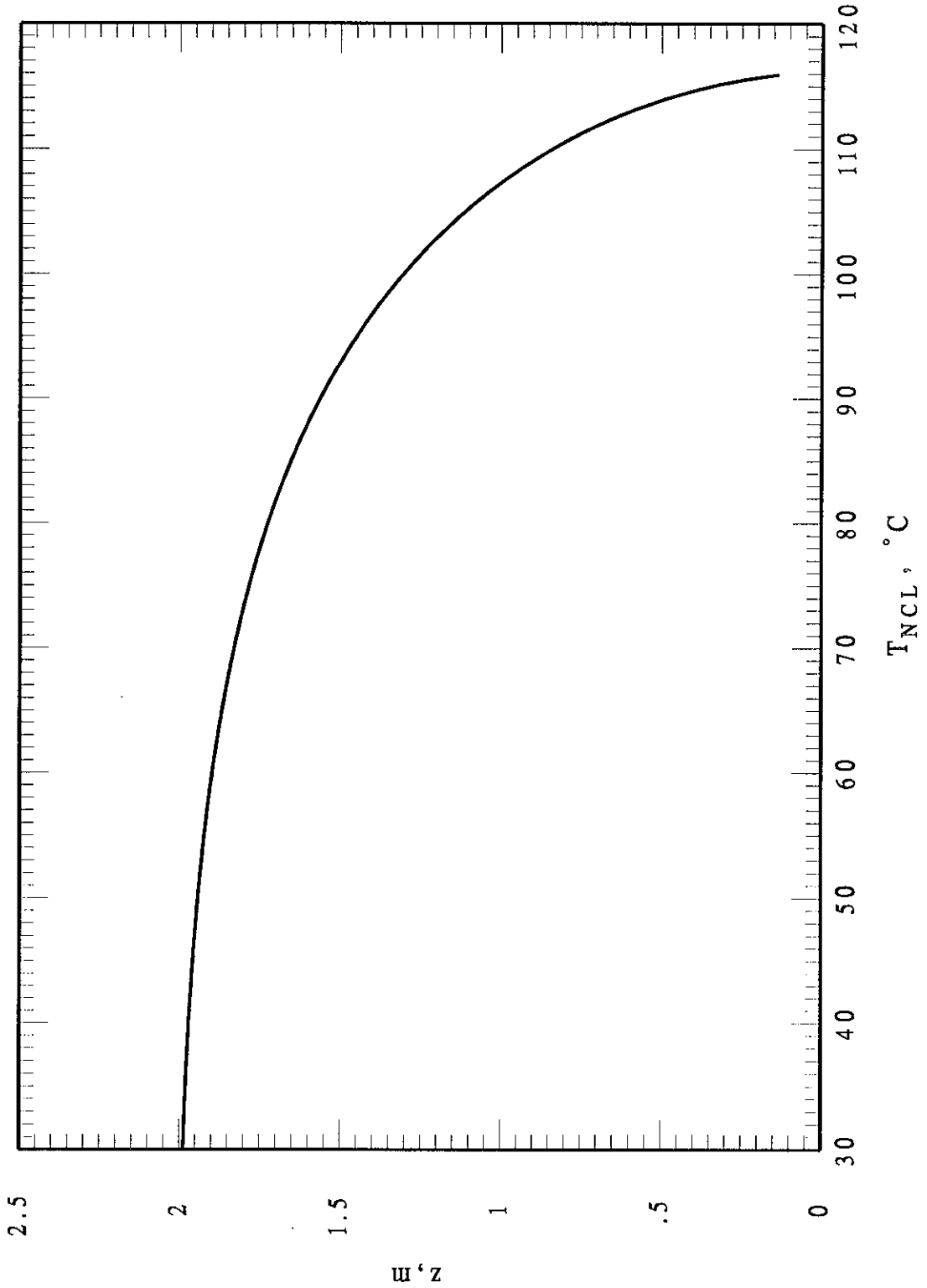

Table C-1. Parameter Values for the Buoyant Parcel Yielding Criterion (Tank 241-AZ-102).

$\alpha_0 = \alpha_{NB} = 0.262$	Initial void fraction.
$H = 7.44$ m	Depth to mid-plane of non-convective layer.
$\rho_\ell = 1100$ kg m^{-3}	Density of supernatant.
$\rho_s = 1490$ kg m^{-3}	Density of void-free non-convective layer material.
$c_s = 4200$ kg m^{-3}	Specific heat of void-free non-convective layer material.
$\tau_y = 100$ Pa	Yield strength of non-convective layer material.
$\varepsilon_y = 1.0$	Strain of non-convective layer material at yielding.
$E_b / E_y = 5.0$	Buoyant-to-yield energy ratio.
$h_{fv} = 2.2 \times 10^6$ J kg^{-1}	Latent heat of evaporation of interstitial water.

C.1 REFERENCES

Meyer, P. A., M. E. Brewster, S. A. Bryan, G. Chen, L. R. Pederson, C. W. Stewart, and G. Terrones, 1997, *Gas Retention and Release Behavior in Hanford Double-Shell Waste Tanks*, PNNL-11536, Rev. 1, Pacific Northwest National Laboratory, Richland, Washington.

Stewart, C. W., M. E. Brewster, P. A. Gauglitz, L. A. Mahoney, P. A. Meyer, K. P. Recknagle, and H. C. Reid, 1996, *Gas Retention and Release Behavior in Hanford Single-Shell Waste Tanks*, PNNL-11391, Pacific Northwest National Laboratory, Richland, Washington.

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APPENDIX D

BUBBLE GROWTH MODEL AND INPUT

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APPENDIX D

BUBBLE GROWTH MODEL AND INPUT

D.1 GASCAVGRTH.FOR: Calculations for Chapter 4 Figures

```
C GAS CAVITY GROWTH IN HOT WATER
C M EPSTEIN / G HAUSER
C 9-FEB-2000
C CORRECTIONS MADE 20-APR-2000
C
      IMPLICIT REAL*8 (A-H,O-Z)
      DATA PI /3.14159D0/
      CHARACTER*3 BTYPE
      DIMENSION TLA(6), D0A(6)
      DATA TLA /90.D0, 95.D0, 99.D0, 99.D0, 99.D0, 99.D0/
      DATA D0A /5.D-3, 5.D-3, 5.D-3, 1.D-3, 5.D-3, 1.D-2/

C
C INPUT
C
      RHOL=1100.D0
      G=9.8D0
      TL=100.D0
      DIFF=9.2D-5
      D0=5.D-3
      UB=0.2D0
      U=1.D0
      PHS=1.0136D5
      H=5.D0
      BTYPE='WET'
      STEPS=10000.D0
C
C WRITE BACK INPUT
C
C
      A=72.55D0
      B=-7.2067D3
      C=-7.1385D0
      D=4.046D-6
      E=2.D0
C
C FIRST DO CASES FOR TLA AND DOA ARRAYS DEFINED ABOVE; TOTAL OF SIX CASES
C WITH VARYING TL AND D0 PLOTS ARE H VS V AND VEQ
C
      DO I=1,6
         TL=TLA(I)
         T=TL+273.16D0
         D0=D0A(I)
C
         IF (I.EQ.3)
     &   OPEN(UNIT=2,FILE='GASCAVGRTH1.STORY',STATUS='NEW')
         WRITE(2,*) 'RHOL=',RHOL
         WRITE(2,*) 'G=',G
```

```
          WRITE(2,*) 'D=',D
          WRITE(2,*) 'U=',U
          WRITE(2,*) 'PHS=',PHS
          WRITE(2,*) 'D0=',D0
          WRITE(2,*) 'BTYPE=',BTYPE
          WRITE(2,*) 'STEPS=',STEPS
          CLOSE(UNIT=2)
          IF (I.EQ.6)
     &    OPEN(UNIT=2,FILE='GASCAVGRTH2.STORY',STATUS='NEW')
          WRITE(2,*) 'RHOL=',RHOL
          WRITE(2,*) 'G=',G
          WRITE(2,*) 'D=',D
          WRITE(2,*) 'U=',U
          WRITE(2,*) 'PHS=',PHS
          WRITE(2,*) 'TL=',TL
          WRITE(2,*) 'BTYPE=',BTYPE
          WRITE(2,*) 'STEPS=',STEPS
          CLOSE(UNIT=2)
          DO J=1,100
             H=FLOAT(J)/10.D0
             TERM1=C*LOG(T)
             TERM2=D*T**E
             PEQ=EXP(A+B/T+TERM1+TERM2)
             V0=4.E0/3.D0*PI*(D0/2.D0)**3
             B1=PEQ/(RHOL*G)*SQRT(24.D0*DIFF*UB/(U**2*V0))
             B2=(PHS+RHOL*G*H)/PEQ
             YF=RHOL*G*H/PEQ
C
C INITIAL CONDITIONS
C
             Y=0.D0
             IF (BTYPE.EQ.'WET') THEN
                BT=1.D0
             END IF
             IF (BTYPE.EQ.'DRY') THEN
                BT=0.D0
             END IF
             X=BT
             DY=YF/STEPS
C
C INTEGRATION
C
             IF (I.EQ.1)
     &       OPEN(UNIT=1,FILE='GASCAVGRTH1.OUT',STATUS='NEW')
             IF (I.EQ.2)
     &       OPEN(UNIT=1,FILE='GASCAVGRTH2.OUT',STATUS='NEW')
             IF (I.EQ.3)
     &       OPEN(UNIT=1,FILE='GASCAVGRTH3.OUT',STATUS='NEW')
             IF (I.EQ.4)
     &       OPEN(UNIT=1,FILE='GASCAVGRTH4.OUT',STATUS='NEW')
             IF (I.EQ.5)
     &       OPEN(UNIT=1,FILE='GASCAVGRTH5.OUT',STATUS='NEW')
             IF (I.EQ.6)
     &       OPEN(UNIT=1,FILE='GASCAVGRTH6.OUT',STATUS='NEW')
             DO WHILE(Y.LT.YF)
                Y=Y+DY
                V=(B2-BT)/(B2-Y-X)
```

```
                DXDY=(B1*SQRT(V)*(B2-Y)*LOG(1.D0+(1.D0-X)/(B2-Y))-
     &                (X*V*V)/(B2-BT))/(V+X*V*V/(B2-BT))
C                WRITE(1,*) Y,V,X,DXDY
                X=X+DXDY*DY
             END DO
             IF (BTYPE.EQ.'WET'.AND.PEQ.LT.PHS) THEN
                VEQ=(B2-1.D0)/(B2-Y-1.D0)
             ELSE
                VEQ=0.D0
             END IF
C             WRITE(*,*) H,V
             WRITE(1,*) H,V,VEQ
          END DO
          CLOSE(UNIT=1)
       END DO
C
C NOW DO ONE MORE CASE FOR D0=5 MM (5.E-3 M) H=5 M; U=1 M/S; AND UB=.2 M/S
C PLOTS WILL BE TL VS V AND VEQ
C
       D0=5.D-3
       H=5.D0
       U=1.D0
       UB=.2D0
C
       OPEN(UNIT=1,FILE='GASCAVGRTH.OUT',STATUS='NEW')
       DO J=8000,11000
          TL=FLOAT(J)/100.D0
          T=TL+273.16D0
          TERM1=C*LOG(T)
          TERM2=D*T**E
          PEQ=EXP(A+B/T+TERM1+TERM2)
          V0=4.E0/3.D0*PI*(D0/2.D0)**3
          B1=PEQ/(RHOL*G)*SQRT(24.D0*DIFF*UB/(U**2*V0))
          B2=(PHS+RHOL*G*H)/PEQ
          YF=RHOL*G*H/PEQ
C
C INITIAL CONDITIONS
C
          Y=0.E0
          IF (BTYPE.EQ.'WET') THEN
             BT=1.D0
          END IF
          IF (BTYPE.EQ.'DRY') THEN
             BT=0.D0
          END IF
          X=BT
          DY=YF/STEPS
C
C INTEGRATION
C
          DO WHILE(Y.LT.YF)
             Y=Y+DY
             V=(B2-BT)/(B2-Y-X)
             DXDY=(B1*SQRT(V)*(B2-Y)*LOG(1.D0+(1.D0-X)/(B2-Y))-
     &                (X*V*V)/(B2-BT))/(V+X*V*V/(B2-BT))
             X=X+DXDY*DY
          END DO
```

```
         IF (BTYPE.EQ.'WET'.AND.PEQ.LT.PHS) THEN
            VEQ=(B2-1.D0)/(B2-Y-1.D0)
         ELSE
            VEQ=0.D0
         END IF
         WRITE(1,*) TL,V,VEQ
      END DO
      CLOSE(UNIT=1)
      STOP
      END
```

D.2 GASCAVGRTH.GCL: Plot Script for Chapter 4 Figures

```
INPUT FILE 1 IS GASCAVGRTH1.OUT
      INPUT FILE 2 IS GASCAVGRTH2.OUT
      INPUT FILE 3 IS GASCAVGRTH3.OUT
      INPUT FILE 4 IS GASCAVGRTH4.OUT
      INPUT FILE 5 IS GASCAVGRTH5.OUT
      INPUT FILE 6 IS GASCAVGRTH6.OUT
      NUMBER OF COLUMNS IN IS 3
      COLUMN 1 LABEL IS H
      COLUMN 2 LABEL IS V
      COLUMN 3 LABEL IS VEQ

      X AXIS TICS IS 10
      Y AXIS TICS IS 10
      FRAME

      TEXT STYLE IS ROMAN+SOLID
      NOTAG
      SWITCH CHARACTER IS ^
      INSTRUCTION CHARACTER IS #
      LINE CONTINUATION CHARACTER IS $
      ROTATE Y AXIS MARKERS 0 DEGREES
      STORY CHARACTER SIZE IS .18
      PLACE STORY AT GOOD LOCATION

      PAGE
      BEGIN STORY
d#D.3;#o#U.3;#=5 mm
U=1.0 m/s
U#D.3;#b#U.3;#=0.2m/s
P#D.3;#hs#U.3;#=0.1MPa
      END STORY
      Y AXIS LABEL IS V#D.3;#b#U.3;#(H)/V#D.3;#b#U.3;#(0)
      X AXIS LABEL IS H,m
      X AXIS SCALE IS FROM 0 BY 1 TO 10
!      Y AXIS SCALE IS FROM 0 BY 50 TO 200
      PLOT H VS V FROM FILE 1 USING THICK LINE
! CURVE LABEL IS #U.5;#90^g^C<CENTERED>
      PLOT H VS V FROM FILE 2 USING THICK LINE
! CURVE LABEL IS #U.5;#95^g^C<CENTERED>
      PLOT H VS V FROM FILE 3 USING THICK LINE CURVE LABEL IS
#U.3;#99^g^C<CENTERED>.8
      PLOT H VS VEQ FROM FILE 1 USING THICK DASHED LINE CURVE LABEL IS
#U.3;#90^g^C<CENTERED>.8
```

```
      PLOT H VS VEQ FROM FILE 2 USING THICK DASHED LINE CURVE LABEL IS
#U.3;#95^g^C<CENTERED>.8
      PLOT H VS VEQ FROM FILE 3 USING THICK DASHED LINE CURVE LABEL IS
#U.3;#T#D.3;#^=^#U.3;#=99^g^C<CENTERED>.8
!      CAPTION IS Fig.4-3 Bubble expansion ratio versus depth of supernatent
pool; pool temperature$
! T#D.3;#^=^#U.3;# as a parameter. Dashed curves refer to zero mass transfer
resistance.
      DISPLAY

      PAGE
      BEGIN STORY
T#D.3;#^=^#U.3;#=99^g^C
U=1.0 m/s
U#D.3;#b#U.3;#=0.2m/s
P#D.3;#hs#U.3;#=0.1MPa
      END STORY
      PLOT H VS V FROM FILE 4 USING THICK LINE CURVE LABEL IS
#U.3;#d#D.3;#o#U.3;#=1mm<CENTERED>.8
      PLOT H VS V FROM FILE 5 USING THICK LINE CURVE LABEL IS
#U.3;#5mm<CENTERED>.8
      PLOT H VS V FROM FILE 6 USING THICK LINE CURVE LABEL IS
#U.3;#10mm<CENTERED>.8
      PLOT H VS VEQ FROM FILE 4 USING THICK DASHED LINE
!      CAPTION IS Fig.4-4 Bubble expansion ratio versus depth of supernatent
pool; initial bubble$
! diameter as a parameter. Dashed curve refers to zero mass transfer
resistance.
      DISPLAY

      PAGE
      BEGIN STORY
d#D.3;#o#U.3;#=5mm
H=5.0m
U=1.0 m/s
U#D.3;#b#U.3;#=0.2m/s
P#D.3;#hs#U.3;#=0.1MPa
      END STORY
      INPUT FILE 1 IS GASCAVGRTH.OUT
      NUMBER OF COLUMNS IS 3
      COLUMN 1 LABEL IS TL
      COLUMN 2 LABEL IS V
      COLUMN 3 LABEL IS VEQ
      X AXIS SCALE IS FROM 80 BY 5 TO 110
      X AXIS TICS IS 5
      X AXIS LABEL IS Temperature, ^g^C
      Y AXIS SCALE IS FROM 0 BY 100 TO 800
      PLOT TL VS MIN(800,V) FROM FILE 1 USING THICK LINE
!      CAPTION IS Fig.4-5 Bubble expansion ratio versus convective layer
temperature (<100^g^C) or$
! buoyant parcel temperature T#D.3;#nc#U.3;# during buoyant displacement.
Dashed curve refers to$
! zero mass transfer resistance.
      DISPLAY

      NO STORY
      NO CAPTION
```

```
X AXIS LABEL IS •
Y AXIS LABEL IS •
X WINDOW IS FROM 0 TO 99.99
PLOT TL VS MIN(800,VEQ) FROM FILE 1 USING THICK DASHED LINE
X AXIS SCALE IS SAME
Y AXIS SCALE IS SAME
DISPLAY
```

APPENDIX E

CLUSTER ENTRAINMENT MODEL AND INPUT

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APPENDIX E

CLUSTER ENTRAINMENT MODEL AND INPUT

E.1 TANK_BUMP.FOR: Chapter 5 Calculations

```
C TANK BUMP COMPUTER PROGRAM
C M EPSTEIN / G HAUSER
C 6-MAR-2000
C ALL VARIABLES ARE IN SI UNITS
C
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 ML,MLEN,MLEN0,M,K,MAER,MUG,JG,MDOTV
      LOGICAL NOT_ESCAPING,DONE
C
C INPUT
C
      OPEN(UNIT=1,FILE='TANK_BUMP.INP',STATUS='OLD')
      READ(1,*) UB        !BUBBLE VELOCITY
      READ(1,*) GRAV      !GRAVITATIONAL CONSTANT
      READ(1,*) DIF       !BUBBLE GAS H2/WATER VAPOR DIFFUSION COEFFICIENT
      READ(1,*) TL1       !INITIAL TEMERATURE OF NONCONVECTIVE LAYER
C                          (STARTING VALUE)
      READ(1,*) TL2       !INITIAL TEMERATURE OF NONCONVECTIVE LAYER
C                          (ENDING VALUE)
      READ(1,*) DTL       !TEMERATURE OF NONCONVECTIVE LAYER (INCREMENT)
C NOTE IF DTL = 0.0 THEN ONLT TL1 CASE WILL BE RUN AND DETAILED OUTPUT SAVED
      READ(1,*) H0        !INITIAL DEPTH OF CONVECTIVE LAYER
      READ(1,*) PHS0      !INITIAL HEAD SPACE PRESSURE
      READ(1,*) VHS0      !INITIAL HEAD SPACE VOLUME
      READ(1,*) HOUT      !INITIAL HEIGHT OF OUTLET PIPE ABOVE SURFACE
C                         !OF CONVECTIVE LAYER
      READ(1,*) VBC0      !INITIAL VOLUME OF BUBBLE CLUSTER
      READ(1,*) DB0       !INITIAL DIAMETER OF REPRESENTATIVE BUBBLE
      READ(1,*) VL        !VOLUME OF CONVECTIVE LAYER
      READ(1,*) RHOL      !DENSITY OF CONVECTIVE LAYER
      READ(1,*) R         !IDEAL GAS CONSTANT
      READ(1,*) M         !MOLECULAR WEIGHT OF HEADSPACE GAS
      READ(1,*) GAMA      !SPECIFIC HEAT RATIO OF HEADSPACE GAS
      READ(1,*) K         !OVERALL LOSS COEFICIENT FOR RISER PIPE
      READ(1,*) HRISER    !VERTICAL HEIGHT OF RISER PIPE
      READ(1,*) ARISER    !FLOW AREA IN RISER
      READ(1,*) MUG       !VISCOSITY OF BUBBLE GAS (VAPOR)
      READ(1,*) RHOG      !DENSITY OF BUBBLE GAS (VAPOR)
      READ(1,*) SIG       !SURFACE TENSION OF LIQUID WASTE
      READ(1,*) ALPHA     !VOID FRACTION OF BUBBLE CLUSTER
      READ(1,*) PHEPA     !HEPA FILTER FAILURE PRESSURE
      READ(1,*) IRELEASE  !=1 ALL AEROSOL RELEASED
C                         !=0 RELEASE DURING DEPRESSUIZATION
      READ(1,*) MLEN0     !INITIAL MASS OF LIQUID IN BUBBLE CLUSTER
      READ(1,*) CL        !SPECIFIC HEAT OF LIQUID
      READ(1,*) HVL       !LIQUID HEAT OF EVAPORIZATION
      READ(1,*) TCL       !TEMPERATURE OF CONVECTIVE LAYER
      READ(1,*) MV        !MOLECULAR WEIGHT OF LIQUID
```

```
      READ(1,*) E0        !ENTRAINMENT COEEFFICIENT
C
      READ(1,*) DTAU      !INTEGRATION TIME STEP
      READ(1,*) DPR       !PRINTOUT TIME STEP
      READ(1,*) TAUEND    !FORCED END OF PROBLEM TIME (FOR DEBUGGING)
      TLI=TL1
      IF (DTL.GT.0.D0)
     &  OPEN(UNIT=4,FILE='TANK_BUMP.HISTORY',STATUS='UNKNOWN')
      DONE=.FALSE.
      DO WHILE (.NOT.DONE)
         IF (DTL.EQ.0.D0) DONE=.TRUE.
C
         PI=ACOS(0.D0)*2.D0
C
C
C CALCULATE INITIAL VOLUME OF REPRESENTATIVE BUBBLE
         VB0=PI/6.D0*DB0**3
C
C CALCULATE VAPOR PRESSURE AT BUBBLE SURFACE
         TL=TLI
         PEQ=1.102D11*EXP(-5185.D0/TL)
C
C INITIAL CONDITIONS AT TIME TAU=0)
         TAU=0.D0
         VBBAR=1.D0
         E=PEQ
         MLEN=MLEN0
         ZBC=0.D0
         H=H0
         ML=0.D0
         PR=DPR
C
         IF (DTL.EQ.0.0) THEN
            OPEN(UNIT=3,FILE='TANK_BUMP.OUT',STATUS='UNKNOWN')
            OPEN(UNIT=7,FILE='TANK_BUMP.PRN',STATUS='NEW',
     &           CARRIAGECONTROL='LIST',RECL=200)
         END IF
C
         DO WHILE(ZBC.LT.H.AND.TAU.LT.TAUEND)
C
C CALCULATE VAPOR PRESSURE AT BUBBLE SURFACE
            PEQ=1.102D11*EXP(-5185.D0/TL)
C
C CALCULATE VOLUME OF BUBBLE CLUSTER
            VBC=VBC0*VBBAR
C
C CALCULATE BUBBLE CLUSTER RISE VELOCITY

            U=0.76D0*(GRAV**3*VBC)**(1.D0/6.D0)
C
C DEPTH OF CONVECTIVE LAYER
            H=H0*((VL+VBC)/(VL+VBC0))
C
C HEADSPACE PRESSURE
            PHS=(VHS0**GAMA*PHS0)/(VHS0+VBC0-VBC)**GAMA
C
```

```
C DIFFERENTIAL EQUATION FOR VERTICAL LOCATION OF CENTER OF BUBBLE CLUSTER
            DZBCDT=U
C
C NORMALIZED BUBBLE VOLUME
            VBBAR=(E+PHS+RHOL*GRAV*H-PEQ)/(PHS+RHOL*GRAV*(H-ZBC))
C
C CALCULATE PRESSURE IN NONCONVECTIVE LAYER
         PNC=PHS+RHOL*GRAV*(H-ZBC)
C
C DIFFERENTIAL EQUATION FOR E
            DEDT=SQRT(24.D0*DIF/VB0*UB*VBBAR)*PNC*
     &            LOG(1.D0+(PEQ-E/VBBAR)/(PNC-PEQ))
C
C BUBBLE CLUSTER SURFACE AREA
            ABC=4.83D0*(VBC+MLEN/RHOL)**(2.D0/3.D0)
C
C VAPOR GENERATION RATE
            MDOTV=MV*VBC0/(R*TL)*DEDT
C
C DIFFERENTIAL EQUATION FOR LIQUID MASS IN BUBBLE CLUSTER
            DMLENDT=RHOL*ABC*E0*U-MDOTV
C
C DIFFERENTIAL EQUATION FOR TEMPERATURE OF LIQUID IN BUBBLE CLUSTER
            DTLDT=-((TL-TCL)*RHOL*E0*U*ABC)/MLEN-MDOTV*HVL/(MLEN*CL)
C
C BUBBLE PRESSURE
            PV=E/VBBAR
C
C LIQUID ESCAPE THROUGH RISER
            DP=PHS-PHS0+RHOL*GRAV*(H-H0-HOUT-HRISER)
            NOT_ESCAPING=(DP.LE.0.D0.OR.H.LE.H0+HOUT)
            IF (NOT_ESCAPING) THEN
               DMLDT=0.D0
            ELSE
               DMLDT=SQRT((2.D0*DP*RHOL)/K)*ARISER
            END IF
C
C OUTPUT
            IF (TAU.GE.PR.AND.DTL.EQ.0.0) THEN
               WRITE(7,100) TAU,DMLENDT,DEDT,MDOTV,U,ABC,DTLDT,TL,
     &                      MLEN,VBC
 100           FORMAT(10(1PG13.5))
               WRITE(3,*) ' '
               WRITE(3,*) TAU,ZBC,E,VBC,U,H,PHS,VBBAR,PV,DZBCDT,DEDT,
     &                 PEQ-PV,DEDT/SQRT(24.D0*DIF/VB0*U*VBBAR),
     &                 ML,DP,MLEN,TL,
     &                 -5185.D0/LOG((PHS+RHOL*GRAV*(H-ZBC))/1.102D11)
               PR=PR+DPR
            END IF
C
C INTEGRATE
            ZBC=ZBC+DZBCDT*DTAU
            E=E+DEDT*DTAU
            ML=ML+DMLDT*DTAU
            MLEN=MLEN+DMLENDT*DTAU
            TL=TL+DTLDT*DTAU
            TAU=TAU+DTAU
```

```
          END DO
          IF (DTL.EQ.0.0) THEN
             WRITE(7,100) TAU,DMLENDT,DEDT,MDOTV,U,ABC,DTLDT,TL,
     &                    MLEN,VBC
             WRITE(3,*) ' '
             WRITE(3,*) TAU,ZBC,E,VBC,U,H,PHS,VBBAR,PV,DZBCDT,DEDT,
     &            PEQ-PV,DEDT/SQRT(24.D0*DIF/VB0*U*VBBAR),
     &            ML,DP,MLEN,TL,
     &                  -5185.D0/LOG((PHS+RHOL*GRAV*(H-ZBC))/1.102D11)
          END IF
          IF (PHS.GT.PHEPA) THEN
C
C INITIAL HEADSPACE DENSITY
             RHOHS0=(PHS0*M)/(R*TL)
C
C FINAL HEADSPACE DENSITY
             RHOHS=RHOHS0*PHS/PHS0
C
C AEROSOL GENERATION EFFICIENCY
             JG=ALPHA*U
             EFF=7.13D-4*((MUG**4*RHOG**2*(RHOL-RHOG)**3)/
     &          (SIG**9*GRAV**5))**(1.D0/8.D0)*JG**3
C
C AEROSOL RELEASED (MASS)
             IF (IRELEASE.EQ.1) FACTOR=1.D0
             IF (IRELEASE.EQ.0)
     &          FACTOR=(1.D0-(PHS0/PHS)**(2.D0-1.D0/GAMA))
             MAER=EFF*RHOHS*VBC*FACTOR
          ELSE
             MAER=0.D0
          END IF
          IF (DTL.EQ.0.0) THEN
             OPEN(UNIT=2,FILE='TANK_BUMP.STORY',STATUS='UNKNOWN')
             WRITE(2,*) ' MASS AEROSOL RELEASED=',MAER,'Kg'
          END IF
          IF (DTL.GT.0.0) THEN
             WRITE(4,*) ' '
             WRITE(4,*) TLI,VBBAR,MAER,U,ML,PHS
             WRITE(*,*) TLI,VBBAR
             TLI=TLI+DTL
             IF (TLI.GT.TL2) DONE=.TRUE.
          END IF
       END DO
       CLOSE(UNIT=1)
       CLOSE(UNIT=2)
       CLOSE(UNIT=3)
       CLOSE(UNIT=4)
       STOP
       END
```

E.2 TANK_BUMP.INP: Chapter 5 Input

```
0.2        !UB; BUBBLE VELOCITY
 9.8D0      !GRAV; GRAVITATIONAL CONSTANT
 9.2D-5     !DIF; BUBBLE GAS H2/WATER VAPOR DIFFUSION COEFFICIENT
 373.0      !TL1; INITIAL TEMERATURE OF NONCONVECTIVE LAYER (STARTING VALUE)
```

```
 373.0      !TL2; INITIAL TEMERATURE OF NONCONVECTIVE LAYER (ENDING VALUE)
 0.0        !DTL; TEMERATURE OF NONCONVECTIVE LAYER (INCREMENT)
 8.D0       !H0; INITIAL DEPTH OF CONVECTIVE LAYER
 1.0119D5   !PHS0; INITIAL HEAD SPACE PRESSURE
 1800.D0    !VHS0; INITIAL HEAD SPACE VOLUME
 4.D0       !HOUT; INITIAL HEIGHT OF OUTLET PIPE ABOVE SURFACE OF CONVECTIVE
LAYER
 32.D0      !VBC0; INITIAL VOLUME OF BUBBLE CLUSTER
 5.D-3      !DB0; INITIAL DIAMETER OF REPRESENTATIVE BUBBLE
 3200.D0    !VL; VOLUME OF CONVECTIVE LAYER
 1210.D0    !RHOL; DENSITY OF CONVECTIVE LAYER
 8314.D0    !R; IDEAL GAS CONSTANT
 29.D0      !M; MOLECULAR WEIGHT OF HEADSPACE GAS
 1.4D0      !GAMA; SPECIFIC HEAT RATIO OF HEADSPACE GAS
 2.D0       !K; OVERALL LOSS COEFICIENT FOR RISER PIPE
 4.D0       !HRISER; VERTICAL HEIGHT OF RISER PIPE
 0.2D0      !ARISER; FLOW AREA IN RISER
 1.2D-5     !MUG; VISCOSITY OF BUBBLE GAS (VAPOR)
 0.6D0      !RHOG; DENSITY OF BUBBLE GAS (VAPOR)
 0.059      !SIG; SURFACE TENSION OF LIQUID WASTE
 0.66666D0  !ALPHA; VOID FRACTION OF BUBBLE CLUSTER
 1.D5       !PHEPA; HEPA FILTER FAILURE PRESSURE 1.356D5
 1          !IRELEASE; =1 RELEASE ALL AEROSOL; =0 ONLY DURING DEPRESS
 4.D4       !MLEN0; INITIAL MASS OF LIQUID IN BUBBLE CLUSTER
 4200.D0    !CL; SPECIFIC HEAT OF LIQUID
 2.2D6      !HVL; LIQUID HEAT OF EVAPORIZATION
 373.D0     !TCL; TEMPERATURE OF CONVECTIVE LAYER
 18.D0      !MV; MOLECULAR WEIGHT OF LIQUID
 0.1D0      !E0; ENTRAINMENT COEEFFICIENT

 1.D-5      !INTEGRATION TIME STEP
 0.001D0    !PRINT OUT TIME STEP
 100.D0     !FORCED END OF PROBLEM
```

E.3 Validation of HADCRT1.4 + Tank Bump Models Code

This sub-section demonstrates proper functioning of the HADCRT 1.4 + Bump Models code by showing that it reproduces the stand-alone tank bump model, which is listed in Appendix E.1 and discussed in Section 5.0. If HADCRT 1.4 + Bump Models (hereafter referred to as the code) reproduces the stand-alone results, then the code has been correctly assembled and the tank bump model has been merged with the integral features of the code.

Consider the simple case of an open headspace with an infinite amount of supernatant and the following inputs:

```
 0.2        !UB; BUBBLE VELOCITY
 9.8D0      !GRAV; GRAVITATIONAL CONSTANT
 9.2D-5     !DIF; BUBBLE GAS H2/WATER VAPOR DIFFUSION COEFFICIENT
 373.00     !TL1; INITIAL TEMP NONCONVECTIVE LAYER (STARTING VALUE)
 373.00     !TL2; INITIAL TEMP NONCONVECTIVE LAYER (ENDING VALUE)
 0.0        !DTL; TEMERATURE OF NONCONVECTIVE LAYER (INCREMENT)
  8.D0      !H0; INITIAL DEPTH OF CONVECTIVE LAYER
 1.0119D5   !PHS0; INITIAL HEAD SPACE PRESSURE
 1800.D10   !VHS0; INITIAL HEAD SPACE VOLUME
```

```
4.D0        !HOUT; INITIAL HEIGHT OF OUTLET PIPE ABOVE
32.D0       !VBC0; INITIAL VOLUME OF BUBBLE CLUSTER
5.D-3       !DB0; INITIAL DIAMETER OF REPRESENTATIVE BUBBLE
3200.D10      !VL; VOLUME OF CONVECTIVE LAYER
1210.D0     !RHOL; DENSITY OF CONVECTIVE LAYER
8314.D0     !R; IDEAL GAS CONSTANT
29.D0       !M; MOLECULAR WEIGHT OF HEADSPACE GAS
1.3D0       !GAMA; SPECIFIC HEAT RATIO OF HEADSPACE GAS
2.D0        !K; OVERALL LOSS COEFICIENT FOR RISER PIPE
4.D0        !HRISER; VERTICAL HEIGHT OF RISER PIPE
0.2D0       !ARISER; FLOW AREA IN RISER
1.4D-5      !MUG; VISCOSITY OF BUBBLE GAS (VAPOR)
0.7D0       !RHOG; DENSITY OF BUBBLE GAS (VAPOR)
0.059       !SIG; SURFACE TENSION OF LIQUID WASTE
0.66666D0 !ALPHA; VOID FRACTION OF BUBBLE CLUSTER
100        !PHEPA; HEPA FILTER FAILURE PRESSURE 1.356D5
1           !IRELEASE; =1 RELEASE AEROSOL; =0 ONLY DURING DEPRESS
4.D4        !MLEN0; INITIAL MASS OF LIQUID IN BUBBLE CLUSTER
4200.D0     !CL; SPECIFIC HEAT OF LIQUID
2.2D6       !HVL; LIQUID HEAT OF EVAPORIZATION
373.D0      !TCL; TEMPERATURE OF CONVECTIVE LAYER
18.D0       !MV; MOLECULAR WEIGHT OF LIQUID
0.1D0       !E0; ENTRAINMENT COEEFFICIENT
1.D-5       !INTEGRATION TIME STEP
0.1D0       !PRINT OUT TIME STEP
100.D0      !FORCED END OF PROBLEM
```

The HADCRT input file that replicates this run is shown in Appendix E.4 and is referred to as TEST1.DAT. Only the tank bump models are activated for the comparison.

TANK_BUMP.FOR results are listed on the following pages for these quantities: bubble volume ratio (gas volume divided by initial gas volume), parcel mass of liquid, and bubble rise velocity. The first two quantities reflect integral results and provide a good basis for comparison.

The preceding TANK_BUMP.FOR results must be compared to code results, which are shown below in Figure E.4.

Agreement between the two calculations demonstrates that the code is functioning as intended. Agreement is not perfect, however, for several reasons. The code uses the relatively complex integration scheme described in Section 5.5 TANK_BUMP.FOR uses a simple explicit integration scheme, and hence, requires a very small time step. The code calculation continues after the parcel bursts through the supernatant top and accounts for the added energy of vapor and aerosol added to the headspace. TANK_BUMP.FOR stops once the supernatant surface is penetrated. The code calculates temperature-dependent properties; TANK_BUMP.FOR does not. Calculations are also very sensitive to time step.

Figure E.1 TANK_BUMP.FOR Results for Test Bubble Rise Velocity

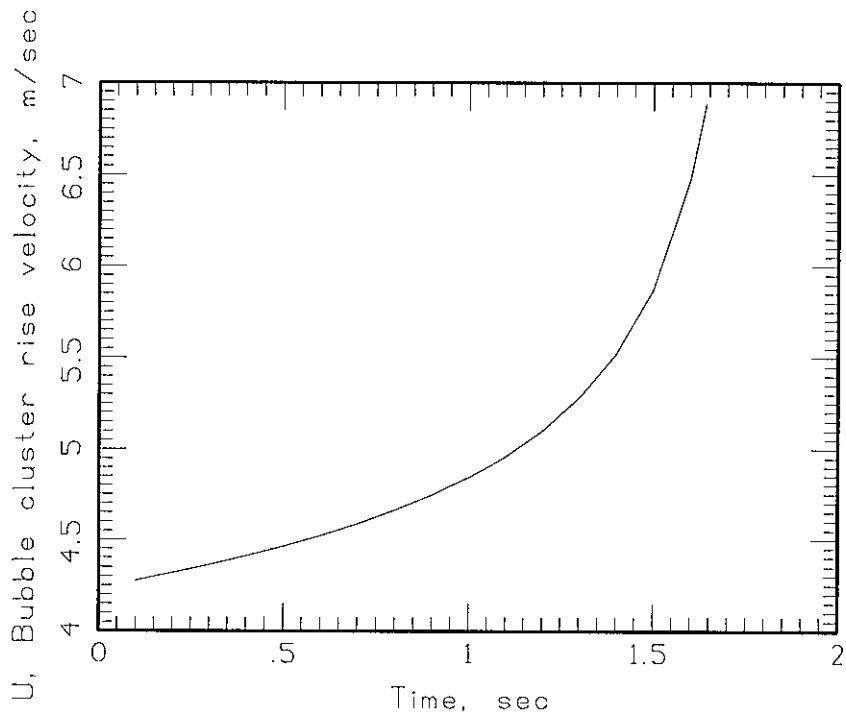


Figure E.2 TANK_BUMP Results for Test Volume Expansion Ratio

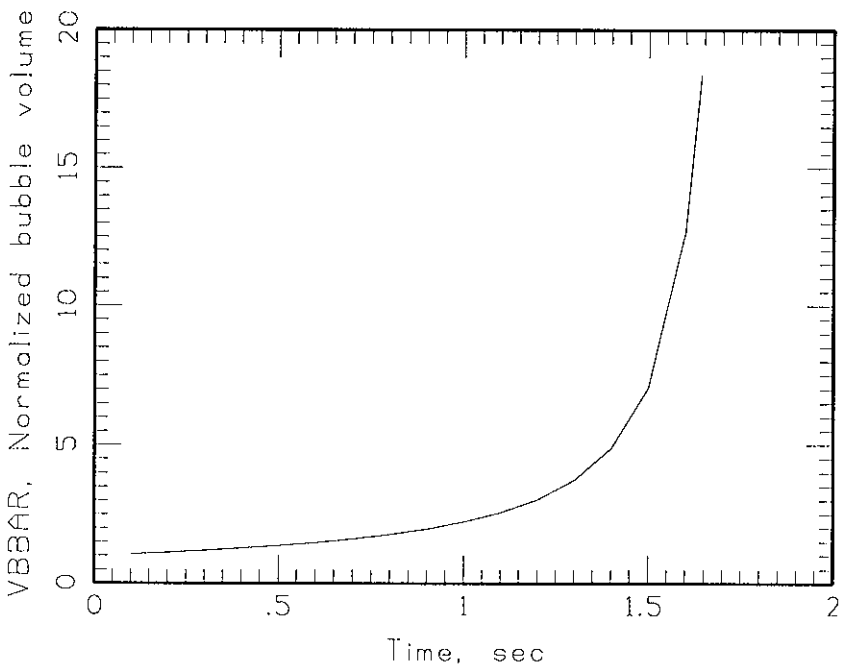


Figure E.3 TANK_BUMP.FOR Results for Test Mass of Liquid

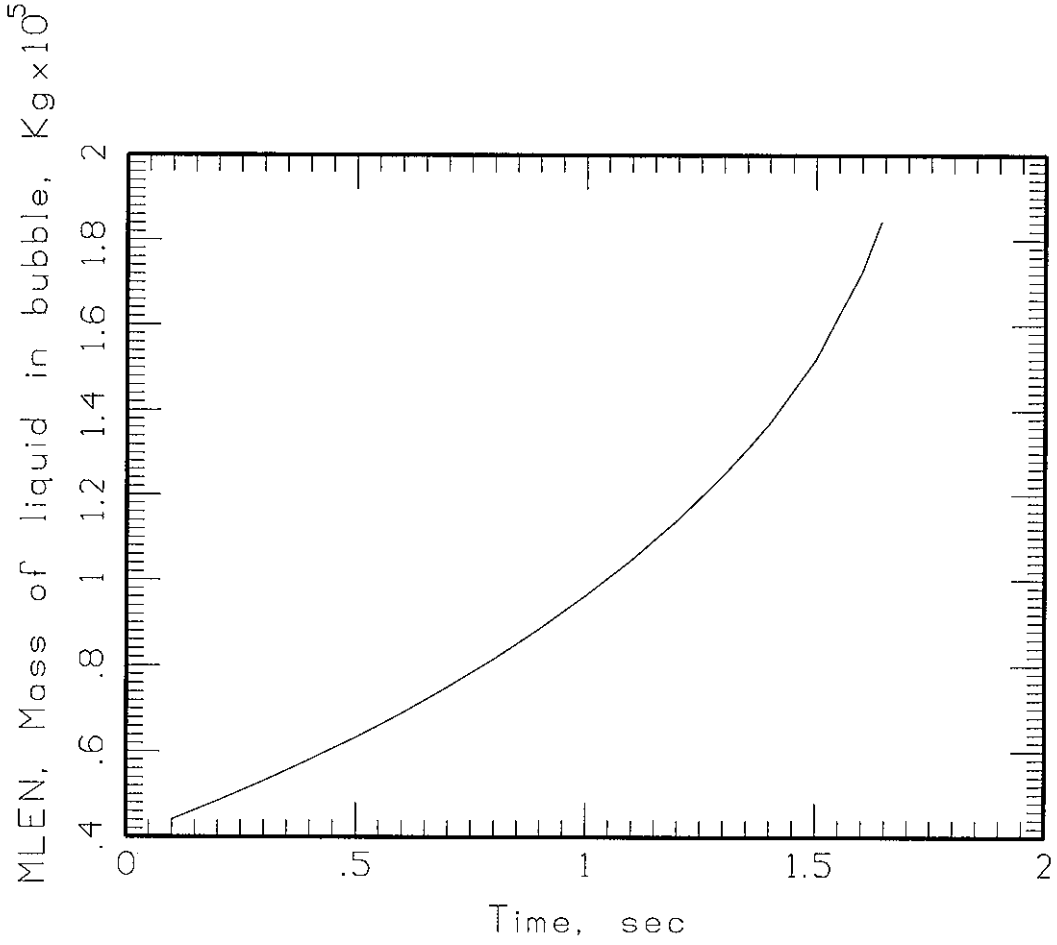
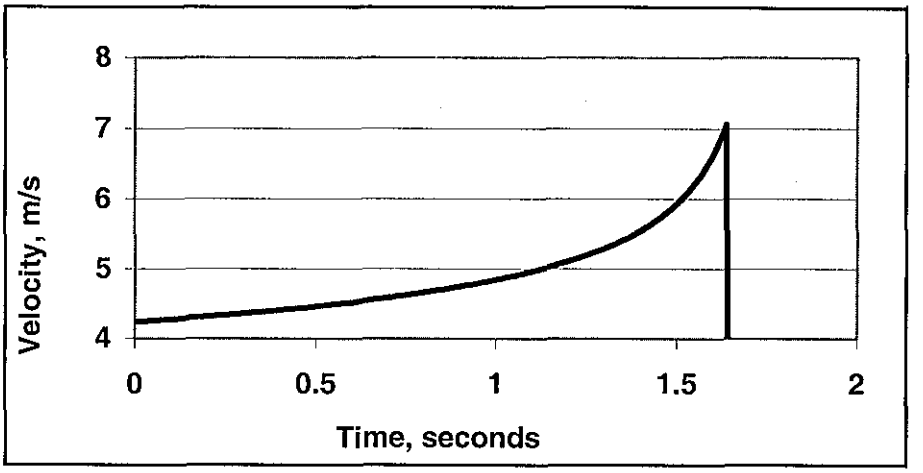
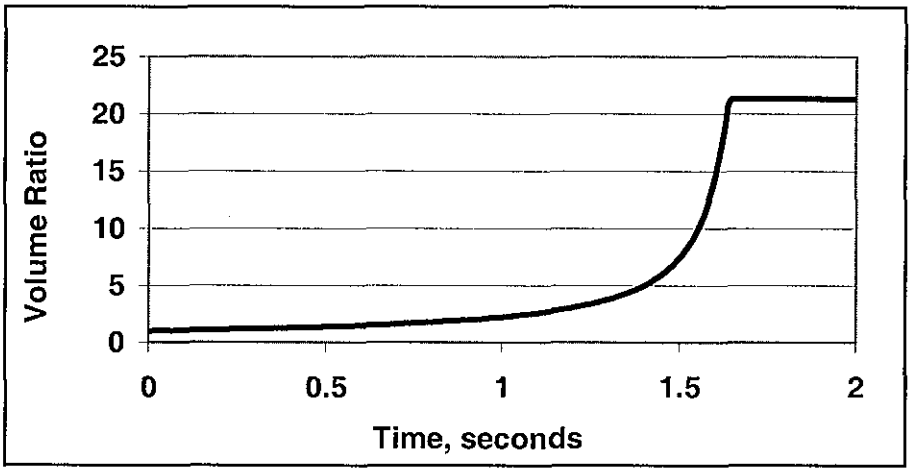
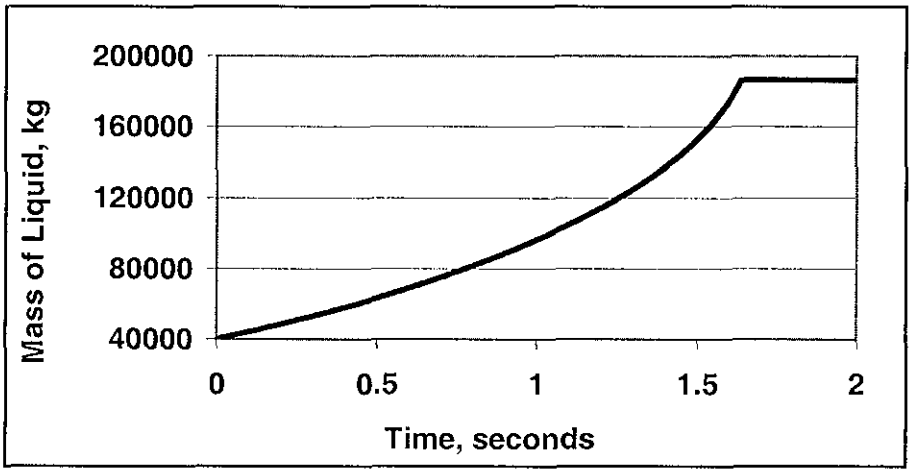


Figure E.4 Code Results for TANK_BUMP.FOR Comparison







E.4 HADCRT Test Input File for Comparison with TANK_BUMP.FOR

```
*******************************************************************
*   TANK BUMP PV test
*
*******************************************************************
*
*-----------------------------------------------------------------
CONTROL     ! Major keyword group
*-----------------------------------------------------------------
 TITLE      ! Keyword; next line is title, title can be any length*  -

*****************************************************************
       TEST
*****************************************************************

 END TITLE ! Anything after END is a comment
*
 TIMING     ! Keyword
   TSTART      0.     !  START TIME, >0 FOR RESTART RUN
   TLAST    2.5 !  END TIME
   DTMIN              !  MIN TIMESTEP (Seconds)
     0.0  0.001
     0.1  0.001
     0.2  0.001
     0.3  0.001
     1.0  0.001
     2.0  0.001
     3.0  0.001
   DTMAX              !  MAX TIMESTEP (Seconds)
     0.0  0.001
     0.1  0.001
     0.2  0.001
     0.3  0.001
     1.0  0.001
     2.0  0.001
     3.0  0.001
  DTPRIN             !  PRINT INTERVAL (Seconds)
     0.0  0.25
     1.0  0.25
     2.0  0.25
     3.0  0.25
     4.0  0.25
    10.0  100.0
    100.  1000.0
   1000.  10000.0
   PLTMIN             !  MIN PLOT INTERVAL (Seconds)
     0.0  0.01
     1.0  0.01
     2.0  0.01
     3.0  0.01
    10.0  0.01
    100.  0.01
   1000.  0.01
   PLTMAX             !  MAX INTERVAL WITHOUT PLOT (Seconds)
     0.0  0.01
```

```
     1.0  0.01
     2.0  0.01
    10.0  0.01
    100.  0.01
   1000.  0.01
   DTRST            !  RESTART INTERVAL (Seconds)
   0.0      100000.
*
   FTPCH      0.003       !  FRACTIONAL CHANGE IN T AND P
   FAECH      0.003       !  FRACTIONAL CHANGE IN aerosol mass
   FPPLCH     0.03         !  FRACTIONAL CHANGE FOR PLOTTING
 END TIMING ! TIMING is a comment.
*
*.................................................................
 PLOT      ! Keyword for plotting section
* Plotting syntax:
*
* PRESSURE n rlist - Pressure, Pa
* GAS-T  n rlist  - Gas Temperature, K
* HS-TI  n hlist  - Heat Sink Temperature - Inner Surface, K
* HS-TO  n hlist  - Heat Sink Temperature - Outer Surface, K
* HS-TA  n hlist  - Heat Sink Temperature - Average, K
* AEROSOL n rlist - Aerosol Mass (Total), kg
* GAS-W  n jlist  - Mass Flowrate, kg/s
* GAS-WX n jlist  - CounterCurrent Mass Flowrate, kg/s
* SPECIAL-X n xlist - Special model state variable
* SPECIAL-R n xlist - Special model rate variable
* GAS-X    GASNAME n rlist  - Gas Mole Fraction
* GAS-RH   GASNAME n rlist  - Gas Relative Humidity
* GAS-MASS GASNAME n rlist - Gas Mass (Species), kg
* AER-MASS GASNAME n rlist - Aerosol Mass (Species), kg
* MASS     GASNAME n rlist - Total Mass (Species), kg
* LIQ-MASS - GASNAME n rlist - Deposited Mass (Species), kg
*
* Pressure, Gas Temperature, and total aerosol mass require a region
* list
*
* Heat Sink Temperatures need a heat sink number list
*
* Flowrates need a junction number list
*
* Gas concentration, relative humidity, individual species gas mass,
* individual species aerosol mass, total (gas+aerosol) individual
* species mass, and individual species deposited liquid mass require
* a region and gas name
*
* BUMP special state & rate variables are:
*  1=  Bubble height
*  2=  Volume ratio
*  3=  Vapor pressure
*  4=  Headspace volume
*
  PRESSURE          1   1      ! Pressure in 1, 2, 3
  AEROSOL           1   1     ! Mass of total aerosol
  SPECIAL-X         6   1 2 3 4  5  6
  SPECIAL-X         2   8 9
  SPECIAL-R         4   1 2 3 4
```

```
  SPECIAL-R          2   8 9
 END PLOT  ! PLOT is a comment
*
*.................................................................
 ACTIVE MODELS ! Keyword; MODELS is a comment; 1 = on, 0 = off
  IJUNC   0    ! Junction flow model
  ICCFLW  0    ! Counter-current flow model
  IHSINK  0    ! Heat sinks
  ICNDS   0    ! Condensation
  IASED   0    ! Aerosol Sedimentation
  IALEAK  0    ! Aerosol Leakage
  IFOG    0    ! Fog formation
  ISRC    1    ! User-defined sources
  ISENS   0    ! Sensitivity runs
  IBUMP   1    ! BUMP Runs
  IPLTYP  2    ! SPREADSHEET
 END ACTIVE MODELS ! ACTIVE MODELS  is a comment
*
*.................................................................
 MODEL PARAMETERS
  AGAMMA   2.5   ! Shape factor for nonsphericity for coagulation
  ACHI     1.0   ! Shape factor for nonsphericity for stokes'law
  AFEO     1.0   ! Collision efficiency: 1.0 Fuchs, 0.33 Prupacher-Klett
 END MODEL PARAMETERS
*
*
C-----------------------------------------------------------------------
C      SOURCE GROUP:  GROUPS REPEATED FOR INPUT # OF REGIONS
C        END OF GROUP DESIGNATED BY 'REGION' OR 'END' KEYWORDS
C      ENTER: TIME, TEMP, FLOWRATES, POWER
*
* STEAM SOURCE FROM VAPORIZATION
* BASED ON 40 KW / 2.2E6 = 0.022 KG/S
* HEAT SOURCE IS POWER - STEAM - OVERBURDEN = ABOUT 10 KW
*
* SOURCES       1                !-- KEYWORD AND # SOURCE GROUPS
*  REGION  1  GASES  1           !-- REGION #, # GASES; <0 MEANS AEROSOL
*  STEAM                         !-- Gas
*0.0   100.0   0.022E0   1.E4     !   TIME, TEMP (C), KG/S, WATTS
*1.E3  100.0   0.022E0   1.E4
*1.E5  100.0   0.022E0   1.E4
*  END REGION                    !  END OF SOURCE IN THIS REGION
* END SOURCE                     !  END ALL SOURCES
*
*
 CELSIUS

END CONTROL    ! End of CONTROL keyword group
*
*-----------------------------------------------------------------------
VOLUMES    1      ! total number of control volumes
*-----------------------------------------------------------------------
* No more than 5 columns (regions) at a time
* Units:
* VOLUME m^3, SED_AREA m^2, ELEVATION m, TEMP_GAS K, PRESSURE  Pa
*
*
```

```
*              HEADSPACE
 REGIONS       1
  VOLUME       1.e9
  SED_AREA     411.
  ELEVATION    0.0
  TEMP_GAS     100.0
  PRESSURE     1.0119E5
 END REGIONS  ! REGIONS is a comment
*
*.................................................................
* Gas composition of each region; specify mole fraction of each gas
* No more than five columns at a time
*
* **30% H2 in air using 1% H2O, 20% O2, 79% N2 Initially
*
 GASES          1
  STEAM        0.95
  OXYGEN       0.01
  NITROGEN     0.04
 END GASES          ! GASES is a comment
*
*.................................................................
* Aerosol concentration of each region (kg/m^3)
* No more than five columns at a time
*
AEROSOLS       1
 WASTE        0.000
END AEROSOLS ! AEROSOLS is a comment
*
END VOLUMES ! VOLUMES is a comment
*
*
*-----------------------------------------------------------------
BUMP! Input Section for "DCRT.For" Model
*-----------------------------------------------------------------
TANK
  IRBUMP       1           ! BUMP region index
  HEIGHT_CL    8.00         ! Conv layer height
  T_WASTE      373.0      ! Non-Conv Waste temp, K
  T_SUPER      373.0       ! Supernatant Temp.
  VOLUME_CL    3200.E10       ! Conv layer volume, m^3
  GAS_VOL      32.00       ! Volume of released gas, m^3
  MASS_LIQ     4.00E4       ! Mass of liquid in cluster
  NBMAX         1       ! Number of total bumps
END TANK
*
*.................................................................
WASTE
  DENSITY_CL  1210.       ! Conv layer density, kg/m^3
  SURT_CL     0.059       ! Conv layer surface tension, N/m
END
*.................................................................
MODEL
  BUB_DIAM  0.005         ! Bubble diameter, m
  DIFFB     9.2E-5        ! Diffusion coefficient
  FBENT     1.0           ! Multiplier on Ishii release model
  ENTB      0.1E0         ! Entrainment mult for Ricou-Spalding
```

```
  TINTB      436.E0        ! Time between bumps
  TBUMP      200.          ! Development use only
END MODEL
*
*.................................................................
*
END DCRT
*
```

APPENDIX F

HADCRT CHANGES AND INPUT

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APPENDIX F

HADCRT CHANGES AND INPUT

Changes to HADRT 1.4 are listed here. These changes include new coding written specifically for this work (BUMP.FOR) and changes to existing routines. The assembly of HADCRT 1.4 + Tank Bump Models is shown in Appendix E, where it is demonstrated that the code produces results that are very close to the results of the stand-alone model described in Appendix E.

F.1 BUMP.FOR: Addition to HADCRT for Chapter 8

```
C*********************************************************************
C
C     HADCRT: CREATED FOR THE PROJECT HANFORD MANAGEMENT COMPANY (PHMC)
C
C     WITH A LIMITED USE AND OWNERSHIP LICENSE GRANTED BY:
C
C     FAUSKE & ASSOCIATES, INC. (FAI)
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C
C*********************************************************************

      SUBROUTINE BUMP (ICALL)
      IMPLICIT REAL (A-H, K-Z)
C=====================================================================
C
C     TANK BUMP CALCULATION ROUTINE
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C
C     INCLUDES:
C       BUBBLE GROWTH PHASE
C       AEROSOL RELEASE & MIXING CUP PHASE
C       BLOWDOWN (NO ACTION)
C     ICALL = 1: NORMAL CALL FROM RATES
C             2: FROM INTEGRATE, ASSIGN VOLUME UPDATE
C
C=====================================================================
      INCLUDE 'PARAMS.CMG'
      INCLUDE 'CNTRL.CML'
      INCLUDE 'GASN.CML'
      INCLUDE 'GASP.CML'
      INCLUDE 'BUMP.CML'
      INCLUDE 'REGIN.CML'
      INCLUDE 'STATE1.CML'
      INCLUDE 'STATE2.CML'
      INCLUDE 'RATES1.CML'
      INCLUDE 'RATES2.CML'
      INCLUDE 'JUNCS.CML'
      INCLUDE 'TIMEIN.CML'
      INCLUDE 'STATE.CMG'
      DIMENSION WENT(INGAS)
      DIMENSION TMX0(10),DTMX0(10),TMN0(10),DTMN0(10)
      DIMENSION TPMX0(10),DTPMX0(10),TPMN0(10),DTPMN0(10)
      DIMENSION TPRN0(10),DTPRN0(10)
      DATA IFIRST /1/
      DATA PI /3.14159E0/, RGAS /8314.E0/, GRAV /9.81E0/
C---------------------------------------------------------------------
C     INITIALIZE ANYTHING NEEDED ON FIRST PASS
C     IWASTE= GAS INDEX OF 'WASTE' FOR ENTRAINMENT
C---------------------------------------------------------------------
      IF (IFIRST .EQ. 1) THEN
          IFIRST= 0
C
C     PHASE OF CALCULATIONS:
C     CONVENTION: TIME = 0 IS START OF FIRST BUBBLE RISE
C
C     IBRISE= 1: BUBBLE RISE
C             0: AFTER RELEASE
C     CHANGE WHEN TIMER EXPIRES: TBNEXT IS TIME OF NEXT BUMP
C      NBUMP= NUMBER OF BUMPS, UP TO INPUT VALUE OF NBMAX
C
          IBRISE= 1
          TBNEXT= 1.E6
          NBUMP= 1.E0
C
C         POINTERS
C
          IWASTE= IGNAM('WASTE      ',GAS,INGAS)
          IH2O=   IGNAM('STEAM      ',GAS,INGAS)
          IH2 =   IGNAM('HYDROGEN   ',GAS,INGAS)
          IO2 =   IGNAM('OXYGEN     ',GAS,INGAS)
          IC2 =   IGNAM('CARBON_DIO',GAS,INGAS)
          ICO =   IGNAM('CARBON_MON',GAS,INGAS)
          IN2 =   IGNAM('NITROGEN   ',GAS,INGAS)
C          IH2OTR= IGNAM('STEATRAC   ',GAS,INGAS)
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```
C          IWASTR= IGNAM('WASTTRAC  ',GAS,INGAS)
C
C         ZERO OUT VECTORS OF ENTRAINED MATERIAL AND SPECIAL STATE VARS
C
      DO 120 II=1,INXSP
         XSP(II)= 0.E0
 120  CONTINUE
C
C     ASSIGNMENT OF SPECIAL VECTOR:
C     1  ZBUB  BUBBLE CLUSTER AVG HEIGHT, STARTS AT ZERO
C     2  VRAT  RATIO OF BUBBLE VOLUME V/V0, STARTS AT 1.E0
C     3  PBUB  STEAM PRESSURE IN BUBBLE
C     4  VHS   HEADSPACE VOLUME
C     5  ZW    (FOR PLOTS) WATER LEVEL
C     6  GAMMA (FOR PLOTS) GAMMA
C     7  WOUT  (FOR PLOTS) OUTFLOW
C     8  TBC   BUBBLE CLUSTER LIQUID TEMPERATURE
C     9  MLBC  BUBBLE CLUSTER LIQUID MASS
C     10 FROUDE NUMBER
C         AND EQUILIBRIUM PRESSURE
C         AND SAVE INITIAL GAS VOLUME
C
          VB0= 4.E0/3.E0 * PI * DB0**3
          TCL= TSUPR
          VOLHS0 = VOLR(IRBUMP)
          VBC= VBC0
          HCL= ZW0
          PEQ= SPV(TWASTE, IH2O)
          XSP(1)= 0.E0
          XSP(2)= 1.E0
          XSP(3)= PEQ
          XSP(4)= VOLHS0
          XSP(5)= ZW0
          XSP(6)= GAMM(IRBUMP)
          XSP(8)= TWASTE
          XSP(9)= MLBC0
          XSP(10)= 0.E0
C
C     SAVE INPUT TIMESTEP CONTROL INFORMATION:
C     USER PROVIDES THROUGH TIMEIN.CML:
C     TIDTMAX(10), DTMAX1(10)    MAX TIMESTEP CONTROL LOOKUPS
C     TIDTMIN(10), DTMIN1(10)    MIN TIMESTEP CONTROL LOOKUPS
C     THESE ARE SAVED RESPECTIVELY AS:
C     TMX0(10),  DTMX0(10),
C     TMN0(10),  DTMN0(10)
C
C     INPUTS AND SAVED VALUES ARE BASED ON THE FOLLOWING RULE:
C     ENTRIES 1-5 APPLY DURING BUBBLE RISE
C     ENTRIES 6-10 APPLY BETWEEN BUBBLE RISE EVENTS
C     THEREFORE 5 ENTRIES MUST BE MADE FOR BUBBLE RISE,
C         SO THAT INPUTS 6-X ARE READ
C     TIME LOOKUP VALUES TIDTMAX() AND TIDTMIN() ARE RELATIVE
C         TO THE START OF EACH PHASE
C
C     SAME APPLIES TO PLOTS, SAVED AS TPMX0() ETC
C     SAME APPLIES TO PRINT, SAVED AS TPRN0(), DTPRN0()
C
```

```
          DO 130 II=1,10
          TMX0(II)= TIDTMAX(II)
          DTMX0(II)= DTMAX1(II)
          TMN0(II)= TIDTMIN(II)
          DTMN0(II)= DTMIN1(II)
          TPMX0(II)= TIPLTMAX(II)
          DTPMX0(II)= PLTMAX1(II)
          TPMN0(II)= TIPLTMIN(II)
          DTPMN0(II)= PLTMIN1(II)
          TPRN0(II)= TIDTPRIN(II)
          DTPRN0(II)= DTPRIN1(II)
 130      CONTINUE
C
      ENDIF
C
C-----------------------------------------------------------------------
C     ADJUST VOLUME AFTER INTEGRATION
C-----------------------------------------------------------------------
      IF (ICALL .EQ. 2 .AND. IBRISE .EQ. 1) THEN
          VOLR(IRBUMP)= XSP(4)
          RETURN
      ENDIF
C-----------------------------------------------------------------------
C     INITIALIZATION EACH PASS: ONLY CASE ICALL = 1 REMAINS
C-----------------------------------------------------------------------
      RZBUB= 0.E0
      RVRAT= 0.E0
      RPBUB= 0.E0
      RVHS=  0.E0
      QENTR= 0.E0
      WENTW= 0.E0
      RTBC= 0.E0
      RMLBC= 0.E0
C
      DO 250 II=1,INGAS
         WENT(II)= 0.E0
 250  CONTINUE
      DO 260 II=1,INXSP
         RXSP(II)= 0.E0
 260  CONTINUE
C-----------------------------------------------------------------------
C
C     INTEGRATE BUBBLE RISE AND GET PV WORK
C     1  ZBUB  BUBBLE CLUSTER AVG HEIGHT, STARTS AT ZERO
C     2  VRAT  RATIO OF BUBBLE VOLUME V/V0, STARTS AT 1.E0
C     3  PBUB  STEAM PRESSURE IN BUBBLE
C     4  VHS   HEADSPACE VOLUME
C     8  TBC  BUBBLE CLUSTER TEMPERATURE, STARTS AT TWASTE
C     9  MLBC  MASS OF LIQUID IN BUBBLE CLUSTER
C
C     SAVE THESE FOR REFERENCE:
C     5  HCL   WATER LEVEL
C     6  GAMM() GAMMA
C     7  WOUT   OUTFLOW
C     10 FROUDE NUMBER
C
C-----------------------------------------------------------------------
```

```
C
C     RENAME SPECIAL VARIABLES FOR SCRUTABILITY
C
      ZBUB= XSP(1)
      VRAT= XSP(2)
      PBUB= XSP(3)
      VHS=  XSP(4)
      TBC= XSP(8)
      MLBC= XSP(9)
C
C     DECIDE ON PHASE OF PROBLEM:
C     NEED AUXILIARY RELATIONS IF DURING RISE PHASE
C
      IF (IBRISE .EQ. 1) THEN
          VBC= VBC0 * VRAT
          HCL= ZW0 * (VLIQ + VBC)/(VLIQ + VBC0)
      ENDIF
C
C     TRANSITION BETWEEN PHASES:  END OF BUMP
C        ADD AEROSOL, MIX BUBBLE AND HEADSPACE,
C        NEW PRESSURE & TEMPERATURE
C
      IF (IBRISE .EQ. 1  .AND.  ZBUB .GE. HCL) THEN
          IR= IRBUMP
          IBRISE = 0
          TBNEXT= TIME + TINTB
          XSP(5)= HCL
          XSP(6)= GAMM(IR)
          XSP(10)= 0.E0
C      ENTRAINED WASTE
          UBUB= 0.76 * SQRT(GRAV) * VBC**(1.E0/6.E0)
          USUP= 0.6666E0 * UBUB
          EGROUP= (MUGR(IR)**4 * RHOG(IR)**2 * (RHOLIQ-RHOG(IR))**3)
     &          / (SURWAS**9 * GRAV**5)
          ENT= FBENT * 7.13E-4 * EGROUP**0.125 * USUP**3
          MAER= ENT*RHOG(IR)*VBC
C      STEAM AND WASTE ENTHALPIES; USE WASTE AT HEADSPACE TEMP
          WENT(IWASTE)= 1.E0
          HWASTE= HGSRC(2,PR(IRBUMP),TBC,WENT,0.E0)
          WENT(IWASTE)= 0.E0
          WENT(IH2O)= 1.E0
          HSTM= HGSRC(1,PR(IR),TBC,WENT,0.E0)
          WENT(IH2O)= 0.E0
C      MIXING CUP VALUES
          RHOSTM= PR(IR)*MWG(IH2O)/RGAS/TWASTE
          MG(IH2O,IR)= MG(IH2O,IR) + VBC*RHOSTM
          MA(IWASTE,IR)= MA(IWASTE,IR) + MAER
          UG(IR)= UG(IR) + MAER*HWASTE + HSTM*VBC*RHOSTM
          VOLR(IR)= VOLHS0 + VBC0
          XSP(4)= VOLHS0 + VBC0
          TGES= TGR(IRBUMP)
          PGES= PR(IRBUMP)
          CALL GAST(1,IREG,IGAS,MWG,MG,MA,MLA,MFG,NFG,MGT,NGT,MAT,
     @            FWG, MLAT)
          CALL PTREG1
     I   (VOLR(IR),TGES,PGES,MG,UG(IR),IR,TIME,
     I    MFG,NFG,MGT(IR),NGT(IR),MA,
```

```
     O    TGR(IR),PR(IR),PPG,RHOG(IR),DPDT(IR),MCE(IR),DPDMG,
     O    UGI,HGI,UAG(IR),DPDV(IR),
     O    CPGR(IR),GAMM(IR),HLSAT,RHOL,IPTREG)
C
C         TIMESTEP CONTROL FOR PERIOD BETWEEN BUMPS,
C            SAVED IN PLACES 6-10
C
          DO 332 II=1,5
          TIDTMAX(II)= TIME + TMX0(II+5)
          DTMAX1(II)= DTMX0(II+5)
          TIDTMIN(II)= TIME + TMN0(II+5)
          DTMIN1(II)= DTMN0(II+5)
          TIPLTMAX(II)= TIME + TPMX0(II+5)
          PLTMAX1(II)= DTPMX0(II+5)
          TIPLTMIN(II)= TIME + TPMN0(II+5)
          PLTMIN1(II)= DTPMN0(II+5)
          TIDTPRIN(II)= TIME + TPRN0(II+5)
          DTPRIN1(II)= DTPRN0(II+5)
 332      CONTINUE
C
      ENDIF
C
C     TRANSITION BETWEEN PHASES:  NEXT BUMP
C         RE-INITIALIZE THE XSP VECTOR
C
      IF (IBRISE .EQ. 0 .AND.
     &    TIME+DELT/2.E0 .GE.  TBNEXT .AND.
     &    NBUMP .LT. NBMAX) THEN
C
          IBRISE= 1
          NBUMP= NBUMP + 1
C
          PEQ= SPV(TWASTE, IH2O)
          XSP(1)= 0.E0
          XSP(2)= 1.E0
          XSP(3)= PEQ
          XSP(4)= VOLHS0
          XSP(5)= ZW0
          XSP(6)= GAMM(IRBUMP)
          XSP(8)= TWASTE
          XSP(9)= MLBC0
          XSP(10)= 0.E0
C
          VBC= VBC0
          HCL= ZW0
          ZBUB= XSP(1)
          VRAT= XSP(2)
          PBUB= XSP(3)
          VHS=  XSP(4)
          TBC= XSP(8)
          MLBC= XSP(9)
C
C         TIMESTEP CONTROL FOR BUBBLE RISE,
C            SAVED IN PLACES 1-10
C
          DO 432 II=1,5
          TIDTMAX(II)= TIME + TMX0(II)
```

```
         DTMAX1(II)= DTMX0(II)
         TIDTMIN(II)= TIME + TMN0(II)
         DTMIN1(II)= DTMN0(II)
         TIPLTMAX(II)= TIME + TPMX0(II)
         PLTMAX1(II)= DTPMX0(II)
         TIPLTMIN(II)= TIME + TPMN0(II)
         PLTMIN1(II)= DTPMN0(II)
         TIDTPRIN(II)= TIME + TPRN0(II)
         DTPRIN1(II)= DTPRN0(II)
 432     CONTINUE

      ENDIF
C
      IF (IBRISE .EQ. 1) THEN
C
C     BUBBLE RISE PHASE
C
C
C     FLOW OUT OF HEADSPACE, LAST TIMESTEP VALUE, NEEDED FOR DP/DT,
C        SO SUM OVER JUNCTIONS CONNECTED TO IRBUMP, NOTING:
C  /JUNCS/INJR(IR)     - NUMBER OF JUNCTIONS CONNECTED TO COMPARTMENT-IR
C  /JUNCS/IJPTR(IL,IR)- 'IL'TH JUNCTION INDEX CONNECTED TO COMPARTMENT-IR
C
      IR= IRBUMP
      WOUT= 0.E0
      DO 1100 IL=1,INJR(IR)
         IJ= IJPTR(IL,IR)
         IF (IR .EQ. IR1(IJ)) THEN
            SENSE= 1.E0
         ELSE
            SENSE= -1.E0
         ENDIF
         WOUT= WOUT + WJN(IJ)*SENSE
 1100 CONTINUE
C
C     BUBBLE RISE RATES OF CHANGE:
C        BUBBLE CLUSTER VELOCITY, CHANGE OF V RATIO, CHANGE OF PEQ
C
C     LOCALLY INTEGRATE VRAT AND PBUB EQUATIONS, DUE TO STIFFNESS,
C       KEEPING OTHER VARIABLES AT BEGINNING-OF-TIMESTEP VALUES
C
      PEQ= SPV(TBC, IH2O)
C
      INLOC= 50
      DTLOC= DELT/FLOAT(INLOC)
      VR1= VRAT
      PB1= PBUB
C
      DO 2100 II=1,INLOC
      VBC= VR1*VBC0
      RZBUB= 0.76 * SQRT(GRAV) * VBC**(1.E0/6.E0)
      DENOM= PR(IR) + RHOLIQ*GRAV*(HCL - ZBUB) - PEQ
      A12= 1.E0 - (1.E0 - VRAT)/DENOM *
     &     (  PR(IR)*GAMM(IR)*VBC0/(VHS+VBC0)
     &      + RHOLIQ*GRAV*ZW0*VBC0/(VBC0 + VLIQ) )
      A22 = -VRAT/DENOM
      DET= PBUB*A22 - VRAT*A12
```

```
      PMIX= PR(IR) + RHOLIQ*GRAV*(HCL - ZBUB)
      PDRAT= (PEQ-PBUB)/(PMIX-PEQ)
      B1= SQRT(24.E0*DIFFB*RZBUB*VRAT/VB0)*PMIX*LOG(1.E0 + PDRAT)
      B2= RHOLIQ*GRAV*RZBUB*VRAT/DENOM
     &  - (1.E0-VRAT)/DENOM * PR(IR)*WOUT*GAMM(IR)/MGT(IR)
      RVRAT= (B1*A22 - VRAT*B2) / DET
      RPBUB= -(B1*A12 - PBUB*B2) / DET
      VR1= VR1 + RVRAT*DTLOC
      PB1= PB1 + RPBUB*DTLOC
 2100 CONTINUE
      RVRAT= (VR1 - VRAT) / DELT
      RPBUB= (PB1 - PBUB) / DELT
C
      RVHS= -RVRAT*VBC0
C
C BUBBLE CLUSTER SURFACE AREA AND ENTRAINMENT RATE
C CALCULATE VAPOR GENERATION RATE FIRST
C
      WVAP= MWG(IH2O)*VBC0/RGAS/TBC*(PBUB*RVRAT+RPBUB*VRAT)
      ABC= 4.83D0*(VBC + MLBC/RHOLIQ)**(2.D0/3.D0)
      RMLBC= ENTB*RHOLIQ*ABC*RZBUB - WVAP
C
C TEMPERATURE AS A FUNCTION OF Z
C
      RTBC= -(TBC - TCL)*RMLBC/MLBC -
     @              WVAP*SHFG(TCL/TCR(IH2O),IH2O)/MLBC/4200.E0
      XSP(5)= HCL
      XSP(6)= GAMM(IR)
      XSP(7)= WOUT
      XSP(10)= 0.0345 * (VBC0*RVRAT)**2.E0 /
     &        (GRAV * (VBC0*VRAT + MLBC0/RHOLIQ))**1.6E0
C
      ENDIF
C
C     DUMMY LOCATIONS FOR PHASE BETWEEN & AFTER BUMPS,
C      IN CASE OF FURTHER DEVELOPMENT, OR DEBUG
C
      IF (IBRISE .EQ. 0) THEN
         IDUM=1
      ENDIF
      IF (TIME .GT. TBUMP) THEN
         IDUM=1
      ENDIF
C
C-----------------------------------------------------------------------
C     INCREMENT RATES OF CHANGE - ENTRAIN INTO THE AEROSOL BIN
C-----------------------------------------------------------------------
 3000 CONTINUE
C
C     ENTRAINMENT
C
      DO 3020 II=1,INGAS
      RMG(II,IRBUMP)= RMG(II,IRBUMP) + WENT(II)
 3020 CONTINUE
      RMA(IWASTE,IRBUMP)= WENTW
C
C     HEADSPACE
```

```
C
      RUG(IRBUMP)= RUG(IRBUMP) + QENTR - PR(IRBUMP)*RVHS
C
C     SPECIAL VECTOR
C
      RXSP(1)= RZBUB
      RXSP(2)= RVRAT
      RXSP(3)= RPBUB
      RXSP(4)= RVHS
      RXSP(8)= RTBC
      RXSP(9)= RMLBC
C
      RETURN
      END


      SUBROUTINE BUMPIN
      IMPLICIT REAL (A-H, K-Z)
C-----------------------------------------------------------------------
C     DCRT INPUT ROUTINE
C-----------------------------------------------------------------------
      INCLUDE 'PARAMS.CMG'
      INCLUDE 'CNTRL.CML'
      INCLUDE 'GASN.CML'
      INCLUDE 'BUMP.CML'
C
      LOGICAL LTOK,TOKENL
      CHARACTER*10 WORD,NAME(INGAS)
      CHARACTER*80 LINE
      CHARACTER*20 PWORD(30)
      CHARACTER*1 STAR
C      DIMENSION WGAST(INGAS),IPGAST(INGAS),MATRIX(10,10)
      DATA STAR /'*'/
      DATA TOK/273.15E0/
C
    2 FORMAT(' ',A10,1P,5(1E10.3,3X))
    4 FORMAT(' ',A10,' = ',I2)
    5 FORMAT(A80)
    6 FORMAT(' !',A80)
    8 FORMAT(' ')
      DATA PI /3.14159E0/
C-----------------------------------------------------------------------
C     1.0 INITIALIZE VARIABLES
C-----------------------------------------------------------------------
C
C --- SET DEFAULT VALUES OF ALL DCRT PARAMETERS
C
C     TANK
C
      IRBUMP= 1
      TWASTE= 383.E0
      ZW0= 8.E0
      VLIQ= 3200.E0
      RHOLIQ= 1210.E0
      MLBC0=  40.E3
      NBMAX= 10
C
```

```
C     MODEL
C
      DB0= 0.005
      VBC0= 10.E0
      DIFFB= 9.2E-5
      TBUMP= 1.E6
      ENTB= 0.1E0
      TSUPR= 373.E0
      TINTB= 100.E0
C
      WRITE (*,61)
      WRITE(ILUNIT,61)
  61  FORMAT(/,'   Tank Bump Simulation Input Group ',/)
C-----------------------------------------------------------------------
C     2.0  SEARCH FOR MAJOR KEYWODS - IN ANY ORDER
C-----------------------------------------------------------------------
C
 5000 CONTINUE
C
C --- GET A LINE, LOOK FOR A KEYWORD
C
      READ (INUNIT,5,END=666) LINE
      LTOK= TOKENL(0,0,6,0,0,LINE,PWORD,INTOK)
      IF (INTOK .LT. 1) GOTO 5000
      WORD= PWORD(1)
      IF (WORD .EQ. STAR) GOTO 5000
C
C  ---  IDENTIFY A MAJOR KEYWORD
C
C-----------------------------------------------------------------------
C --- TIMING KEYWORD GROUP
C-----------------------------------------------------------------------
      IF (WORD .EQ. 'TANK') THEN
 200      CONTINUE
          READ (INUNIT,5,END=666) LINE
          LTOK= TOKENL(0,0,6,0,0,LINE,PWORD,INTOK)
          IF (INTOK .LT. 1) GOTO 200
          WORD= PWORD(1)
          IF (WORD .EQ. STAR) GOTO 200
          IF (WORD .EQ. 'END') GOTO 5000
C
C         GET HERE IF A KEYWORD IN THE GROUP EXPECTED
C
          IF (WORD .EQ. 'IRBUMP') THEN
              IF (INTOK .LT. 2) GOTO 777
              IRBUMP= INTNUM(PWORD(2))
              WRITE (*,4) WORD,IRBUMP
              WRITE(ILUNIT,4) WORD,IRBUMP
              GOTO 200
          ENDIF
C
          IF (WORD .EQ. 'HEIGHT_CL') THEN
                IF (INTOK .LT. 2) GOTO 777
                ZW0= RELNUM(PWORD(2))
                WRITE (*,2) WORD,ZW0
                WRITE(ILUNIT,2) WORD,ZW0
                GOTO 200
```

```
          ENDIF
C
          IF (WORD .EQ. 'T_WASTE') THEN
              IF (INTOK .LT. 2) GOTO 777
              TWASTE= RELNUM(PWORD(2))
              WRITE (*,2) WORD,TWASTE
              WRITE(ILUNIT,2) WORD,TWASTE
              GOTO 200
          ENDIF
C
          IF (WORD .EQ. 'T_SUPER') THEN
              IF (INTOK .LT. 2) GOTO 777
              TSUPR= RELNUM(PWORD(2))
              WRITE (*,2) WORD,TSUPR
              WRITE(ILUNIT,2) WORD,TSUPR
              GOTO 200
          ENDIF
C
          IF (WORD .EQ. 'VOLUME_CL') THEN
                IF (INTOK .LT. 2) GOTO 777
                VLIQ= RELNUM(PWORD(2))
                WRITE (*,2) WORD,VLIQ
                WRITE(ILUNIT,2) WORD,VLIQ
                GOTO 200
          ENDIF
C
          IF (WORD .EQ. 'GAS_VOL') THEN
              IF (INTOK .LT. 2) GOTO 777
              VBC0= RELNUM(PWORD(2))
              WRITE (*,2) WORD,VBC0
              WRITE(ILUNIT,2) WORD,VBC0
              GOTO 200
          ENDIF
C
          IF (WORD .EQ. 'MASS_LIQ') THEN
              IF (INTOK .LT. 2) GOTO 777
              MLBC0= RELNUM(PWORD(2))
              WRITE (*,2) WORD,MLBC0
              WRITE(ILUNIT,2) WORD,MLBC0
              GOTO 200
          ENDIF
C
          IF (WORD .EQ. 'NBMAX') THEN
              IF (INTOK .LT. 2) GOTO 777
              NBMAX= RELNUM(PWORD(2))
              WRITE (*,2) WORD,NBMAX
              WRITE(ILUNIT,2) WORD,NBMAX
              GOTO 200
          ENDIF
C
C
C
C --- FALL THROUGH HERE IF A COMMENT PRESENT NOT STARTING WITH STAR
          WRITE (*,6) LINE
          WRITE(ILUNIT,6) LINE
          GOTO 200
      ENDIF
```

```
C-----------------------------------------------------------------------
C     MODEL PARAMETER KEYWORD GROUP
C-----------------------------------------------------------------------
      IF (WORD .EQ. 'MODEL') THEN
 300      CONTINUE
          READ (INUNIT,5,END=222) LINE
          LTOK=TOKENL(0,0,6,0,0,LINE,PWORD,INTOK)
          IF (INTOK .LT. 1) GOTO 300
          WORD= PWORD(1)
          IF (WORD .EQ. STAR) GOTO 300
          IF (WORD .EQ. 'END') GOTO 5000
C
          IF (WORD .EQ. 'BUB_DIAM') THEN
              IF (INTOK .LT. 2) GOTO 777
              DB0= RELNUM(PWORD(2))
              WRITE (*,2) WORD,DB0
              WRITE(ILUNIT,2) WORD,DB0
              GOTO 300
          ENDIF
C
          IF (WORD .EQ. 'DIFFB') THEN
              IF (INTOK .LT. 2) GOTO 777
              DIFFB= RELNUM(PWORD(2))
              WRITE (*,2) WORD,DIFFB
              WRITE(ILUNIT,2) WORD,DIFFB
              GOTO 300
          ENDIF
C
          IF (WORD .EQ. 'FBENT') THEN
              IF (INTOK .LT. 2) GOTO 777
              FBENT= RELNUM(PWORD(2))
              WRITE (*,2) WORD,FBENT
              WRITE(ILUNIT,2) WORD,FBENT
              GOTO 300
          ENDIF
C
          IF (WORD .EQ. 'ENTB') THEN
              IF (INTOK .LT. 2) GOTO 777
              ENTB= RELNUM(PWORD(2))
              WRITE (*,2) WORD,ENTB
              WRITE(ILUNIT,2) WORD,ENTB
              GOTO 300
          ENDIF
C
          IF (WORD .EQ. 'TBUMP') THEN
              IF (INTOK .LT. 2) GOTO 777
              TBUMP= RELNUM(PWORD(2))
              WRITE (*,2) WORD,TBUMP
              WRITE(ILUNIT,2) WORD, TBUMP
              GOTO 300
          ENDIF
C
          IF (WORD .EQ. 'TINTB') THEN
              IF (INTOK .LT. 2) GOTO 777
              TINTB= RELNUM(PWORD(2))
              WRITE (*,2) WORD,TINTB
              WRITE(ILUNIT,2) WORD, TINTB
```

```
            GOTO 300
          ENDIF
C
          IF (WORD .EQ. 'TENDB') THEN
            IF (INTOK .LT. 2) GOTO 777
            TENDB= RELNUM(PWORD(2))
            WRITE (*,2) WORD,TENDB
            WRITE(ILUNIT,2) WORD, TENDB
            GOTO 300
          ENDIF
C
C
C
C --- MUST BE A COMMENT, GET ANOTHER PARAMETER
           WRITE (*,6) LINE
           WRITE(ILUNIT,6) LINE
           GOTO 300
C --- END OF ACTIVE MODEL PARAMETERS KEYWORD GROUP
      ENDIF
C-----------------------------------------------------------------------
C     WASTE PROPERTY PARAMETER KEYWORD GROUP
C-----------------------------------------------------------------------
      IF (WORD .EQ. 'WASTE') THEN
 400      CONTINUE
          READ (INUNIT,5,END=222) LINE
          LTOK=TOKENL(0,0,6,0,0,LINE,PWORD,INTOK)
          IF (INTOK .LT. 1) GOTO 400
          WORD= PWORD(1)
          IF (WORD .EQ. STAR) GOTO 400
          IF (WORD .EQ. 'END') GOTO 5000
C
          IF (WORD .EQ. 'DENSITY_CL') THEN
            IF (INTOK .LT. 2) GOTO 777
            RHOLIQ= RELNUM(PWORD(2))
            WRITE (*,2) WORD,RHOLIQ
            WRITE(ILUNIT,2) WORD,RHOLIQ
            GOTO 400
          ENDIF
C
C
          IF (WORD .EQ. 'SURT_CL') THEN
            IF (INTOK .LT. 2) GOTO 777
            SURWAS= RELNUM(PWORD(2))
            WRITE (*,2) WORD,SURWAS
            WRITE(ILUNIT,2) WORD,SURWAS
            GOTO 400
          ENDIF
C
C
C --- MUST BE A COMMENT, GET ANOTHER PARAMETER
           WRITE (*,6) LINE
           WRITE(ILUNIT,6) LINE
           GOTO 400
C --- END OF WASTE PROPERTY KEYWORD GROUP
      ENDIF
C
C-----------------------------------------------------------------------
```

```
C --- NORMAL TERMINATION:  'END' FOUND AS A MAJOR KEYWORD
C-----------------------------------------------------------------------
      IF (WORD .EQ. 'END') THEN
          WRITE (*,667)
          WRITE(ILUNIT,667)
          RETURN
      ENDIF
 667  FORMAT(' DCRT inputs completed',/)
C-----------------------------------------------------------------------
C --- GET HERE IF A COMMENT LINE (NONBLANK, NONSTAR, NONKEYWORD)
C-----------------------------------------------------------------------
      GOTO 5000
C-----------------------------------------------------------------------
C     BOTTOM OF LOOP SEARCHING FOR MAJOR KEYWORDS
C-----------------------------------------------------------------------
C --- ERROR HANDLING
C
 666  CONTINUE
      WRITE (*,668)
      WRITE(ILUNIT,668)
 668  FORMAT(' UNEXPECTED END OF FILE DURING DCRT-TANK INPUT')
      WRITE (*,6) LINE
      WRITE(ILUNIT,6) LINE
      STOP
C
 777  CONTINUE
      WRITE (*,778)
      WRITE(ILUNIT,778)
 778  FORMAT(' NOT ENOUGH TOKENS READING TANK INPUT')
      WRITE (*,6) LINE
      WRITE(ILUNIT,6) LINE
      STOP
C
 222  CONTINUE
      WRITE (*,223)
      WRITE(ILUNIT,223)
 223  FORMAT(' UNEXPECTED END OF FILE READING DCRT MODEL PARAMETERS')
      WRITE (*,6) LINE
      WRITE(ILUNIT,6) LINE
      STOP
C
 555  CONTINUE
      WRITE (*,558)
      WRITE (ILUNIT,558)
 558  FORMAT(' UNEXPECTED END OF FILE DURING DCRT FUEL  INPUT')
      WRITE (*,6) LINE
      WRITE (ILUNIT,6) LINE
      STOP
C
      END
```

F.2 BUMP.CML: Addition to HADCRT for Chapter 8

```
      COMMON /BUMP1/
     &    IRBUMP, ZW0,    TWASTE, RHOLIQ, VLIQ,   FBENT,
```

```
     &    DB0,    VBC0,   DIFFB,  TBUMP,  SURWAS, ENTB,
     &    MLBC0,  NBMAX,  TINTB,  TSUPR
```

F.3 Differences in AMIO.FOR: Addition to HADCRT for Chapter 8

```
Comparing files AMIO.FOR and C:\BUMP03\AMIO.FOR
***** AMIO.FOR
C-----------------------------------------------------------------------
C --- FIRE  KEYWORD GROUP
C-----------------------------------------------------------------------
      IF (WORD .EQ. 'FIRE') THEN
      CALL FIRIN(0)
      GOTO 5000
***** C:\BUMP03\AMIO.FOR
C-----------------------------------------------------------------------
C --- BUMP  KEYWORD GROUP
C-----------------------------------------------------------------------
      IF (WORD .EQ. 'BUMP') THEN
      CALL BUMPIN
      GOTO 5000
*****

***** AMIO.FOR
C-----------------------------------------------------------------------
C --- OPERATIONS  KEYWORD GROUP
C-----------------------------------------------------------------------
      IF (WORD .EQ. 'OPERATIONS') THEN
      CALL OPSIN(0)
      GOTO 5000
***** C:\BUMP03\AMIO.FOR
C-----------------------------------------------------------------------
C --- FIRE  KEYWORD GROUP
C-----------------------------------------------------------------------
      IF (WORD .EQ. 'FIRE') THEN
      CALL FIRIN(0)
      GOTO 5000
*****

***** AMIO.FOR
C-----------------------------------------------------------------------
C --- GET HERE IF A COMMENT LINE (NONBLANK, NONSTAR, NONKEYWORD)
***** C:\BUMP03\AMIO.FOR
C-----------------------------------------------------------------------
C --- OPERATIONS  KEYWORD GROUP
C-----------------------------------------------------------------------
      IF (WORD .EQ. 'OPERATIONS') THEN
      CALL OPSIN(0)
      GOTO 5000
      ENDIF
C-----------------------------------------------------------------------
C --- GET HERE IF A COMMENT LINE (NONBLANK, NONSTAR, NONKEYWORD)
*****

***** AMIO.FOR
      IDCRT= 0
```

```
      ILXFER= 0
***** C:\BUMP03\AMIO.FOR
      IDCRT= 0
        IBUMP= 0
      ILXFER= 0
*****

***** AMIO.FOR
C
          IF (WORD .EQ. 'IWIND') THEN
***** C:\BUMP03\AMIO.FOR
C
          IF (WORD .EQ. 'IBUMP') THEN
              IF (INTOK .LT. 2) GOTO 333
              IBUMP=INTNUM(PWORD(2))
              WRITE(ILUNIT,4) WORD,IBUMP
              GOTO 300
          ENDIF
C
          IF (WORD .EQ. 'IWIND') THEN
*****
```

F.4 Differences in AMOD.FOR: Addition to HADCRT for Chapter 8

```
Comparing files amod.for and C:\BUMP03\AMOD.FOR
***** amod.for
      IF (IDCRT .EQ. 1) CALL DCRT
      IF (IWIND .EQ. 1) CALL WSCALE
***** C:\BUMP03\AMOD.FOR
      IF (IDCRT .EQ. 1) CALL DCRT
        IF (IBUMP .EQ. 1) CALL BUMP(1)
      IF (IWIND .EQ. 1) CALL WSCALE
*****

***** amod.for
C
      RETURN
***** C:\BUMP03\AMOD.FOR
C
C! FOR BUMP ROUTINE, GAS VOLUME
      CALL BUMP(2)
      RETURN
*****
```

F.5 Differences in CNTRL.CML: Addition to HADCRT for Chapter 8

```
Comparing files CNTRL.CML and C:\BUMP03\CNTRL.CML
***** CNTRL.CML
     &        IWIND,  IWIGE,  IGROX,  ISLUDGE,IAEB,   IGRMAX, IABREV,
     &        ICELSIUS, IOUTPUT, IHSBOIL, IDIFLW,
     &        IMROWN,IMCOLN(30),ICOLN(20,30),IHSN(20,30),INODN(20,30)
***** C:\BUMP03\CNTRL.CML
```

```
     &        IWIND,  IWIGE,  IGROX,  ISLUDGE,IAEB,   IGRMAX, IABREV,
     &        ICELSIUS, IOUTPUT, IHSBOIL, IDIFLW,
     &        IBUMP,
     &        IMROWN,IMCOLN(30),ICOLN(20,30),IHSN(20,30),INODN(20,30)
*****
```

F.6 Tank 241-AZ-102 Input File

```
*********************************************************************
*   TANK BUMP PV test
*
*********************************************************************
*
*-------------------------------------------------------------------
CONTROL     ! Major keyword group
*-------------------------------------------------------------------
 TITLE      ! Keyword; next line is title, title can be any length*  -

*****************************************************************
       AZ 102 TANK BUMP
*****************************************************************

 END TITLE ! Anything after END is a comment
*
*.................................................................
 TIMING     ! Keyword
   TSTART     0.     !  START TIME, >0 FOR RESTART RUN
   TLAST  50000.    !  END TIME
   DTMIN             !  MIN TIMESTEP (Seconds)
     0.0  0.001
     1.0  0.001
     2.0  0.001
     3.0  0.001
     4.0  0.01
    10.0  0.1
    100.  0.1
   1000.  1.0
   DTMAX             !  MAX TIMESTEP (Seconds)
     0.0  0.005
     1.0  0.005
     2.0  0.005
     3.0  0.005
     4.0  0.01
    10.0  0.1
    100.  0.1
   1000.  5.0
  DTPRIN            !  PRINT INTERVAL (Seconds)
     0.0  0.25
     1.0  0.25
     2.0  0.25
     3.0  0.25
     4.0  0.25
    10.0  100.0
    100.  1000.0
   1000.  10000.0
```

```
   PLTMIN            !  MIN PLOT INTERVAL (Seconds)
     0.0  0.01
     1.0  0.01
     2.0  0.01
     3.0  0.01
     4.0  0.01
    10.0  1.0
    100.  10.0
   1000.  100.0
   PLTMAX            !  MAX INTERVAL WITHOUT PLOT (Seconds)
     0.0  0.1
     1.0  0.1
     2.0  0.1
     3.0  0.1
     4.0  0.1
    10.0  10.0
    100.  100.0
   1000.  1000.0
   DTRST             !  RESTART INTERVAL (Seconds)
   0.0      100000.
*
   FTPCH      0.003       !  FRACTIONAL CHANGE IN T AND P
   FAECH      0.003       !  FRACTIONAL CHANGE IN aerosol mass
   FPPLCH     0.03         !  FRACTIONAL CHANGE FOR PLOTTING
 END TIMING ! TIMING is a comment.
*
*.....................................................................
 PLOT      ! Keyword for plotting section
* Plotting syntax:
*
* PRESSURE n rlist - Pressure, Pa
* GAS-T  n rlist  - Gas Temperature, K
* HS-TI  n hlist  - Heat Sink Temperature - Inner Surface, K
* HS-TO  n hlist  - Heat Sink Temperature - Outer Surface, K
* HS-TA  n hlist  - Heat Sink Temperature - Average, K
* AEROSOL n rlist - Aerosol Mass (Total), kg
* GAS-W  n jlist  - Mass Flowrate, kg/s
* GAS-WX n jlist  - CounterCurrent Mass Flowrate, kg/s
* SPECIAL-X n xlist - Special model state variable
* SPECIAL-R n xlist - Special model rate variable
* GAS-X    GASNAME n rlist  - Gas Mole Fraction
* GAS-RH   GASNAME n rlist  - Gas Relative Humidity
* GAS-MASS GASNAME n rlist - Gas Mass (Species), kg
* AER-MASS GASNAME n rlist - Aerosol Mass (Species), kg
* MASS     GASNAME n rlist - Total Mass (Species), kg
* LIQ-MASS - GASNAME n rlist - Deposited Mass (Species), kg
*
* Pressure, Gas Temperature, and total aerosol mass require a region
* list
*
* Heat Sink Temperatures need a heat sink number list
*
* Flowrates need a junction number list
*
* Gas concentration, relative humidity, individual species gas mass,
* individual species aerosol mass, total (gas+aerosol) individual
* species mass, and individual species deposited liquid mass require
```

```
* a region and gas name
*
* BUMP special state & rate variables are:
*  1=  Bubble height
*  2=  Volume ratio
*  3=  Vapor pressure
*  4=  Headspace volume
*
*
  PRESSURE            3   1 2 3 4     ! Pressure in 1, 2, 3
  GAS-T               3   1 2 3 4    ! Temps in regions 1,2,3
  GAS-X  NITROGEN     3   1 2 3 4     ! N2 concentration in
  GAS-X  OXYGEN       3   1 2 3 4     ! O2 concentration in
  GAS-X  STEAM        3   1 2 3 4     ! H2O concentration in
  GAS-W               5   1 2 3 4  5   ! Uni-directional mass flowrate
  GAS-WX              5   1 2 3 4  5   ! Counter-current mass flowrate
  AEROSOL             4   1 2 3 4    ! Mass of total aerosol
  AER-MASS  WASTE     4   1 2 3 4    ! Mass of WASTE aerosol
  AER-MASS  STEAM     4   1 2 3 4    ! Mass of STEAM aerosol
  LIQ-MASS  WASTE     4   1 2 3 4     ! Mass of deposited WASTE
  LIQ-MASS  STEAM     4   1 2 3 4     ! Mass of deposited/condensed STEAM
  SPECIAL-X           6   1 2 3 4  5  6
  SPECIAL-X           2   8 9
  SPECIAL-R           4   1 2 3 4
  SPECIAL-R           2   8 9
 END PLOT  ! PLOT is a comment
*
*.................................................................
 ACTIVE MODELS ! Keyword; MODELS is a comment; 1 = on, 0 = off
  IJUNC   1     ! Junction flow model
  ICCFLW  1     ! Counter-current flow model
  IHSINK  1     ! Heat sinks
  ICNDS   0     ! Condensation
  IASED   1     ! Aerosol Sedimentation
  IALEAK  1     ! Aerosol Leakage
  IFOG    1     ! Fog formation
  ISRC    1     ! User-defined sources
  ISENS   0     ! Sensitivity runs
  IBUMP   1     ! BUMP Runs
  IPLTYP  2     ! SPREADSHEET
 END ACTIVE MODELS ! ACTIVE MODELS  is a comment
*
*.................................................................
 MODEL PARAMETERS
  AGAMMA   2.5   ! Shape factor for nonsphericity for coagulation
  ACHI     1.0   ! Shape factor for nonsphericity for stokes'law
  AFEO     1.0   ! Collision efficiency: 1.0 Fuchs, 0.33 Prupacher-Klett
 END MODEL PARAMETERS
*
*
C-----------------------------------------------------------------------
C       SOURCE GROUP:  GROUPS REPEATED FOR INPUT # OF REGIONS
C         END OF GROUP DESIGNATED BY 'REGION' OR 'END' KEYWORDS
C       ENTER: TIME, TEMP, FLOWRATES, POWER
*
* STEAM SOURCE FROM VAPORIZATION
* BASED ON 40 KW / 2.2E6 = 0.022 KG/S
```

```
* HEAT SOURCE IS POWER - STEAM - OVERBURDEN = ABOUT 10 KW
*
* SOURCES        1                  !-- KEYWORD AND # SOURCE GROUPS
*  REGION  1  GASES  1              !-- REGION #, # GASES; <0 MEANS AEROSOL
*  STEAM                            !-- Gas
*0.0   100.0   0.022E0   1.E4       !   TIME, TEMP (C), KG/S, WATTS
*1.E3  100.0   0.022E0   1.E4
*1.E5  100.0   0.022E0   1.E4
*  END REGION                       !  END OF SOURCE IN THIS REGION
* END SOURCE                        !  END ALL SOURCES
*
*
 CELSIUS

END CONTROL     ! End of CONTROL keyword group
*
*-----------------------------------------------------------------------
VOLUMES    4       ! total number of control volumes
*-----------------------------------------------------------------------
* No more than 5 columns (regions) at a time
* Units:
* VOLUME m^3, SED_AREA m^2, ELEVATION m, TEMP_GAS K, PRESSURE  Pa
*
*                          SLUICE     PUMP
*             HEADSPACE    PIT 1      PIT 2       Atmosphere
 REGIONS      1            2          3           4
  VOLUME      1564.        40.0       20.0       1.E9
  SED_AREA    411.         0.1        0.0        0.00
  ELEVATION   0.0          5.0        5.0         8.0
  TEMP_GAS    100.0       75.0       75.0        25.01
  PRESSURE    1.0119E5     1.013E5    1.013E5     1.013E5
 END REGIONS  ! REGIONS is a comment
*
*.......................................................................
* Gas composition of each region; specify mole fraction of each gas
* No more than five columns at a time
*
* **30% H2 in air using 1% H2O, 20% O2, 79% N2 Initially
*
 GASES          1         2         3          4
  STEAM        0.95      0.01      0.01       0.01
  OXYGEN       0.01      0.20      0.20       0.20
  NITROGEN     0.04      0.79      0.79       0.79
 END GASES          ! GASES is a comment
*
*.......................................................................
* Aerosol concentration of each region (kg/m^3)
* No more than five columns at a time
*
AEROSOLS       1         2         3          4
 WASTE        0.000     0.0       0.0        0.0
END AEROSOLS ! AEROSOLS is a comment
*
END VOLUMES ! VOLUMES is a comment
*
*-----------------------------------------------------------------------
HEAT_SINKS     2         ! Total number of heat sinks
```

```
*-----------------------------------------------------------------------
* No more than 5 columns at a time,
*
* Syntax:
* IGEOM  1 for plane, 0 or 2 for cylinder
* RHO    Density (kg/m^3)
* KHS    Thermal Conductivity (W/m/K)
* CPHS   Specific Heat (J/kg/K)
* QV      Volumetric Heat Generation (W/m^3)
* XRI     Inner Radius (m)
* XRO     Outer Radius (m); for plane wall, thickness = XRO-XRI
* AHS     One-sided heat sink area (m^2)
* TIINIT  Initial inside surface temperature (C)
* TOINIT  Initial outside surface temperature (C)
* IMSLAB  Number of slabs; 3 is minimum
* IREGI   Region index for inner surface or 0 (insulated)
*         or -1 for constant temperature
* TIHS    Region surface temperature when IREGI = -1  (C)
* IREGO   Region index for outer surface or 0 (insulated)
*         or -1 for constant temperature
* TOHS    Region surface temperature when IREGO = -1  (C)
* XLHS    Characteristic length for natural convection (m)
* EHSI    Emissivity of inner surface
* EHSO    Emissivity of outer surface
*
*
 SINKS         1             2
*
 IGEOM        1              1
 RHO        1200.00       2000.0
 KHS        1000.0          1.0
 CPHS         3300.         800.0
 QV         0.0               0.0
 XRI           0.0          0.0
 XRO           8.0          4.0
 AHS          411.0        411.0
 TIINIT       100.00       100.0
 TOINIT       100.00         25.0
 IMSLAB         20           20
 IREGI           1            1
 TIHS          100.0        100.0
 IREGO           0           4
 TOHS          100.0         25.0
 XLHS           10.0         10.0
 EHSI           0.3          0.7
 EHSO           0.3          0.7
 END
*
END HEAT_SINKS ! HEAT_SINKS is a comment
*-----------------------------------------------------------------------
JUNCTIONS   6  ! # Junctions
*-----------------------------------------------------------------------
* 1) TANK TO ENV - INLET
* 2) TANK TO ENV - OUTLET
* 3) TANK TO PIT1
* 4) TANK TO PIT2
* 5) PIT1 TO ENV
```

```
* 6) PIT2 TO ENV
*
*
* Syntax:
*  IJTYP   Junction Type: 1 = Normal, 2 = HEPA, 3 = Cover
*  IR1     Upstream Region
*  IR2     Downstream Region
*  AJN     Area (m^2)
*  ABYP    Bypass area for HEPA junction (m^2)
*  PHEPA   HEPA Filter Failure Pressure (Pa)
*  ACOV    Cover Area (m^2)
*  MCOV    Cover Weight (kg)
*  Z1JN    Elevation wrt floor of IR1 opening (m)
*  Z2JN    "          "   "    "   IR2   "     "
*  CJN     Loss coefficient multiplies 0.5*rho*v^2
*  IHORIZ  Orientation: 1 = horizontal, 0 = vertical
*  XWJN    Characteristic width, m
*  XHJN    Characteristic height, m
*  XLJN    Characteristic length, m
*  DFJN    Decontamination Factor
*  N90     No. of 90 bends
*
     PATHS        1        2        3        4
*
 IJTYP    1        1        1        1
 IR1      1        1        1        1
 IR2      4        4        2        3
 IHORIZ   1        1        1        1
 XWJN     0.20     0.50     0.010    0.010
 XHJN     0.20     0.50     0.010    0.010
 XLJN     100.0    100.0    1.0      1.0
 AJN      0.030    0.200    0.053    0.00133
 Z1JN     4.0      8.0      5.0      5.0
 Z2JN     0.0      0.0      1.0      1.0
 CJN      4.0      4.0      2.0      2.0
 DFJN     1.0      1.0      1.0      1.0
 N90       0        0        0        0
   END PATHS  ! PATHS is a comment.
*
     PATHS        5        6
*
 IJTYP     3        3
 IR1       2        3
 IR2       4        4
 IHORIZ    1        1
 XWJN     0.01     0.01
 XHJN     0.01     0.01
 XLJN     0.3      0.3
* AJN      0.32     0.08
  AJN     0.0      0.0
 Z1JN     0.6      0.6
 Z2JN     0.0      0.0
 CJN      2.0      2.0
 DFJN     1.0      1.0
 N90       0        0
  END PATHS  ! PATHS is a comment.
*
```

```
END JUNCTIONS    ! JUNCTIONS is a comment.
*
*-----------------------------------------------------------------------
BUMP! Input Section for "DCRT.For" Model
*-----------------------------------------------------------------------
TANK
  IRBUMP      1          ! BUMP region index
  HEIGHT_CL   8.23        ! Conv layer height
  T_WASTE     388.0      ! Non-Conv Waste temp, K
  T_SUPER     373.0      ! Supernatant Temp.
  VOLUME_CL   3377.      ! Conv layer volume, m^3
  GAS_VOL     10.67      ! Volume of released gas, m^3
  MASS_LIQ    70.0E3      ! Mass of liquid in cluster
  NBMAX       6.E0      ! Number of total bumps
END TANK
*
*.................................................................
WASTE
  DENSITY_CL  1140.      ! Conv layer density, kg/m^3
  SURT_CL     0.059      ! Conv layer surface tension, N/m
END
*.................................................................
MODEL
  BUB_DIAM  0.005        ! Bubble diameter, m
  DIFFB     9.2E-5       ! Diffusion coefficient
  FBENT     1.0          ! Multiplier on Ishii release model
  ENTB      0.1E0        ! Entrainment mult for Ricou-Spalding
  TINTB    5484.E0       ! Time between bumps
  TBUMP     200.         ! Development use only
END MODEL
*
*.................................................................
*
END DCRT
*
```

F.7 Comparison of Tanks 241-AZ-102 and 241-AZ-101 Input Files

```
Comparing files AZ102.DAT and AZ101.DAT
***** AZ102.DAT
*****************************************************************
         AZ 102 TANK BUMP
*****************************************************************
***** AZ101.DAT
*****************************************************************
         AZ 101 TANK BUMP
*****************************************************************
*****

***** AZ102.DAT
 TIMING    ! Keyword
   TSTART     0.    !  START TIME, >0 FOR RESTART RUN
   TLAST  50000.   !  END TIME
   DTMIN           !  MIN TIMESTEP (Seconds)
***** AZ101.DAT
```

```
 TIMING     ! Keyword
   TSTART      0.0     !  START TIME, >0 FOR RESTART RUN
   TLAST  20000.    !  END TIME
   DTMIN             !  MIN TIMESTEP (Seconds)
*****

***** AZ102.DAT
     3.0  0.25
     4.0  0.25
    10.0  100.0
***** AZ101.DAT
     3.0  0.25
    10.0  100.0
*****

***** AZ102.DAT
     4.0  0.01
    10.0  1.0
    100.  10.0
***** AZ101.DAT
     4.0  0.01
    10.0  0.1
    100.  10.0
*****

***** AZ102.DAT
     4.0  0.1
    10.0  10.0
    100.  100.0
***** AZ101.DAT
     4.0  0.1
    10.0  1.0
    100.  100.0
*****

***** AZ102.DAT
*
   FTPCH       0.003        !  FRACTIONAL CHANGE IN T AND P
   FAECH       0.003        !  FRACTIONAL CHANGE IN aerosol mass
   FPPLCH      0.03          !  FRACTIONAL CHANGE FOR PLOTTING
 END TIMING ! TIMING is a comment.
***** AZ101.DAT
*
   FTPCH       0.001        !  FRACTIONAL CHANGE IN T AND P
   FAECH       0.001       !  FRACTIONAL CHANGE IN aerosol mass
   FPPLCH      0.1         !  FRACTIONAL CHANGE FOR PLOTTING
   INCUBT      10.0
   FRLXDT       0.1
 END TIMING ! TIMING is a comment.
*****

***** AZ102.DAT
*
*
  PRESSURE           3    1 2 3 4     ! Pressure in 1, 2, 3
***** AZ101.DAT
*
```

```
  PRESSURE          3   1 2 3 4    ! Pressure in 1, 2, 3
*****

***** AZ102.DAT
  ICCFLW  1     ! Counter-current flow model
  IHSINK  1     ! Heat sinks
  ICNDS   0     ! Condensation
  IASED   1     ! Aerosol Sedimentation
***** AZ101.DAT
  ICCFLW  1     ! Counter-current flow model
  IHSINK  1    ! Heat sinks
  ICNDS   1     ! Condensation
  IASED   1     ! Aerosol Sedimentation
*****

***** AZ102.DAT
  IFOG    1     ! Fog formation
  ISRC    1     ! User-defined sources
  ISENS   0     ! Sensitivity runs
***** AZ101.DAT
  IFOG    1     ! Fog formation
  ISRC    0     ! User-defined sources
  ISENS   0     ! Sensitivity runs
*****

***** AZ102.DAT
  IBUMP   1     ! BUMP Runs
  IPLTYP  2     ! SPREADSHEET
 END ACTIVE MODELS ! ACTIVE MODELS  is a comment
***** AZ101.DAT
  IBUMP   1     ! BUMP Runs
  IPLTYP  2
 END ACTIVE MODELS ! ACTIVE MODELS  is a comment
*****

***** AZ102.DAT
*
*
 CELSIUS

END CONTROL     ! End of CONTROL keyword group
***** AZ101.DAT
*
 CELSIUS
*
END CONTROL     ! End of CONTROL keyword group
*****

***** AZ102.DAT
 REGIONS      1          2          3          4
  VOLUME      1564.      40.0       20.0       1.E9
  SED_AREA    411.       0.1        0.0        0.00
***** AZ101.DAT
 REGIONS      1          2          3          4
  VOLUME      1764.      40.0       20.0       1.E9
  SED_AREA    411.       0.1        0.0        0.00
*****
```

```
***** AZ102.DAT
*-----------------------------------------------------------------------
HEAT_SINKS     2         ! Total number of heat sinks
*-----------------------------------------------------------------------
***** AZ101.DAT
*-----------------------------------------------------------------------
HEAT_SINKS     1         ! Total number of heat sinks
*-----------------------------------------------------------------------
*****

***** AZ102.DAT
*
 SINKS         1             2
*
 IGEOM         1             1
 RHO        1200.00       2000.0
 KHS        1000.0          1.0
 CPHS         3300.         800.0
 QV         0.0             0.0
 XRI           0.0          0.0
 XRO           8.0          4.0
 AHS         411.0        411.0
 TIINIT      100.00       100.0
 TOINIT      100.00         25.0
 IMSLAB        20           20
 IREGI          1            1
 TIHS        100.0        100.0
 IREGO          0           4
 TOHS        100.0         25.0
 XLHS         10.0         10.0
 EHSI         0.3          0.7
 EHSO         0.3          0.7
 END
***** AZ101.DAT
*
 SINKS         1
*
 IGEOM         1
 RHO        1200.00
 KHS          0.6
 CPHS         4200
 QV         0.0
 XRI           0.0
 XRO           1.0
 AHS         411.
 TIINIT      100.00
 TOINIT      100.00
 IMSLAB        20
 IREGI          1
 TIHS        100.0
 IREGO          0
 TOHS        100.0
 XLHS         10.0
 EHSI         1.0
 EHSO         1.0
 END
```

```
*****

***** AZ102.DAT
 N90        0        0        0        0
   END PATHS  ! PATHS is a comment.
***** AZ101.DAT
 N90        0        0        0        0
* ABYP       0        0        0        0
* PHEPA      0        0        0        0
* ACOV       0        0        0        0
* MCOV       0        0        0        0
   END PATHS  ! PATHS is a comment.
*****

***** AZ102.DAT
*
 IJTYP      3        3
 IR1        2        3
***** AZ101.DAT
*
 IJTYP      1        1
 IR1        2        3
*****

***** AZ102.DAT
 XLJN      0.3      0.3
* AJN       0.32     0.08
  AJN      0.0      0.0
 Z1JN      0.6      0.6
***** AZ101.DAT
 XLJN      0.3      0.3
 AJN       0.00     0.00
 Z1JN      0.6      0.6
*****

***** AZ102.DAT
 N90        0        0
  END PATHS  ! PATHS is a comment.
***** AZ101.DAT
 N90        0        0
* DP1        0        0
* DP2        0        0
* ABYP       0        0
* PHEPA      0        0
* ACOV      5.00     9.50
* MCOV      6.8E3    16.6E3
  END PATHS  ! PATHS is a comment.
*****

***** AZ102.DAT
  VOLUME_CL   3377.       ! Conv layer volume, m^3
  GAS_VOL     10.67       ! Volume of released gas, m^3
  MASS_LIQ    70.0E3       ! Mass of liquid in cluster
  NBMAX       6.E0       ! Number of total bumps
END TANK
***** AZ101.DAT
  VOLUME_CL   3377.       ! Conv layer volume, m^3
```

```
  GAS_VOL      6.92        ! Volume of released gas, m^3
  MASS_LIQ     36.6E3      ! Mass of liquid in cluster
  NBMAX        6.0    ! Number of total bumps
END TANK
*****

***** AZ102.DAT
WASTE
  DENSITY_CL  1140.        ! Conv layer density, kg/m^3
  SURT_CL     0.059        ! Conv layer surface tension, N/m
***** AZ101.DAT
WASTE
  DENSITY_CL  1240.        ! Conv layer density, kg/m^3
  SURT_CL     0.059        ! Conv layer surface tension, N/m
*****

***** AZ102.DAT
  ENTB       0.1E0         ! Entrainment mult for Ricou-Spalding
  TINTB     5484.E0        ! Time between bumps
  TBUMP      200.          ! Development use only
END MODEL
***** AZ101.DAT
  ENTB       0.1E0         ! Entrainment mult for Ricou-Spalding
  TINTB       26.0        ! Time between bumps
  TBUMP      1.E6        ! Development use only
END MODEL
*****
```

F.8 Comparison of Tanks 241-AZ-102 and 241-AY-102 Input Files

```
Comparing files AZ102.DAT and AY102.DAT
***** AZ102.DAT
*****************************************************************
         AZ 102 TANK BUMP
*****************************************************************
***** AY102.DAT
*****************************************************************
         AY-102 TANK BUMP
*****************************************************************
*****

***** AZ102.DAT
   TSTART      0.     !  START TIME, >0 FOR RESTART RUN
   TLAST   50000.    !  END TIME
   DTMIN             !  MIN TIMESTEP (Seconds)
***** AY102.DAT
   TSTART      0.     !  START TIME, >0 FOR RESTART RUN
   TLAST  200000.    !  END TIME
   DTMIN             !  MIN TIMESTEP (Seconds)
*****

***** AZ102.DAT
    10.0  0.1
    100.  0.1
   1000.  1.0
```

```
***** AY102.DAT
    10.0  0.1
    100.  1.0
   1000.  1.0
*****

***** AZ102.DAT
     4.0  0.01
    10.0  0.1
    100.  0.1
   1000.  5.0
  DTPRIN            !  PRINT INTERVAL (Seconds)
***** AY102.DAT
     4.0  0.01
    10.0  1.0
    100.  1.0
   1000.  10.0
  DTPRIN            !  PRINT INTERVAL (Seconds)
*****

***** AZ102.DAT
*
*
  PRESSURE          3   1 2 3 4    ! Pressure in 1, 2, 3
***** AY102.DAT
*
  PRESSURE          3   1 2 3 4    ! Pressure in 1, 2, 3
*****

***** AZ102.DAT
 REGIONS      1           2           3           4
  VOLUME      1564.       40.0        20.0        1.E9
  SED_AREA    411.        0.1         0.0         0.00
***** AY102.DAT
 REGIONS      1           2           3           4
  VOLUME      2935.       40.0        20.0        1.E9
  SED_AREA    411.        0.1         0.0         0.00
*****

***** AZ102.DAT
  IRBUMP      1          ! BUMP region index
  HEIGHT_CL   8.23        ! Conv layer height
  T_WASTE     388.0      ! Non-Conv Waste temp, K
  T_SUPER     373.0      ! Supernatant Temp.
  VOLUME_CL   3377.      ! Conv layer volume, m^3
  GAS_VOL     10.67      ! Volume of released gas, m^3
  MASS_LIQ    70.0E3      ! Mass of liquid in cluster
  NBMAX       6.E0      ! Number of total bumps
END TANK
***** AY102.DAT
  IRBUMP      1          ! BUMP region index
  HEIGHT_CL   4.28        ! Conv layer height
  T_WASTE     383.0      ! Non-Conv Waste temp, K
  T_SUPER     373.0      ! Supernatant Temp.
  VOLUME_CL   1757.      ! Conv layer volume, m^3
  GAS_VOL     10.38      ! Volume of released gas, m^3
  MASS_LIQ    66.4E3      ! Mass of liquid in cluster
```

```
  NBMAX         1       ! Number of total bumps
END TANK
*****

***** AZ102.DAT
WASTE
  DENSITY_CL  1140.       ! Conv layer density, kg/m^3
  SURT_CL     0.059       ! Conv layer surface tension, N/m
***** AY102.DAT
WASTE
  DENSITY_CL  1150.       ! Conv layer density, kg/m^3
  SURT_CL     0.059       ! Conv layer surface tension, N/m
*****

***** AZ102.DAT
  ENTB      0.1E0         ! Entrainment mult for Ricou-Spalding
  TINTB    5484.E0        ! Time between bumps
  TBUMP     200.          ! Development use only
***** AY102.DAT
  ENTB      0.1E0         ! Entrainment mult for Ricou-Spalding
  TINTB     436.E0        ! Time between bumps
  TBUMP     200.          ! Development use only
*****
```

F.9 Comparison of Tank 241-AZ-102 and Peak Pressure Input Files

```
Comparing files AZ102.DAT and AZ102I.DAT
***** AZ102.DAT
*****************************************************************
         AZ 102 TANK BUMP
*****************************************************************
***** AZ102I.DAT
*****************************************************************
         AZ 102 TANK BUMP - CLOSED FOR PEAK PRESSURE
*****************************************************************
*****

***** AZ102.DAT
   TSTART     0.     !  START TIME, >0 FOR RESTART RUN
   TLAST  50000.    !  END TIME
   DTMIN             !  MIN TIMESTEP (Seconds)
***** AZ102I.DAT
   TSTART     0.     !  START TIME, >0 FOR RESTART RUN
   TLAST  150000.    !  END TIME
   DTMIN             !  MIN TIMESTEP (Seconds)
*****

***** AZ102.DAT
   DTMAX             !  MAX TIMESTEP (Seconds)
     0.0  0.005
     1.0  0.005
     2.0  0.005
     3.0  0.005
     4.0  0.01
***** AZ102I.DAT
```

```
   DTMAX              !  MAX TIMESTEP (Seconds)
     0.0  0.001
     1.0  0.001
     2.0  0.001
     3.0  0.001
     4.0  0.01
*****

***** AZ102.DAT
 ACTIVE MODELS ! Keyword; MODELS is a comment; 1 = on, 0 = off
  IJUNC   1     ! Junction flow model
  ICCFLW  1     ! Counter-current flow model
  IHSINK  1     ! Heat sinks
  ICNDS   0     ! Condensation
***** AZ102I.DAT
 ACTIVE MODELS ! Keyword; MODELS is a comment; 1 = on, 0 = off
  IJUNC   0     ! Junction flow model
  ICCFLW  0    ! Counter-current flow model
  IHSINK  1    ! Heat sinks
  ICNDS   0     ! Condensation
*****
```

F.10 Comparison of Tank 241-AZ-102 and Level Sensitivity Input Files

```
Comparing files AZ102.DAT and AZ102L.DAT
***** AZ102.DAT
*****************************************************************
         AZ 102 TANK BUMP
*****************************************************************
***** AZ102L.DAT
*****************************************************************
         AZ 102 TANK BUMP - level sensitivity
*****************************************************************
*****

***** AZ102.DAT
   TSTART     0.     !  START TIME, >0 FOR RESTART RUN
   TLAST  50000.    !  END TIME
   DTMIN             !  MIN TIMESTEP (Seconds)
***** AZ102L.DAT
   TSTART     0.     !  START TIME, >0 FOR RESTART RUN
   TLAST  150000.    !  END TIME
   DTMIN             !  MIN TIMESTEP (Seconds)
*****

***** AZ102.DAT
   DTMAX             !  MAX TIMESTEP (Seconds)
     0.0  0.005
     1.0  0.005
     2.0  0.005
     3.0  0.005
     4.0  0.01
***** AZ102L.DAT
   DTMAX             !  MAX TIMESTEP (Seconds)
     0.0  0.001
```

```
     1.0  0.001
     2.0  0.001
     3.0  0.001
     4.0  0.01
*****

***** AZ102.DAT
  ICCFLW  1     ! Counter-current flow model
  IHSINK  1     ! Heat sinks
  ICNDS   0     ! Condensation
***** AZ102L.DAT
  ICCFLW  1    ! Counter-current flow model
  IHSINK  1    ! Heat sinks
  ICNDS   0     ! Condensation
*****

***** AZ102.DAT
 REGIONS      1            2           3            4
  VOLUME      1564.        40.0        20.0        1.E9
  SED_AREA    411.         0.1         0.0         0.00
***** AZ102L.DAT
 REGIONS      1            2           3            4
  VOLUME      1605.1        40.0        20.0        1.E9
  SED_AREA    411.         0.1         0.0         0.00
*****

***** AZ102.DAT
  IRBUMP      1           ! BUMP region index
  HEIGHT_CL   8.23         ! Conv layer height
  T_WASTE     388.0       ! Non-Conv Waste temp, K
***** AZ102L.DAT
  IRBUMP      1           ! BUMP region index
  HEIGHT_CL   8.13         ! Conv layer height
  T_WASTE     388.0       ! Non-Conv Waste temp, K
*****
```

F.11 Comparison of Tank 241-AZ-102 and Weak Sludge Input Files

```
Comparing files AZ102.DAT and AZ102W.DAT
***** AZ102.DAT
*****************************************************************
         AZ 102 TANK BUMP
*****************************************************************
***** AZ102W.DAT
*****************************************************************
         AZ 102 TANK BUMP - weak sludge
*****************************************************************
*****

***** AZ102.DAT
  VOLUME_CL   3377.       ! Conv layer volume, m^3
  GAS_VOL     10.67       ! Volume of released gas, m^3
  MASS_LIQ    70.0E3       ! Mass of liquid in cluster
  NBMAX       6.E0       ! Number of total bumps
END TANK
```

```
***** AZ102W.DAT
  VOLUME_CL    3377.       ! Conv layer volume, m^3
  GAS_VOL      5.34        ! Volume of released gas, m^3
  MASS_LIQ     35.0E3       ! Mass of liquid in cluster
  NBMAX        12.0      ! Number of total bumps
END TANK
*****

***** AZ102.DAT
  ENTB       0.1E0         ! Entrainment mult for Ricou-Spalding
  TINTB     5484.E0        ! Time between bumps
  TBUMP      200.          ! Development use only
***** AZ102W.DAT
  ENTB       0.1E0         ! Entrainment mult for Ricou-Spalding
  TINTB     2742.E0        ! Time between bumps
  TBUMP      200.          ! Development use only
*****
```

F.12 Comparison of Tank 241-AZ-102 and Strong Sludge Input Files

```
Comparing files AZ102.DAT and AZ102S.DAT
***** AZ102.DAT
*****************************************************************
         AZ 102 TANK BUMP
*****************************************************************
***** AZ102S.DAT
*****************************************************************
         AZ 102 TANK BUMP - strong sludge
*****************************************************************
*****

***** AZ102.DAT
  VOLUME_CL    3377.       ! Conv layer volume, m^3
  GAS_VOL      10.67       ! Volume of released gas, m^3
  MASS_LIQ     70.0E3       ! Mass of liquid in cluster
  NBMAX        6.E0       ! Number of total bumps
END TANK
***** AZ102S.DAT
  VOLUME_CL    3377.       ! Conv layer volume, m^3
  GAS_VOL      21.3        ! Volume of released gas, m^3
  MASS_LIQ    140.0E3       ! Mass of liquid in cluster
  NBMAX        3.0     ! Number of total bumps
END TANK
*****

***** AZ102.DAT
  ENTB       0.1E0         ! Entrainment mult for Ricou-Spalding
  TINTB     5484.E0        ! Time between bumps
  TBUMP      200.          ! Development use only
***** AZ102S.DAT
  ENTB       0.1E0         ! Entrainment mult for Ricou-Spalding
  TINTB    10968.E0         ! Time between bumps
  TBUMP      200.          ! Development use only
*****
```

F.13 Comparison of Tank 241-AZ-102 and Maximum Bump Input Files

```
Comparing files AZ102.DAT and BIGBUMP.DAT
***** AZ102.DAT
*****************************************************************
         AZ 102 TANK BUMP
*****************************************************************
***** BIGBUMP.DAT
*****************************************************************
         BIG BUMP
*****************************************************************
*****

***** AZ102.DAT
  IRBUMP       1          ! BUMP region index
  HEIGHT_CL    8.23        ! Conv layer height
  T_WASTE      388.0      ! Non-Conv Waste temp, K
  T_SUPER      373.0      ! Supernatant Temp.
  VOLUME_CL    3377.      ! Conv layer volume, m^3
  GAS_VOL      10.67      ! Volume of released gas, m^3
  MASS_LIQ     70.0E3      ! Mass of liquid in cluster
  NBMAX        6.E0      ! Number of total bumps
END TANK
***** BIGBUMP.DAT
  IRBUMP       1          ! BUMP region index
  HEIGHT_CL    5.00        ! Conv layer height
  T_WASTE      380.0      ! Non-Conv Waste temp, K
  T_SUPER      373.0      ! Supernatant Temp.
  VOLUME_CL    2055.      ! Conv layer volume, m^3
  GAS_VOL      72.59      ! Volume of released gas, m^3
  MASS_LIQ    299.0E3      ! Mass of liquid in cluster
  NBMAX        7.E0      ! Number of total bumps
END TANK
*****

***** AZ102.DAT
WASTE
  DENSITY_CL  1140.       ! Conv layer density, kg/m^3
  SURT_CL     0.059       ! Conv layer surface tension, N/m
***** BIGBUMP.DAT
WASTE
  DENSITY_CL  1100.       ! Conv layer density, kg/m^3
  SURT_CL     0.059       ! Conv layer surface tension, N/m
*****

***** AZ102.DAT
  ENTB       0.1E0        ! Entrainment mult for Ricou-Spalding
  TINTB     5484.E0       ! Time between bumps
  TBUMP      200.         ! Development use only
***** BIGBUMP.DAT
  ENTB       0.1E0        ! Entrainment mult for Ricou-Spalding
  TINTB     3600.E0       ! Time between bumps
  TBUMP      200.         ! Development use only
*****
```

APPENDIX G

SPREADSHEETS FOR BUMP CRITERIA

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G.1 Heat Up Calculations for Tank 241-AZ-101

The following table shows the input and outputs for integration of equations (6-3) and (6-4):

Inputs						
CL Density (kg/m^3)	NCL Density (kg/m^3)	CL Volume (m^3)	NCL Volume (m^3)	CL Specific Heat (J/kg)	NCL Specific Heat (J/kg)	Soil Overburden, m
1240	1620	3377	197	3300	2850	4
Air Temp., K	Soil Temp., K	Area, m^2	hex, $W/m^2/K$	Total Heat Load (W)	Soil Conductivity k_s, (W/m-K)	Tank Radius, m
287	285	411	6.55346	60000.0	1	11

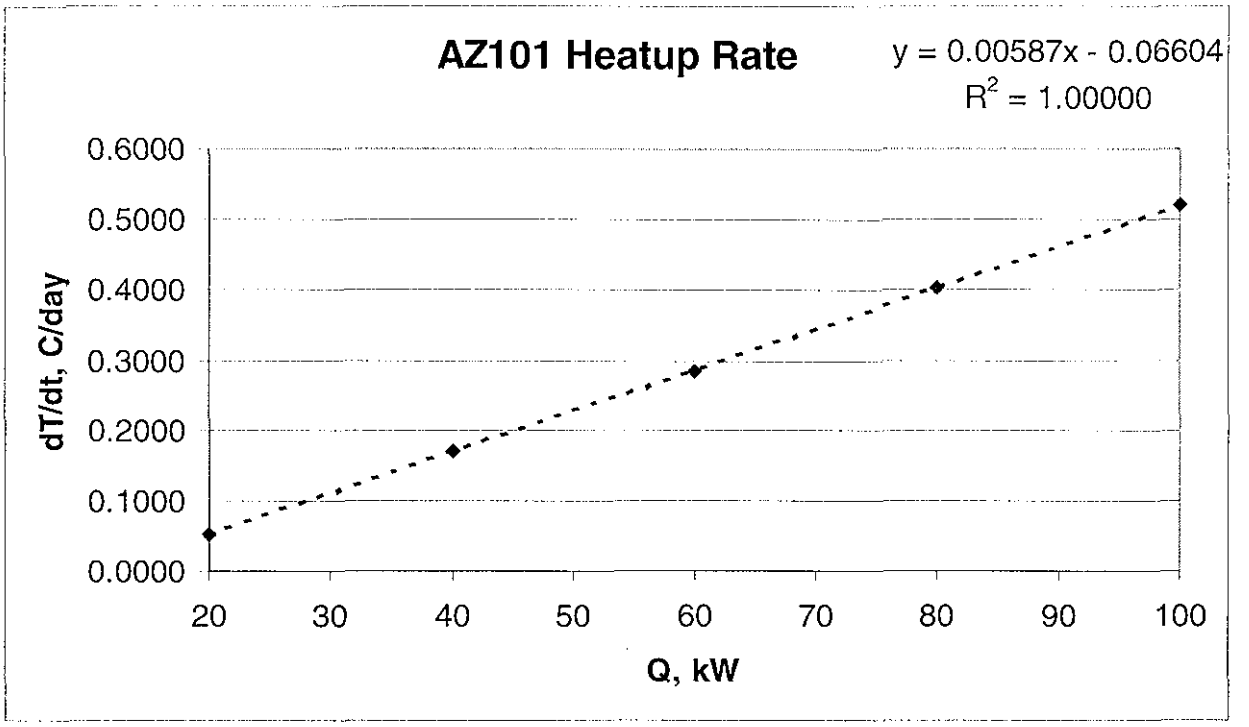
Results	
Heatup Rate, C/day	Heatup Rate Error
0.286	4.05E-07

Integration for Waste Temperatures

Time, seconds	Days	NCL Temp., K	CL Temp., K	CL Heat Load, W	NCL Heat Load, W	Upward Loss, W	Exchange HX, W	Downward Loss, W	NCL Heatup, K/s	CL Heatup, K/s
0	0.00	375.00	364.00	24000.0	36000.0	7911.8	29628.2	3362.7	3.31E-06	3.31E-06
100000	1.16	375.33	364.33	24000.0	36000.0	7945.7	29628.2	3375.1	3.29E-06	3.31E-06
200000	2.31	375.66	364.66	24000.0	36000.0	7979.7	29625.2	3387.4	3.28E-06	3.30E-06
300000	3.47	375.99	364.99	24000.0	36000.0	8013.7	29620.2	3399.7	3.28E-06	3.30E-06
400000	4.63	376.32	365.32	24000.0	36000.0	8047.6	29613.8	3411.9	3.27E-06	3.30E-06
500000	5.79	376.64	365.65	24000.0	36000.0	8081.4	29606.4	3424.1	3.26E-06	3.29E-06
600000	6.94	376.97	365.98	24000.0	36000.0	8115.3	29598.4	3436.3	3.26E-06	3.29E-06
700000	8.10	377.30	366.31	24000.0	36000.0	8149.1	29590.0	3448.5	3.26E-06	3.29E-06
800000	9.26	377.62	366.64	24000.0	36000.0	8182.9	29581.3	3460.7	3.25E-06	3.29E-06
900000	10.42	377.95	366.97	24000.0	36000.0	8216.7	29572.4	3472.8	3.25E-06	3.28E-06
1000000	11.57	378.27	367.30	24000.0	36000.0	8250.4	29563.3	3485.0	3.25E-06	3.28E-06
1100000	12.73	378.60	367.62	24000.0	36000.0	8284.1	29554.2	3497.1	3.24E-06	3.28E-06
1200000	13.89	378.92	367.95	24000.0	36000.0	8317.7	29545.0	3509.2	3.24E-06	3.27E-06
1300000	15.05	379.24	368.28	24000.0	36000.0	8351.4	29535.8	3521.3	3.24E-06	3.27E-06
1400000	16.20	379.57	368.61	24000.0	36000.0	8385.0	29526.6	3533.4	3.23E-06	3.27E-06
1500000	17.36	379.89	368.93	24000.0	36000.0	8418.5	29517.3	3545.5	3.23E-06	3.26E-06
1600000	18.52	380.21	369.26	24000.0	36000.0	8452.1	29508.1	3557.5	3.23E-06	3.26E-06
1700000	19.68	380.54	369.58	24000.0	36000.0	8485.6	29498.8	3569.6	3.22E-06	3.26E-06
1800000	20.83	380.86	369.91	24000.0	36000.0	8519.0	29489.6	3581.6	3.22E-06	3.25E-06
1900000	21.99	381.18	370.24	24000.0	36000.0	8552.5	29480.4	3593.7	3.22E-06	3.25E-06
2000000	23.15	381.50	370.56	24000.0	36000.0	8585.9	29471.1	3605.7	3.21E-06	3.25E-06
2100000	24.31	381.82	370.89	24000.0	36000.0	8619.3	29461.9	3617.7	3.21E-06	3.25E-06
2300000	26.62	382.47	371.53	24000.0	36000.0	8685.9	29443.5	3641.7	3.20E-06	3.24E-06
2600000	30.09	383.43	372.51	24000.0	36000.0	8785.8	29415.8	3677.6	3.20E-06	3.23E-06

A plot of heat up rate as a function of tank heat load is shown in Figure G.1.

Figure G.1 Results of Parametric Study for DST Heat-up Rate for Tank 241-AZ-101



G.2 Heat Up Calculations for Tank 241-AZ-102

The following table shows the input and outputs for integration of equations (6-3) and (6-4):

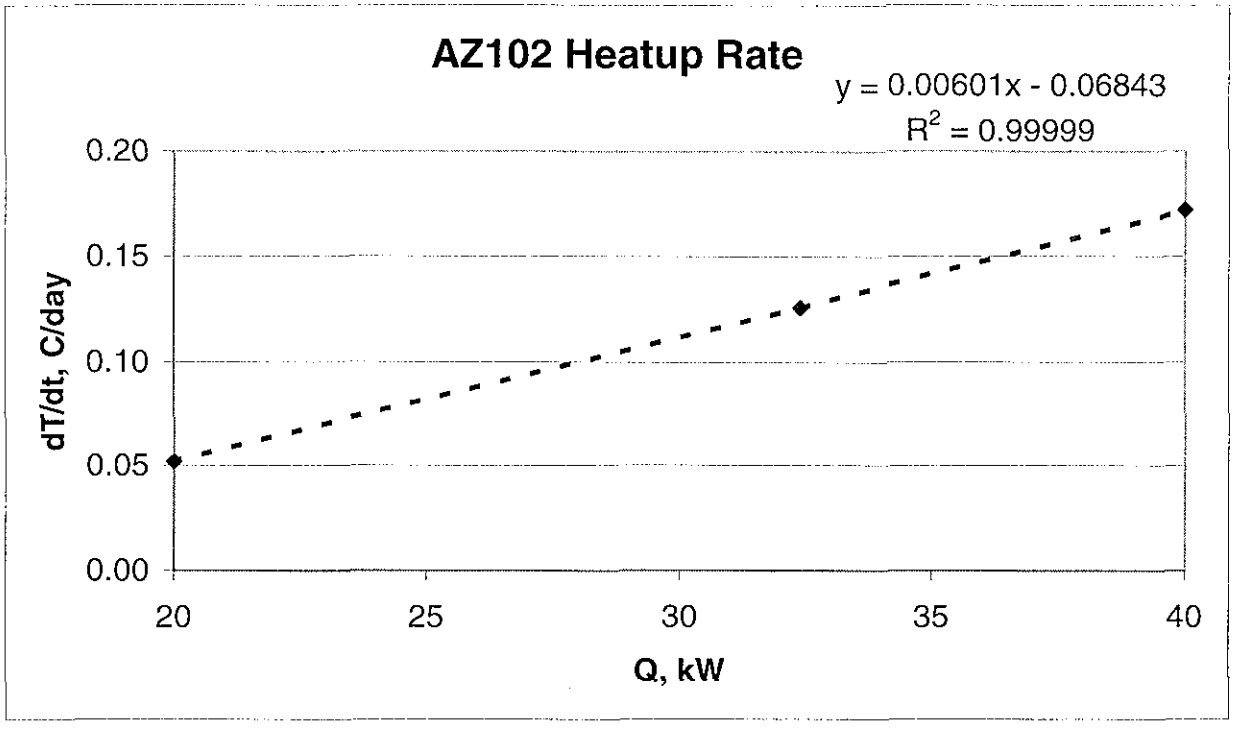
Inputs							Results	
CL Density (kg/m^3)	NCL Density (kg/m^3)	CL Volume (m^3)	NCL Volume (m^3)	CL Specific Heat (J/kg)	NCL Specific Heat (J/kg)	Soil Overburden, m	Heatup Rate, C/day	Heatup Rate Error
1140	1380	3377	397	3300	2850	4	1.28E-01	-2.12E-07
Air Temp., K	Soil Temp., K	Area, m^2	hex, $W/m^2/K$	Total Heat Load (W)	Soil Conductivity k_s, (W/m-K)	Tank Radius, m		
287	285	411	3.0446916	32400.0	1	11		

Integration For Waste Temperatures

Time, seconds	Days	NCL Temp., K	CL Temp., K	CL Heat Load, W	NCL Heat Load, W	Upward Loss, W	Exchange HX, W	Downward Loss, W	NCL Heatup, K/s	CL Heatup, K/s
0	0.00	375.00	364.00	12960.0	19440.0	7911.8	13765.1	3362.7	1.48E-06	1.48E-06
100000	1.16	375.15	364.15	12960.0	19440.0	7927.0	13765.1	3368.3	1.48E-06	1.48E-06
200000	2.31	375.30	364.30	12960.0	19440.0	7942.2	13764.8	3373.8	1.47E-06	1.48E-06
300000	3.47	375.44	364.44	12960.0	19440.0	7957.4	13764.2	3379.3	1.47E-06	1.48E-06
400000	4.63	375.59	364.59	12960.0	19440.0	7972.5	13763.4	3384.8	1.47E-06	1.48E-06
500000	5.79	375.74	364.74	12960.0	19440.0	7987.7	13762.4	3390.3	1.46E-06	1.47E-06
600000	6.94	375.88	364.89	12960.0	19440.0	8002.9	13761.2	3395.7	1.46E-06	1.47E-06
700000	8.10	376.03	365.03	12960.0	19440.0	8018.0	13759.8	3401.2	1.46E-06	1.47E-06
800000	9.26	376.18	365.18	12960.0	19440.0	8033.1	13758.2	3406.7	1.46E-06	1.47E-06
900000	10.42	376.32	365.33	12960.0	19440.0	8048.2	13756.5	3412.1	1.45E-06	1.47E-06
1000000	11.57	376.47	365.48	12960.0	19440.0	8063.3	13754.6	3417.5	1.45E-06	1.47E-06
1100000	12.73	376.61	365.62	12960.0	19440.0	8078.4	13752.7	3423.0	1.45E-06	1.47E-06
1200000	13.89	376.76	365.77	12960.0	19440.0	8093.5	13750.6	3428.4	1.45E-06	1.47E-06
1300000	15.05	376.90	365.92	12960.0	19440.0	8108.5	13748.4	3433.8	1.45E-06	1.46E-06
1400000	16.20	377.05	366.06	12960.0	19440.0	8123.6	13746.2	3439.2	1.44E-06	1.46E-06
1500000	17.36	377.19	366.21	12960.0	19440.0	8138.6	13743.8	3444.6	1.44E-06	1.46E-06
1600000	18.52	377.34	366.35	12960.0	19440.0	8153.6	13741.4	3450.0	1.44E-06	1.46E-06
1700000	19.68	377.48	366.50	12960.0	19440.0	8168.6	13738.9	3455.4	1.44E-06	1.46E-06
1800000	20.83	377.62	366.65	12960.0	19440.0	8183.6	13736.4	3460.7	1.44E-06	1.46E-06
1900000	21.99	377.77	366.79	12960.0	19440.0	8198.6	13733.8	3466.1	1.43E-06	1.46E-06
2000000	23.15	377.91	366.94	12960.0	19440.0	8213.6	13731.1	3471.5	1.43E-06	1.45E-06
2100000	24.31	378.05	367.08	12960.0	19440.0	8228.5	13728.5	3476.8	1.43E-06	1.45E-06
2300000	26.62	378.34	367.37	12960.0	19440.0	8258.4	13723.0	3487.5	1.43E-06	1.45E-06
2600000	30.09	378.77	367.81	12960.0	19440.0	8303.1	13714.6	3503.5	1.42E-06	1.45E-06

A plot of a parametric study on heat load is shown in Figure G.2.

Figure G.2 Results of Parametric Study for DST Heat-Up Rate for Tank 241-AZ-102



APPENDIX H

COMMENTS ON WASTE SATURATION TEMPERATURE

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APPENDIX H

COMMENTS ON WASTE SATURATION TEMPERATURE

Waste saturation temperatures were defined in Section 6.2. Here we consider associated uncertainties, namely, the influence of the primary ventilation system and vapor suppression by dissolved salts.

To draw in outside air, the primary ventilation system introduces a pressure differential with respect to the ambient environment that can amount to minus 6 inches w.g. This is not a significant contributor to uncertainty, however, because this pressure differential scarcely alters the supernatant boiling point. A 6-inch w.g. differential is the same as 1500 Pa, or 0.22 psig. For pure water, this reduces boiling point from 100 °C to 99.6 °C. This might be worth considering in the case of pure water, but for DST supernatant this temperature drop is more than offset by vapor suppression. In tank bump scenarios, this issue is moot because loss of ventilation for weeks or months is presupposed.

Tank bump calculations used the 85% vapor suppression value reported by Crea et al. (2000). This is consistent with the first-order approximation stating that vapor pressure for a mixture is the mole fraction weighted average of the vapor pressures for the individual species. In the case of the supernatant, the components are water and dissolved salts with little vapor pressure. Vapor suppression expressed as a fraction of pure water vapor pressure is then the same as the mole fraction of water, to a good approximation.

The Hu and Barker (2002) database lists supernatant water mass fraction, which allows us to infer the dissolved solids mole fraction and show that the 85% value is reasonable. For DSTS 241-AZ-101, 241-AZ-102, and 241-AY-102 the respective water weight fractions in the supernatant are 87%, 73%, and 84%. Many of DSTs have much lower water mass fractions; e.g. Tank 241-SY-101 has a water mass fraction of 61% for the supernatant. Mole fraction of water is then

$$N_w = \frac{1}{1+\left(\frac{1}{x}-1\right)\times\frac{MW_{H20}}{MW_s}} \qquad \text{Equation Section 8(H-1)}$$

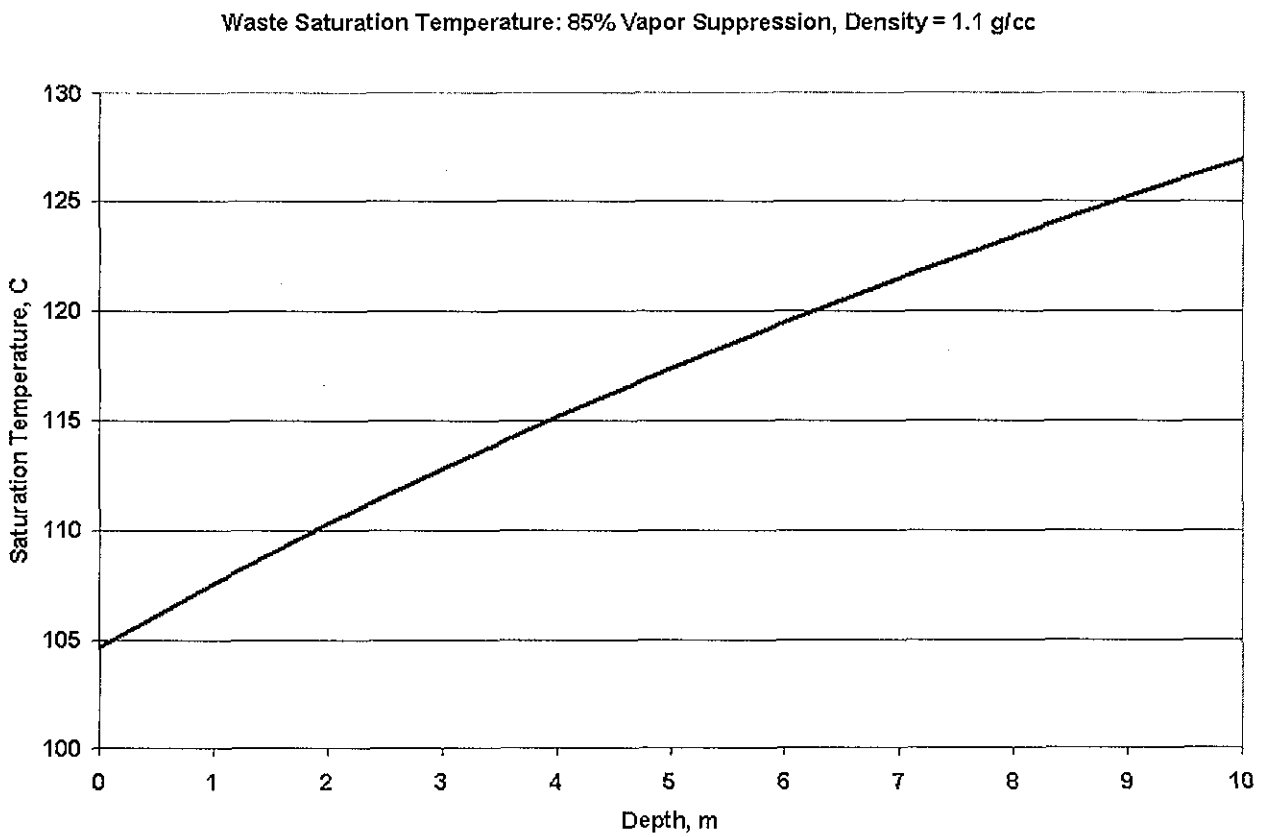
where x is the mass fraction of water, MW is molecular weight, and the subscript s denotes the dissolved solids. For the solids, molecular weight is not known, but is assumed to be 40 gm/gm-mole, which is the value for sodium hydroxide. If x is 73%, N_w is then 86%; if x = 87%, N_w = 94%; and if x = 60%, N_w = 77%. This shows that the use of the 85% value is acceptable as a single point-estimate for all the DSTs.

Supernatant vapor pressure is then suppressed by 85%, relative to the pure water value. The boiling point is then the saturation temperature at 119,235.3 Pa (101,350 Pa/85%). Examining the steam tables shows this temperature is 104.6 °C.

For the NCL, the hydrostatic pressure is included. To compute hydrostatic pressure at the NCL mid-plane, use the following:

$$P_{NCL} = P_{amb} + \rho_{CL}\, g\,(H_{CL} + H_{NCL}/2) \qquad \text{(H-2)}$$

For Tank 241-AZ-101, appropriate values are ρ_{CL} = 1240 kg/m^3, HCL = 8.23 m, and H_{NCL} = 0.48 m. Hydrostatic pressure at the mid-plane is then 204,382 Pa. To find boiling point, examine the steam tables for saturation temperature at 240,448 Pa (204382 / 0.85 Pa) and find 126 °C. The following plot shows saturation temperature as a function of depth for a supernatant density of ρ_{CL} = 1100 kg/m^3.



APPENDIX I

QUALITY ASSURANCE DOCUMENTS

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APPENDIX I

QUALITY ASSURANCE DOCUMENTS

Included here are:

1. Calculation Note Cover Sheet
2. Authorship and Reviewer Table
3. Calculation Note Methodology Checklist

FAUSKE & ASSOCIATES, INC.

CALCULATION NOTE COVER SHEET

SECTION TO BE COMPLETED BY AUTHOR(S):

Page I-2

Calc-Note Number FAI/00-14 Revision Number 0

Title Hanford Waste Tank Bump Accident and Consequence Analysis

Project Nuclear Safety & Licensing Project No. or Shop Order CHG01B

Purpose: Re-evaluate Hanford waste tank bump accident.

Results Summary: Physical models, criteria, frequency, and consequences are provided.

References of Resulting Reports, Letters, or Memoranda (Optional)

Author(s): Name (Print or Type)	Signature	Completion Date
Michael Epstein	Michael Epstein	5/31/00
Boro Malinovic	Boro Malinovic	5/31/00
Martin G. Plys	M. Plys	5/31/00
George Hauser	G. M. Hauser	5/31/00

SECTION TO BE COMPLETED BY VERIFIER(S):

Verifier(s): Name (Print or Type)	Signature	Completion Date
Martin G. Plys	M. Plys	5/31/00
Boro Malinovic	Boro Malinovic	5/31/00

Method of Verification: Design Review ____, Independent Review or Alternate Calculations X, Testing ____

Other (specify) ____

SECTION TO BE COMPLETED BY MANAGER:

Responsible Manager: Name (Print or Type)	Signature	Approval Date
Martin G. Plys	M. Plys	5/31/00

Section	Author(s)	Reviewer(s)
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4	M. Epstein	M. G. Plys
5	M. Epstein	M. G. Plys
6	B. Malinovic	M. G. Plys
7	B. Malinovic	M. G. Plys
8	M. G. Plys	B. Malinovic
9.1	M. Epstein	M. G. Plys
9.2	B. Malinovic	M. G. Plys
App. A	M. G. Plys	B. Malinovic
App. B	M. Epstein	M. G. Plys
App. C	M. Epstein	M. G. Plys
App. D	G. M. Hauser	M. G. Plys
App. E	G. M. Hauser	M. G. Plys
App. F	M. G. Plys	B. Malinovic
App. I	N/A	N/A
App. J	N/A	N/A

CALC NOTE NUMBER FAI/00-14 REV. 0 PAGE I-4 .

CALCULATION NOTE METHODOLOGY CHECKLIST

CHECKLIST TO BE COMPLETED BY AUTHOR(S) (CIRCLE APPROPRIATE RESPONSE)

1. Is the subject and/or the purpose of the design analysis clearly stated? ..... YES • NO

2. Are the required inputs and their sources provided? ..... YES • NO • N/A

3. Are the assumptions clearly identified and justified? ..... YES • NO • N/A

4. Are the methods and units clearly identified? ..... YES • NO • N/A

5. Have the limits of applicability been identified? ..... YES • NO • N/A
(Is the analysis for a 3 or 4 loop plant or for a single application.)

6. Are the results of literature searches, if conducted, or other background data provided? ..... YES • NO • N/A

7. Are all the pages sequentially numbered and identified by the calculation note number? ..... YES • NO

8. Is the project or shop order clearly identified? ..... YES • NO

9. Has the required computer calculation information been provided? ..... YES • NO • N/A

10. Were the computer codes used under configuration control? ..... YES • NO • N/A

11. Were the computer code(s) used applicable for modeling the physical and/or computational problems identified? ..... YES • NO • N/A
(Is the correct computer code being used for the intended purpose.)

12. Are the results and conclusions clearly stated? ..... YES • NO

13. Are Open Items properly identified ..... YES • NO • N/A

14. Were approved Design Control practices followed without exception? ..... YES • NO • N/A
(Approved Design Control practices refers to guidance documents within NSD that state how the work is to be performed, such as how to perform a LOCA analysis.)

15. Have all related contract requirements been met? ..... YES • NO • N/A

NOTE: If **NO** to any of the above, Page Number containing justification: _____

APPENDIX J

CHECKLIST FOR TECHNICAL PEER REVIEW

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APPENDIX J

CHECKLIST FOR TECHNICAL PEER REVIEW

Document Reviewed: RPP-6213, Rev. 3, Hanford Waste Tank Bump Accident and Consequence Analysis

Scope of Review (e.g., document section or portion of calculation): Changes incorporated as a result of Rev. 3 of the document (pgs. 1-1, 2-2, 4-13, 4-14, Addendum 1)

Yes	No	NA*	
[x]	[ ]	[ ]	1. Previous reviews are complete and cover the analysis, up to the scope of this review, with no gaps.
[x]	[ ]	[ ]	2. Problem is completely defined.
[x]	[ ]	[ ]	3. Accident scenarios are developed in a clear and logical manner.
[x]	[ ]	[ ]	4. Analytical and technical approaches and results are reasonable and appropriate. *(ORP QAPP criterion 2.8)*
[x]	[ ]	[ ]	5. Necessary assumptions are reasonable, explicitly stated, and supported. *(ORP QAPP criterion 2.2)*
[ ]	[ ]	[x]	6. Computer codes and data files are documented.
[x]	[ ]	[ ]	7. Data used in calculations are explicitly stated.
[x]	[ ]	[ ]	8. Bases for calculations, including assumptions and data, are consistent with the supported safety basis document (e.g., the Tank Farms Final Safety Analysis Report).
[x]	[ ]	[ ]	9. Data were checked for consistency with original source information as applicable. *(ORP QAPP criterion 2.9)*
[x]	[ ]	[ ]	10. For both qualitative and quantitative data, uncertainties are recognized and discussed, as appropriate. *(ORP QAPP criterion 2.17)*
[x]	[ ]	[ ]	11. Mathematical derivations were checked including dimensional consistency of results. *(ORP QAPP criterion 2.16)*
[x]	[ ]	[ ]	12. Models are appropriate and were used within their established range of validity or adequate justification was provided for use outside their established range of validity.
[x]	[ ]	[ ]	13. Spreadsheet results and all hand calculations were verified.
[x]	[ ]	[ ]	14. Calculations are sufficiently detailed such that a technically qualified person can understand the analysis without requiring outside information. *(ORP QAPP criterion 2.5)*
[ ]	[ ]	[x]	15. Software input is correct and consistent with the document reviewed.
[ ]	[ ]	[x]	16. Software output is consistent with the input and with the results reported in the document reviewed.
[ ]	[ ]	[x]	17. Software verification and validation are addressed adequately. *(ORP QAPP criterion 2.6)*
[x]	[ ]	[ ]	18. Limits/criteria/guidelines applied to the analysis results are appropriate and referenced. Limits/criteria/guidelines were checked against references. *(ORP QAPP criterion 2.9)*
[x]	[ ]	[ ]	19. Safety margins are consistent with good engineering practices.
[x]	[ ]	[ ]	20. Conclusions are consistent with analytical results and applicable limits.
[x]	[ ]	[ ]	21. Results and conclusions address all points in the purpose. *(ORP QAPP criterion 2.3)*

[x]	[ ]	[ ]	22. All references cited in the text, figures, and tables are contained in the reference list.
[x]	[ ]	[ ]	23. Reference citations (e.g., title and number) are consistent between the text callout and the reference list.
[x]	[ ]	[ ]	24. Only released (i.e., not draft) references are cited. *(ORP QAPP criterion 2.1)*
[x]	[ ]	[ ]	25. Referenced documents are retrievable or otherwise available.
[x]	[ ]	[ ]	26. The most recent version of each reference is cited, as appropriate. *(ORP QAPP criterion 2.1)*
[x]	[ ]	[ ]	27. There are no duplicate citations in the reference list.
[x]	[ ]	[ ]	28. Referenced documents are spelled out (title and number) the first time they are cited.
[x]	[ ]	[ ]	29. All acronyms are spelled out the first time they are used.
[x]	[ ]	[ ]	30. The Table of Contents is correct.
[x]	[ ]	[ ]	31. All figure, table, and section callouts are correct.
[x]	[ ]	[ ]	32. Unit conversions are correct and consistent.
[x]	[ ]	[ ]	33. The number of significant digits is appropriate and consistent.
[ ]	[ ]	[x]	34. Chemical reactions are correct and balanced.
[x]	[ ]	[ ]	35. All tables are formatted consistently and are free of blank cells.
[x]	[ ]	[ ]	36. The document is complete (pages, attachments, and appendices) and in the proper order.
[x]	[ ]	[ ]	37. The document is free of typographical errors.
[x]	[ ]	[ ]	38. The tables are internally consistent.
[x]	[ ]	[ ]	39. The document was prepared in accordance with HNF-2353, Section 4.3, Attachment B, "Calculation Note Format and Preparation Instructions".
[x]	**[ ]**	**[ ]**	**Concurrence**

Jimmy Starling 7/28/03

Reviewer (Printed Name and Signature) Date

- If No or NA is chosen, an explanation must be provided on this form.

1. Revision 3 of this document does not use special computer codes or software; therefore, items 6, 15, 16, and 17 are considered not applicable.
2. Revision 3 of this document does not involve any chemical reactions.

CHECKLIST FOR TECHNICAL PEER REVIEW

Document Reviewed: RPP-6213, Rev. 3

Yes	No	NA*		
[ ]	[ ]	[X]	1.	Previous reviews are complete and cover the analysis, up to the scope of this review, with no gaps.
[ ]	[ ]	[X]	2.	Problem is completely defined.
[ ]	[ ]	[X]	3.	Accident scenarios are developed in a clear and logical manner.
[ ]	[ ]	[X]	4.	Analytical and technical approaches and results are reasonable and appropriate. *(ORP QAPP criterion 2.8)*
[ ]	[ ]	[X]	5.	Necessary assumptions are reasonable, explicitly stated, and supported. *(ORP QAPP criterion 2.2)*
[ ]	[ ]	[X]	6.	Computer codes and data files are documented.
[ ]	[ ]	[X]	7.	Data used in calculations are explicitly stated.
[ ]	[ ]	[X]	8.	Bases for calculations, including assumptions and data, are consistent with the supported safety basis document (e.g., the Tank Farms Final Safety Analysis Report).
[ ]	[ ]	[X]	9.	Data were checked for consistency with original source information as applicable. *(ORP QAPP criterion 2.9)*
[ ]	[ ]	[X]	10.	For both qualitative and quantitative data, uncertainties are recognized and discussed, as appropriate. *(ORP QAPP criterion 2.17)*
[ ]	[ ]	[X]	11.	Mathematical derivations were checked including dimensional consistency of results. *(ORP QAPP criterion 2.16)*
[ ]	[ ]	[X]	12.	Models are appropriate and were used within their established range of validity or adequate justification was provided for use outside their established range of validity.
[ ]	[ ]	[X]	13.	Spreadsheet results and all hand calculations were verified.
[ ]	[ ]	[X]	14.	Calculations are sufficiently detailed such that a technically qualified person can understand the analysis without requiring outside information. *(ORP QAPP criterion 2.5)*
[ ]	[ ]	[X]	15.	Software input is correct and consistent with the document reviewed.
[ ]	[ ]	[X]	16.	Software output is consistent with the input and with the results reported in the document reviewed.
[ ]	[ ]	[X]	17.	Software verification and validation are addressed adequately. *(ORP QAPP criterion 2.6)*
[ ]	[ ]	[X]	18.	Limits/criteria/guidelines applied to the analysis results are appropriate and referenced. Limits/criteria/guidelines were checked against references. *(ORP QAPP criterion 2.9)*
[ ]	[ ]	[X]	19.	Safety margins are consistent with good engineering practices.
[ ]	[ ]	[X]	20.	Conclusions are consistent with analytical results and applicable limits.

[ ] [ ] [X] 21. Results and conclusions address all points in the purpose. *(ORP QAPP criterion 2.3)*
[X] [ ] [ ] 22. All references cited in the text, figures, and tables are contained in the reference list.
[X] [ ] [ ] 23. Reference citations (e.g., title and number) are consistent between the text callout and the reference list.
[X] [ ] [ ] 24. Only released (i.e., not draft) references are cited. *(ORP QAPP criterion 2.1)*
[X] [ ] [ ] 25. Referenced documents are retrievable or otherwise available.
[X] [ ] [ ] 26. The most recent version of each reference is cited, as appropriate. *(ORP QAPP criterion 2.1)*
[X] [ ] [ ] 27. There are no duplicate citations in the reference list.
[X] [ ] [ ] 28. Referenced documents are spelled out (title and number) the first time they are cited.
[X] [ ] [ ] 29. All acronyms are spelled out the first time they are used.
[X] [ ] [ ] 30. The Table of Contents is correct.
[X] [ ] [ ] 31. All figure, table, and section callouts are correct.
[X] [ ] [ ] 32. Unit conversions are correct and consistent.
[ ] [ ] [X] 33. The number of significant digits is appropriate and consistent.
[ ] [ ] [X] 34. Chemical reactions are correct and balanced.
[X] [ ] [ ] 35. All tables are formatted consistently and are free of blank cells.
[X] [ ] [ ] 36. The document is complete (pages, attachments, and appendices) and in the proper order.
[X] [ ] [ ] 37. The document is free of typographical errors.
[X] [ ] [ ] 38. The tables are internally consistent.
[ ] [ ] [X] 39. The document was prepared in accordance with HNF-2353, Section 4.3, Attachment B, "Calculation Note Format and Preparation Instructions".

Comments: RPP-6213, Rev. 3

Tech. Edit: CJ LYNCH CJ Lynch 7-28-03
Reviewer (Printed Name and Signature) Date

* If No or NA is chosen, an explanation must be provided on this form.

ADDENDUM 1

RESPONSE TO COMMENT NO. 4 OF MAY 21, 2003, RELATIVE TO TANK BUMP REPORT 6213, REV. 2, AND TANK BUMP ANALYSIS CLOSE-OUT

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ADDENDUM 1

RESPONSE TO COMMENT NO. 4 OF MAY 21, 2003, RELATIVE TO TANK BUMP REPORT 6213, REV. 2, AND TANK BUMP ANALYSIS CLOSE-OUT

Tomaszewski
Response to IRT Comment No. 4, Final

Fauske & Associates, Inc.

DATE: July 25, 2003

TO: Thomas Tomaszewski (CH2M-Hill)
Martin G. Plys

FROM: Boro Malinovic

SUBJECT: **Response to Comment No. 4 of May 21, 2003 Relative to Tank Bump Report RPP-6213, Rev. 2 and Tank Bump Accident Analysis Close-out**

This memorandum responds to IRT Comment No. 4, dated May 21, 2003 and by doing so demonstrates that tank bumps are not possible in DST AZ-101, AZ-102 and AY-102. The comment is repeated here verbatim:

4. ***Section 4.2, pages 4-13&14, and Tables 4-1 and 4-2.*** *The present model calculates the noncondensable gas generation rate at the boiling temperature by using the Arrhenius equation to extrapolate from the known gas generation rate at the prevailing nonconvective layer temperature. Equation 4-19 uses the activation energy for thermolysis as the basis for extrapolation. This is inappropriate and results in over-prediction of gas generation rate by several hundred percent. As indicated in HNF-3851, Table 5-1, noncondensible gas generation in the three DSTs of interest, AZ-101, AZ-102, AY-102, is dominated by radiolysis, not thermolysis. HNF-3851, Section 4.4, provided activation energies for organic radiolysis and thermolysis, with the value for radiolysis about half of that for thermolysis. Table 4-1 of the present report shows the gas generation rates at boiling temperature increase by about 25 to 40 times over values at prevailing tank temperatures. If the more appropriate radiolysis activation energy is used in equation 4-19, the increase will be much smaller. This underscores another large factor of conservatism in the analysis.*

The comment is accurate: thermolytic activation energy was used for the sake of conservatism. Activation energies for thermolysis and radiolysis are listed in RPP-5926, Rev. 2 as 89.3 kJ/gm-mole and 44.3 kJ/gm-mole, respectively. As the reviewer noted, radiolysis activation energy is about half the thermolysis activation energy. RPP-6213, Rev. 2 uses an activation

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temperature of 10,740 K (89,300/8.314 K) in Equation 4-19. But RPP-5926, Rev. 2, Table B-4, shows that in the AY-102 NCL, 96% of hydrogen generation is due to radiolysis.

To address the reviewer's comment, calculate best-estimate hydrogen generation rates (HGR) at NCL saturation temperatures by applying the Hu and Barker semi-empirical rate equations shown in Section 2.1 of RPP-5926, Rev. 2. This is an update to the HNF-3851, Section 4.4 referred to in the review comment.

Inputs to the calculation are shown here in Table 1 and 2. With the exception of the waste temperatures, Table 1 is raw data from RPP-5926, Rev 2, Tables B-1 and B-2. The waste temperatures in Table 1 are the saturation temperatures at the NCL mid-plane, not accounting for vapor suppression, as shown in Table 4-1 of RPP-6213, Rev. 2. Table 2 shows more raw data and intermediate input calculations of G-value, which is temperature-dependent for organic radiolytic reactions.

Table 3 shows HGR results for the three HGR components (radiolysis, thermolysis, and corrosion). Calculations assume corrosion rate is not temperature dependent. The key result for each DST is the total HGR expressed as gm-mole/m^3 NCL-day: 0.173, 0.147 and 0.116 for AY-102, AZ-101 and AZ-102, respectively. Calculations were performed in an EXCEL spreadsheet and validated by reproducing the results in RPP-5926, Rev. 2.

Use the hydrogen generation rates from Table 3 to re-evaluate Tables 4-1 and 4-2 from RPP-6213, Rev. 2. Revised Tables 4-1 and 4-2 list new results below. Table 4-2 shows the buoyant displacement parameter (LHS of Equation 4-16 for HGR) is much less than one in all three cases.

To conclude, realistic calculations show that none of the three tanks can attain bump conditions. This conclusion is insensitive to uncertainties in hydrogen generation rates because the buoyant displacement parameter varies only with the cube root of hydrogen generation rate. Even if the non-convective layer hydrogen generation rate is arbitrarily doubled for AY-102, the buoyant displacement parameter increases to only 0.8. To conclude, realistic calculations for DST buoyant displacement parameters show that tank bumps are impossible.

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Table 1: Inputs to Hydrogen Generation Rate Calculations for AY-102, AZ-101 and AZ-102 at NCL Saturation Temperature; both overall DST and NCL properties are given.

Tank	Bulk density D (g/mL)	Waste volume V (kL)	Bulk water [H_2O] (wt%)	Waste temp. T_w (°C)	D_L (g/ml) Liquid Density	Waste level D_w (inch)	Liquid in waste (wt%)
AY-102	1.22	2,403	0.8	112	1.14	230.5	83%
NCL	1.40	646	0.4	112	1.10	62.0	44%
AZ-101	1.26	3,574	0.7	120	1.24	342.8	98%
NCL	1.62	197	0.6	120	1.24	18.9	76%
AZ-102	1.17	3,774	0.8	119	1.14	362.0	96%
NCL	1.38	397	0.6	119	1.14	38.1	66%

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Response to IRT Comment No. 4, Final

Table 2: Inputs and G Values to HGR Calculations for AY-102, AZ-101 and AZ-102 at NCL Saturation Temperature; both overall DST and NCL properties are given.

Tank	Heat load per kg H_L (watt/kg)	Tank heat load H_L (watt)	NO_3 in liquid $[NO_3]_M$ (mole/L)	NO_2 in liquid $[NO_2]_M$ (mole/L)	TOC in liquid $[TOC]_{\%}$ (wt%)	Al in liquid $[Al]_{\%}$ (wt%)	G values for water G_{H2O} (H_2/100eV)	Total G values G_{TOT} (H_2/100eV)
AY-102	1.24E-02	3.64E+04	0.01	0.11	0.14	0.13	0.139	0.383
NCL	4.00E-02	3.61E+04	0.00	0.00	0.14	0.13	0.282	0.526
AZ-101	1.34E-02	6.04E+04	1.03	1.41	0.03	0.62	0.005	0.064
NCL	1.05E-01	3.36E+04	1.03	1.41	0.03	0.62	0.005	0.064
AZ-102	7.36E-03	3.24E+04	0.28	0.71	0.09	0.05	0.005	0.206
NCL	2.95E-02	1.62E+04	0.28	0.71	0.09	0.05	0.005	0.206

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Table 3: Radiolysis, Thermolysis, Corrosion and Total HGR Rates

Tank	HGR from radiolysis RC_{rad} (mole/kg-d)	HGR from thermolysis RC_{therm} (mole/kg-d)	HGR from corrosion RC_{corr} (mole/kg-d)	Total HGR from model RC_{tot} (mole/kg-d)	HGR from radiolysis RC_{rad} (mole/m^3-day)	HGR from thermolysis RC_{therm} (mole/m^3-day)	HGR from corrosion RC_{corr} (mole/m^3-day)	Total HGR from model RC_{tot} (mole/m^3-day)
AY-102 NCL	8.23E-05	4.10E-05	6.25E-07	1.24E-04	1.15E-01	5.73E-02	8.74E-04	1.73E-01
AZ-101 NCL	4.61E-05	4.31E-05	1.50E-06	9.07E-05	7.46E-02	6.99E-02	2.44E-03	1.47E-01
AZ-102 NCL	3.63E-05	4.68E-05	9.45E-07	8.41E-05	5.01E-02	6.46E-02	1.30E-03	1.16E-01

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New Table 4-1: Gas and Steam Generation Rates in the Non-Convective Layer

Tank	Prevailing NCL Temp.	NCL Boiling Temp.	NCL Volumetric Heat Rate	Hydrogen Generation Rate per Unit Volume of NCL, Prevailing Temp - HGR(T_0)	Hydrogen Generation Rate per Unit Volume of NCL, Boiling Temp - HGR(T_{sat})	Vapor Generation, G_v
	K	K	W/m^3	g-mole/m^3-day	g-mole/m^3-day	g-mole/m^3-day
AZ-101	348.15	393	170.1	0.021	0.147	371
AZ-102	345.15	392	40.71	0.011	0.116	89
AY-102	345.15	385	56	0.069	0.173	122

New Table 4-2: Buoyant Displacement Model (Equation 4-16) Predictions

Tank	NCL Density	Sup. Density	NCL Thickness	Hydrostatic Pressure at NCL Mid-Plane	LHS of Eq. 4-16, $G = G_v$	LHS of Eq. 4-16, HGR(T_{sat})
	kg/m^3		m	atm		
AZ-101	1620	1240	0.48	2.02	0.47	0.03
AZ-102	1380	1140	0.97	1.96	1.89	0.21
AY-102	1400	1150	1.57	1.56	5.68	0.64

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