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TANK BUMP ACCIDENT POTENTIAL AND CONSEQUENCES DURING WASTE RETRIEVAL

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Abstract: This report provides an evaluation of the Hanford tank bump accident analysis and consequences for incorporation into the Authorization Basis. The analysis scope is for the feed delivery and retrieval of waste from single-shell and double-shell tanks.

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Richland, Washington
Contractor for the U.S. Department of Energy
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TANK BUMP ACCIDENT POTENTIAL AND CONSEQUENCES DURING WASTE RETRIEVAL

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1.0 PURPOSE AND SCOPE

This report provides an evaluation of Hanford tank bump accident potential and consequences during waste retrieval operations. The purpose of this report is to consider the best available new information to support recommendations for safety controls. A new tank bump accident analysis for safe storage (Epstein et al. 2000) is extended for this purpose.

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. Tank bump scenarios, physical models, and frequency and consequence methods are fully described in Epstein et al. (2000).

The analysis scope is waste retrieval from double-shell tanks (DSTs) including operation of equipment such as mixer pumps and air lift circulators. The analysis considers physical mechanisms for tank bump to formulate criteria for bump potential during retrieval, application of the criteria to the DSTs, evaluation of bump frequency, and consequence analysis of a bump. The result of the consequence analysis is the mass of waste released from tanks; radiological dose is calculated using standard methods (Cowley et al. 2000).

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2.0 SUMMARY OF FINDINGS

Waste retrieval activities have been evaluated to identify credible tank bump accident scenarios, estimate their frequency, and calculate radiological and toxicological consequences stemming from predicted source terms.

Retrieval operations were reviewed with respect to tank bump phenomena and possible scenarios were presented as logic trees. Based on a set of ventilation system success criteria and the tank bump requirements presented in the safe storage accident analysis (Epstein et al. 2000), a scenario for further analysis was developed. This scenario states that during mixer pump operation, the ventilation system fails and mixer pumps are shut down to minimize heat load. Then, the ventilation system cannot be recovered prior to tank self-heating to bump conditions.

Success criteria assume that the ventilation system will maintain waste temperatures below limiting condition for operation (LCO) 3.3.2 for indefinite mixer pump operation, as in the analysis of Crea et al. (2000). The results of the safe storage accident analysis (Epstein et al. 2000) can then be used to immediately state that tank bump during retrieval frequency is beyond extremely unlikely for all DSTs, with the exception of the aging waste facility (AWF) tanks. Safe storage results show that starting from the LCO 3.3.2 temperature limits of 195°F, tank self-heating to bump conditions would require hundreds of days, excepting the AWFs. In addition, this report shows that for DSTs with a total decay heat load of less than 10 kW, tank bumps are impossible, regardless of non-convective layer depth or the fluffing factor.

The AWFs were considered further and Tank 241-AZ-102 was selected as the bounding tank for both frequency and consequence analysis, based on the safe storage results of the analysis (Epstein et al. 2000) and Crea et al. (2000). For the frequency analysis, the duration of mixer pump operation is a key risk metric. A long mixer pump duration increases the likelihood of ventilation system failure during mixer pump operation and heats the waste to reduce the available recovery time. For the planned operations, which have mixer pump operations lasting only a few days, tank bump frequency is beyond extremely unlikely because the available recovery time will be much larger than even the worst corrective maintenance times. Mixer pump operation was studied parametrically, however, to account for prolonged operation caused by schedule delays, procedural errors, and the like. Tank bump frequency becomes credible (greater than 1×10^{-6}/demand) if the mixer pumps operate for approximately one month.

Consequences were calculated for Tank 241-AZ-102 in much the same manner as they were calculated in the safe storage accident analysis (Epstein et al. 2000). Only the first batch operation for Tank 241-AZ-102 was considered; subsequent batches will have smaller waste inventories and heat loads. The main difference between consequence analysis in the safe storage scenario and consequence analysis for the retrieval scenario is the waste properties. A fluffing factor of 2.0 was applied to settled waste, per Crea et al. (2000), which means relative to the safe storage scenario, the non-convective layer has a smaller solids mass (or volume) fraction and smaller yield strength. A fluffing factor value of 2.0 proves to be very conservative, in light of mixing test results that indicate best-estimate values of 1.3 or 1.4. Calculations using the Meyer and Wells (2000) criterion described in the safe storage accident analysis

(Epstein et al. 2000) indicate that a tank bump initiated by retrieval operations is possible only for fluffing factor values greater than 1.7.

For Tank 241-AZ-102, HADCRT parametric runs were performed to study the range of outcomes for a retrieval bump. The HADCRT code is an integrated model for storage tank thermal-hydraulic and accident phenomena (Malinovic et al. 2000). Code revisions for bump phenomena are described in the safe storage accident analysis (Epstein et al. 2000). The parametric runs considered a range of initial gas volumes and two supernatant temperatures, 94 and 100°C. The size of the retrieval bump, in terms of headspace overpressure and aerosol generation, is very sensitive to the supernatant temperature. The 94°C value is identified as a best-estimate, based on the work of Crea et al. (2000), while 100°C is an upper bound assuming pure water properties. The analysis of Crea et al. (2000) shows that when the non-convective layer reaches saturated conditions, the supernatant is not yet saturated and is only 94°C. (As shown in the safe storage accident analysis (Epstein et al. 2000), the supernatant temperature determines the bubble expansion ratio, which is the bubble gas volume exiting the top surface of the supernatant to the initial gas volume.) This series of parametric runs revealed that for the best-estimate supernatant temperature and the expected initial gas volume(s), retrieval tank bump consequences would be much smaller than the consequences calculated for the safe storage scenario. This is because the retrieval scenario bumps should be weak by comparison and the filters should not fail on overpressure.

A bounding, unmitigated scenario was identified for Tank 241-AZ-102, nevertheless, assuming that the initial gas volume in the bump would be half the initial gas volume in the safe storage bump already analyzed. Parametric runs for the strength of a single bump show that with a fluffing factor of 2.0, a retrieval scenario bump of 4.0 m^3 of initial gas released would be nearly as strong as the safe storage scenario bump with 8 m^3 of initial gas released. But halving the initial gas volume means that the total number of bumps is roughly doubled. In the bounding retrieval bump scenario, 29 bumps occur over a span of three weeks. In keeping with the definition of a bounding, unmitigated scenario, HEPA filters were not credited and no account was made of their decontamination factor or pressure drop characteristics.

HADCRT analysis shows that the bumps are spaced so far apart (18 hours) that each individual bump is unaffected by the previous bump. Between bumps, all airborne aerosols are either deposited back to the waste surface or expelled. In other words, the headspace returns to the initial conditions before the next bump occurs. The source term from *n* bumps is then simply *n* multiplied by the source term of a single bump. For a single bump, 0.42 kg of waste are released including 0.01 liters of solid and 0.36 liters of liquid. Note that the solids mass fraction of the released waste is smaller in the retrieval scenario due to fluffing.

As in the safe storage accident analysis (Epstein et al. 2000), radiological consequences were calculated based on methodology identified in Cowley et al. (2000). Radiological and toxicological consequences were calculated for one bump only. The presumption is that after the first bump occurs, mitigating actions would minimize or prevent dose to both the on-site worker and off-site receiver. During an eight-hour shift, total on-site worker dose is 0.003 Sv for a receiver at 100 m. For an eight-hour event, the off-site dose is 6×10^{-6} Sv. Toxicological consequences were calculated using methodology identified in

WHC-SD-WM-SARR-011 (1996) and found to be within guidelines for continuous release assumptions, but not puff release assumptions.

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3.0 OPERATIONS, EQUIPMENT, AND WASTE PARAMETERS CONSIDERED

This section describes the retrieval activities as planned for double-shell Tanks 241-AZ-101, 241-AN-104, and 241-AN-105. Primary information sources are Carlson (1999a and 1999b). Because retrieval operations are amply described in these references and elsewhere, the focus here is only to summarize them in sufficient detail to understand the accident scenarios evaluated in Sections 5.0 and 6.0. In the references, much of the discussion of waste feed delivery activities (the terms waste feed delivery and retrieval are used interchangeably here) pertains to administrative, waste qualification, and transfer processes that have no bearing on tank bump phenomena.

Because the tank bump criteria from the safe storage accident analysis (Epstein et al. 2000) are used again frequently, they are repeated here for convenience. 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. There is an insignificant non-convective layer,
2. Supernatant depth does not exceed 1 m,
3. Total tank heat load can be removed by steady-state conduction through the soil overburden (total tank heat load is less than 8500 W),
4. The time to saturated tank conditions exceeds the time needed for ventilation system repairs using a lumped capacitance (single waste temperature) approach,
5. The time to saturated tank conditions exceeds the time needed for ventilation system repairs using separate energy balances for supernatant and non-convective layers, and
6. Neutral buoyancy cannot be attained in the non-convective layer through buildup of noncondensible gases.

The limiting conditions for operation are also referred to repeatedly. They are as follows (HNF-SD-WM-TSR-006 2000):

LCS / LCO 3.3.2 The WASTE temperature shall be either:

a. ≤ 195°F in all levels of the waste.

OR

b. ≤ 195°F in the top 15 ft. of the waste

AND

≤ 215°F in the waste below 15 ft.

3.1 TANK 241-AZ-101 FEED DELIVERY ACTIVITIES

A logic diagram for Tank 241-AZ-101 waste feed delivery activities is shown in Figure 3-1. This figure is a streamlined version of a logic diagram shown in Carlson (1999b).

Feed qualification is the first feed delivery activity. One set of samples will be used for the entire Tank 241-AZ-101 inventory, which will be delivered in nine batch transfers. Feed qualification begins with five days of mixing using two mixer pumps. After the non-convective layer has been mobilized and the waste is homogeneous, samples are obtained, provided to the feed delivery customer, and analyzed. The mixer pumps are stopped and the waste is cooled in Tank 241-AZ-101 while the samples are qualified.

After the CH2M Hill Hanford Group (CHG) and feed delivery customer concur on the feed qualification, the waste in the tanks is mixed with two mixer pumps for two days to ensure the waste is well mixed. This second mixing process should take less time because the waste should be easier to mobilize. The waste is cooled for five days as preparations take place for the batch transfer. The waste transfer pump transports the waste through the Tank 241-AZ-01A central pump pit, onto the "New AZ Valve Pit," and then to the feed delivery customer. For batch transfers two through nine, the processes of mixing, cooling, and transfer are repeated.

3.2 FEED DELIVERY ACTIVITIES FOR TANKS 241-AN-104 AND 241-AN-105

Waste transfers from Tank 241-AN-105 to the feed delivery customer are described in Carlson (1999a and 1999b). Feed delivery activities for Tank 241-AN-105 are more complicated than for Tank 241-AZ-101 feed delivery activities and consist of degassing, settling, decanting, salt cake dissolution, decanting again, and delivery. These steps are shown in Figure 3-2, which also indicates that the activities description for Tank 241-AN-105 applies just as well to Tank 241-AN-104. Each step is described below with attention to tank bump concerns only.

Degassing involves mixing the settled solids to release flammable gases. (This step is optional and the process might begin with decanting immediately.) To limit the flammable gas release rate, mixer pumps will be operated intermittently and sequentially over the course of a few days. This operating mode also limits the amount of mixing; extensive mixing is not especially desirable because the supernatant must be decanted from the salt cake.

After degassing, the tank is allowed to settle for 30 days. This minimizes the amount of solid in the supernatant and keeps the transfer consistent with the feed delivery specification for low activity waste (LAW) transfers. During this period, only the ventilation system and its ancillary functions must operate.

After 30 days of settling, the supernatant will be decanted by transferring it with in-line dilution from Tank 241-AN-105 to Tank 241-AP-102, which is the "interim waste staging tank".

Figure 3-1. Simplified Logic Diagram for Tank 241-AZ-101 Feed Delivery Activities.

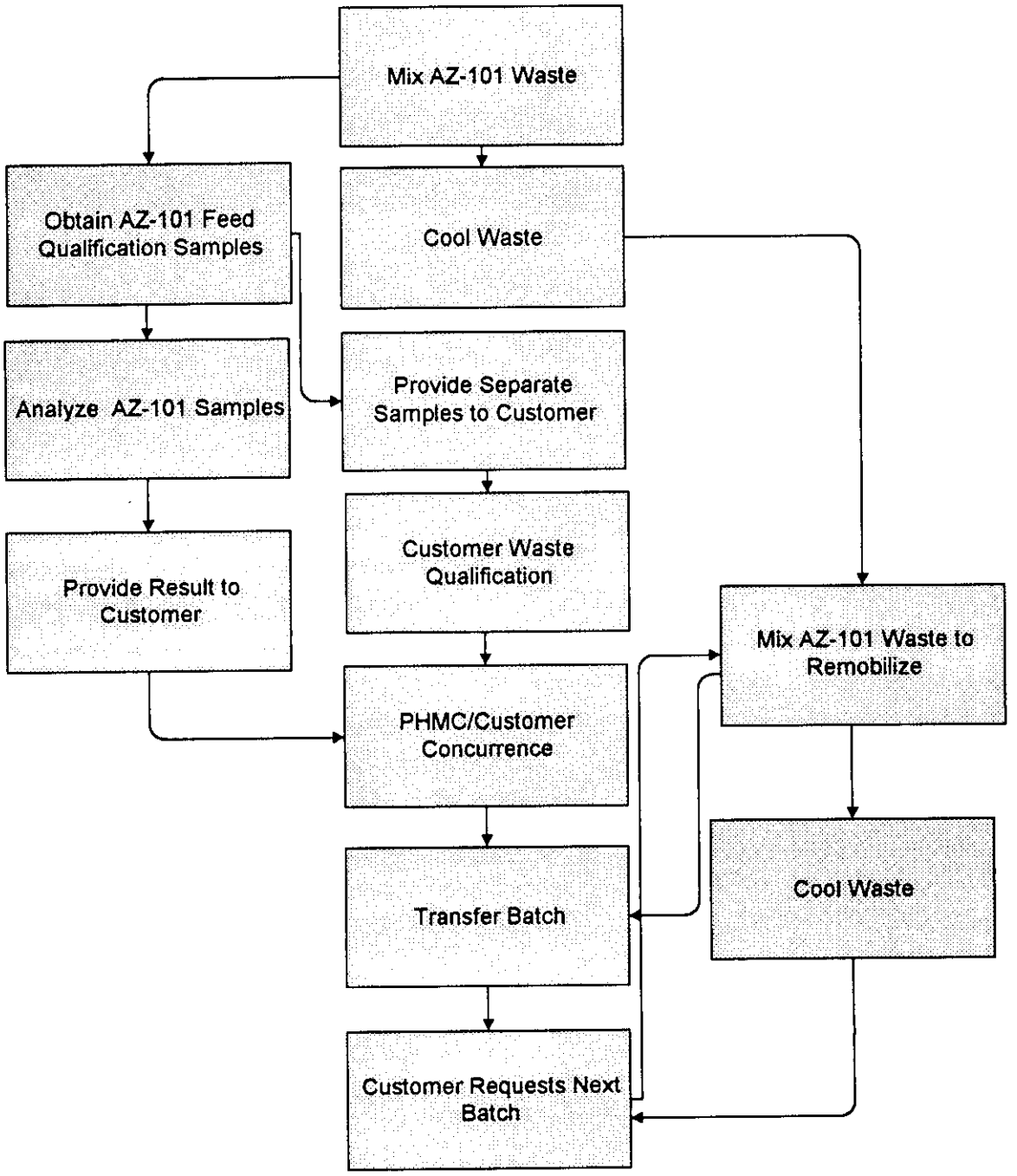
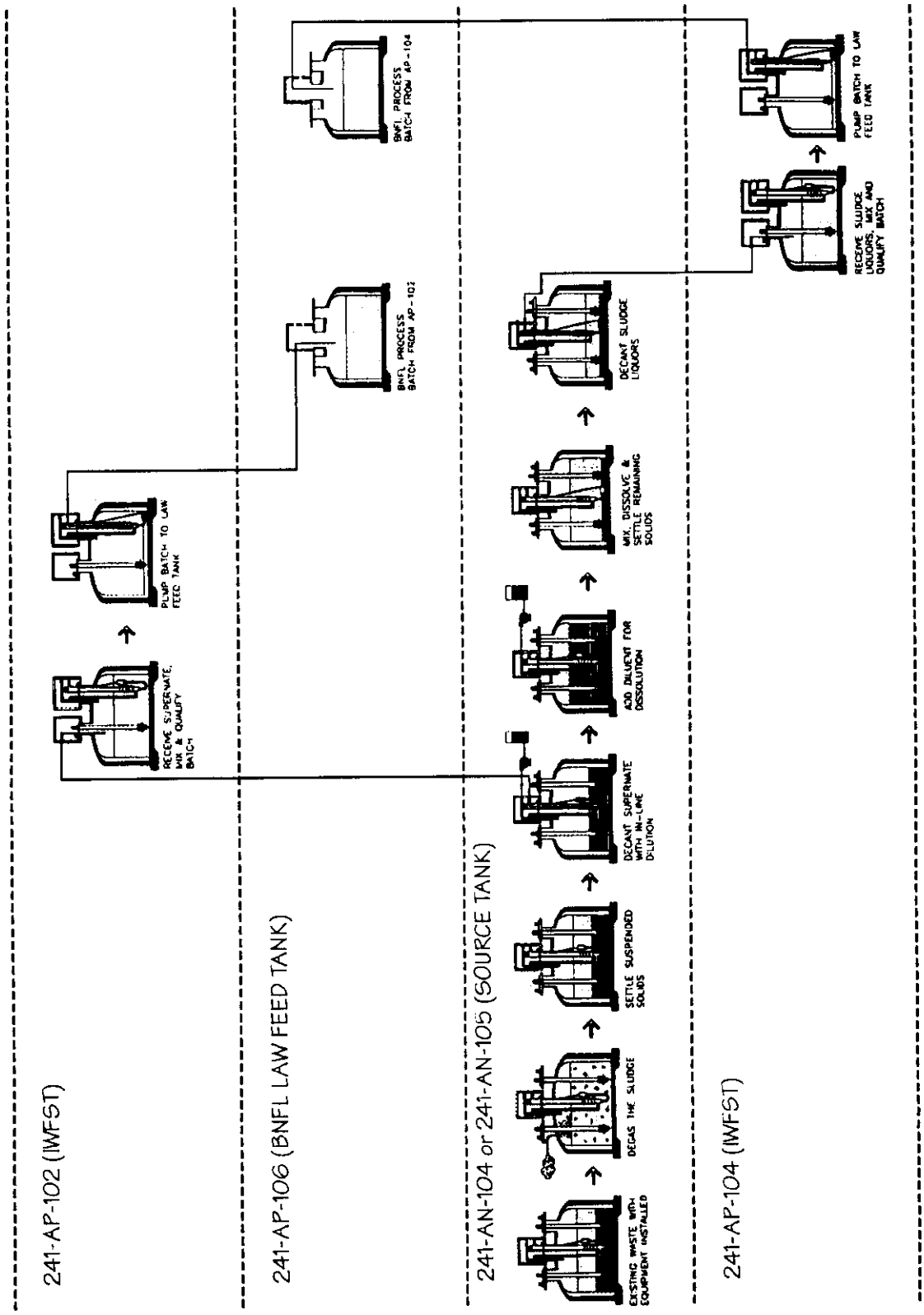


Figure 3-2. Tanks 241-AN-105 and 241-AN-104 Feed Delivery Activities.



Carlson (1999a and 1999b) states that something like 790,000 gallons (2,991 m^3) will be decanted to Tank 241-AP-102, but the actual amount transferred will depend on the effectiveness of settling during the 30-day interim. The Hu et al. (2000) waste database states that there are 2,441 m^3 of supernatant in Tank 241-AN-105.

Salt cake remaining after the first decanting process is then dissolved by the addition of raw water and mixed for seven days. The Waste Feed Delivery Reliability, Availability, and Maintainability (WFD RAM) study (Carlson 1999a and 1999b) assumed that the waste temperature does not exceed limiting conditions for operation (LCO) (HNF-SD-WM-TSR-006 2000). This work makes the same assumption for reasons described below.

A second decanting process will transfer the remaining waste volume in Tank 241-AN-105, except for a heel, to Tank 241-AP-104 for sampling and qualification.

Waste in Tanks 241-AP-102 and 241-AP-104 will be mixed for a short time and sampled for feed delivery qualification.

After meeting feed delivery qualifications, the contents of each tank will be transferred to the customer's low activity waste (LAW) feed tank. This involves one batch transfer for each interim tank.

3.3 TANK BUMP CONSIDERATIONS FOR FEED DELIVERY ACTIVITIES

Feed delivery activities are examined for potential tank bump scenarios. The following assumptions are used in combination with the screening criteria presented in the safe storage tank bump accident analysis (Epstein et al. 2000):

1. Feed delivery activities begin with the current safe storage conditions. Waste temperatures are at current, steady-state values and primary and annulus ventilation systems are functional.

2. Normal mixer pump operation prevents a tank bump, assuming that the supernatant is highly sub-cooled at the start of mixing. The safe storage tank bump analysis lists the conditions required for a tank bump. First, the waste must consist of a heat generating non-convective layer with a deep, overlying supernatant. Another condition is that the supernatant must be saturated or nearly so to create significant expansion of the released gas bubble. Bubble expansion is minimal (a factor of 4 for 10 m of supernatant) for 10°C sub-cooling. If the supernatant is highly sub-cooled at the time of mixer pump start-up, gases released by disturbing the waste will not result in significant bubble expansion. Once the mixer pumps have operated for a time and the non-convective layer is fluidized, the configuration for a bump no longer exists.

3. Primary and annulus ventilation are sized to keep waste temperatures below the LCO 3.3.2 temperature limit requirements, even for indefinite

mixer pump operation. Although the mixing operations described above last for a few days only, the primary and annulus ventilation systems will operate with flow rates to ensure that the LCO 3.3.2 requirements are not exceeded, despite indefinite operation. Crea et al. (2000) shows that this can be accomplished for the aging waste facility tanks by operating the existing primary and annulus ventilation systems within design limits.

4. A success criterion is that primary and annulus ventilation are both needed to maintain waste temperature below tank bump conditions. Success criteria are defined as the minimum sets of equipment needed to maintain a safe, stable state where all waste temperatures meet LCO 3.3.2 and are either steady or declining. Clearly, both the primary and annulus ventilation systems are needed to maintain temperatures below the LCO 3.3.2 requirements, while the mixer pumps are operating indefinitely with a total power of 600 hp. This work assumes the same success criterion is needed to prevent bumps, regardless of mixer pump operation. This amounts to assuming that a failure of either system leads to bump conditions.

   If the primary ventilation system operates, but the annulus ventilation system does not, bump conditions in the non-convective layer are possible, but the supernatant will remain highly sub-cooled. This does not necessarily lead to a safe, stable state, however, because the non-convective layer temperature can exceed the local saturation temperature. The annulus ventilation system alone cannot prevent bumps because the supernatant temperature cannot be maintained. The WFD RAM state that air lift circulators (ALCs) will be used to maintain safe storage. This work does not consider operation of the ALCs because there is no thermal-hydraulic analysis to support ALC operation as a success criterion for retrieval bump scenarios. Moreover, inadvertent use of the ALC can lead to a bump.

5. Waste feed deliveries in all the aging waste facility tanks are the same as the description above for Tank 241-AZ-101.

6. In the aging waste facility tanks, tank bump risk (frequency times consequences) for the first batch bounds the risk from subsequent batches. Each subsequent batch has a somewhat lower tank heat load, supernatant depth, etc. Since there are nine batches planned, the total tank heat load decreases by about 11% after the first batch transfer. This assumption removes the need to perform consequence and frequency calculations for each batch transfer because the first one is bounding for both frequency and consequences.

7. Partial mixing scenarios are considered for both the LAW and AWF tanks. In a partial mixing scenario, mixer pump operation causes a non-uniform height distribution in the non-convective waste. This could happen if a single mixer pump operated very briefly, so as to sweep only a small

portion of the tank and allow the mobilized solids to settle in other parts of the tank.

Tank bump scenarios for feed delivery activities are considered next on the basis of these assumptions and the screening criteria of the safe storage tank bump accident analysis (Epstein et al. 2000).

3.4 TANK BUMP CONSIDERATIONS FOR LAW FEED DELIVERY ACTIVITIES

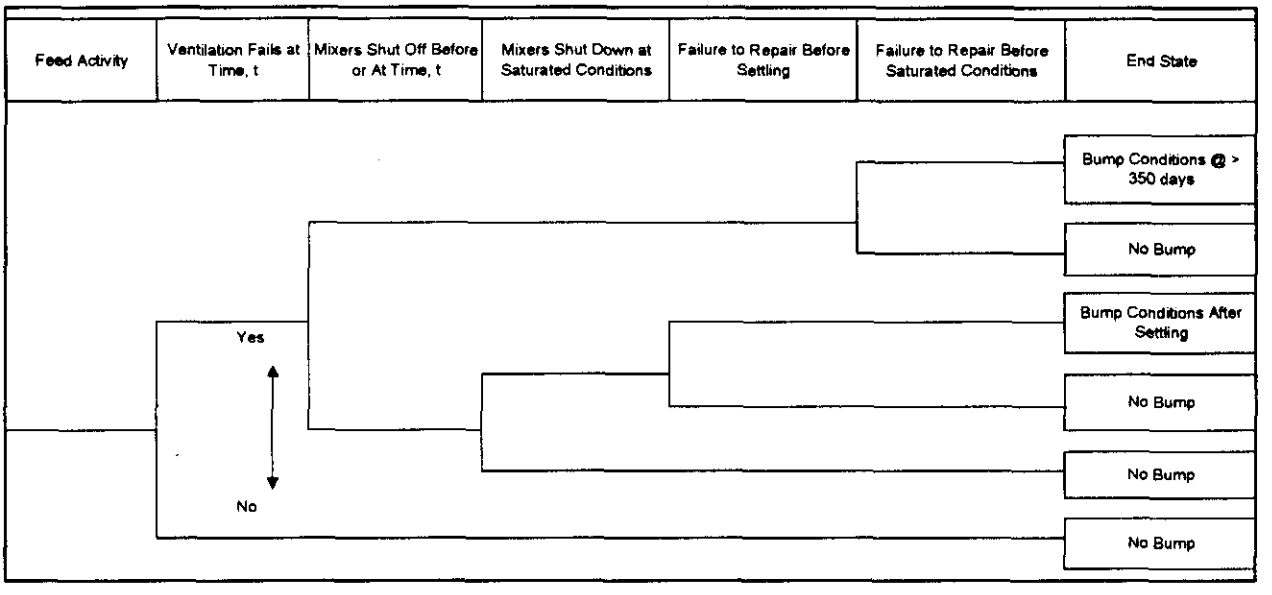
Each of the steps in the LAW feed delivery is considered for tank bump potential. The logic discussed below can be represented by the LAW feed delivery event tree in Figure 3-3.

For the first degassing step, initial mixer operation cannot cause a bump, per assumptions 1 and 2 above. A tank bump caused by indefinite mixer pump operation with operating ventilation can be ruled out on the same basis. If the mixer pump fails or is shut off, but primary and annulus ventilation do not fail, a bump cannot occur on the basis of assumptions 1, 3, and 4. If the mixer pump is shut off (or fails) prior to or concurrent with primary and annulus ventilation system failure, a tank bump is excluded on the basis of bump criterion 4 from the safe storage accident analysis (Epstein et al. 2000). This branch of the tree results in tank self-heating, with the LCO 3.3.2 limits as bounding initial conditions. Assuming the LCO 3.3.2 as the initial conditions, it takes <u>at least</u> 350 days to reach saturated conditions (Table 6-5 of Epstein et al. (2000)). Some tanks can never bump in this scenario, despite the loss of ventilation, because the total tank heat load can be removed by conduction. Section 4.0 demonstrates that for tanks with a heat load less than roughly 10 kW, bumps cannot occur, regardless of non-convective layer height (the fluffing factor) or non-uniform waste distribution caused by partial mixing.

It can be postulated that mixer pump operation continues after primary and annulus ventilation system failure and heats the waste to saturated conditions. This involves two procedural errors: failing to turn off the mixer pumps immediately and then turning them off when the waste temperature approaches bump conditions. A tank bump is then possible after the waste settles, if the tank total heat load is sufficient and if the ventilation system cannot be recovered in the meantime.

For the first degassing procedure, tank bumps are immediately judged to be beyond extremely unlikely. As already stated, the "Bump Conditions @ > 350 days" end state is dismissed based on generic corrective maintenance clock times. The "Bump Conditions After Settling" end state is dismissed because it calls for an equipment failure (Ventilation Fails), two operator errors, and a failure to repair ventilation prior to settling. Operators will use the mixer pumps intermittently, which means they will be acutely aware of the need to stop mixer operation in the event of ventilation failure. Settling could be on the order of a few days, as demonstrated by waste transfer for Tanks 241-C-106 to 241-AY-102 (Ogden and Bratzel 2000) and the Tank 241-AZ-101 mixer tests (Carlson et al. 2000). According to the WFD RAM, a few days would still be enough to recover the annulus or primary ventilation system in many instances, provided that relatively simple restoration activities are needed rather than lengthy corrective maintenance functions.

Figure 3-3. LAW Feed Delivery Tank Bump Event Tree.



Although the "Bump Conditions After Settling" end state can be dismissed on frequency (probabilistic) grounds, the thermal-hydraulic response to this scenario is worth discussion. This branch of the tree assumes that the mixer pumps continue to operate right up to saturated conditions, at which time the mixer pumps are then turned off. This leaves the waste at saturated conditions, but well-mixed, so a bump does not occur immediately. Two processes begin at this point: the waste settles back to a distinct supernatant atop a non-convective layer, and the temperature approaches the steady-state value dictated by decay heat load, upward conduction through the overlying soil and downward conduction to soil underneath. If this steady-state temperature is below saturation, the tank will cool. If it is not, the tank will continue to boil.

Assuming the first degassing procedure is successful, similar conclusions can be drawn for the 30-day settling process. In fact, once the supernatant is decanted, tank bumps are impossible in the source tank, feed tank, and interim waste feed storage tanks (IWFST), based on the safe storage tank bump criteria 1 and 3. According to Hu et al. (2000), a little more than half the total tank power resides in the supernatant for Tank 241-AN-105, and the total tank heat load is 9,340 W (13.4 kW in the pedigreed database). Once the supernatant has been decanted, about 4,700 W remain in the source tank and 4,700 W reside in the IWFST. This can be compared to bump criterion 3 from the safe storage accident analysis (Epstein et al. 2000), which states that 8,500 W can be removed by steady-state conduction through the soil overburden alone. The same argument applies for the other DSTs, with the exception of the AWFs. After dilution, the source tank can be screened based on bump criterion 1, which states there must be a significant non-convective layer. Bump criterion 1 always applies to the IWFST and the customer feed tank.

3.5 TANK BUMP CONSIDERATIONS FOR AGING WASTE FACILITY TANK FEED DELIVERY ACTIVITIES

Figure 3-4 shows an event tree for the AWF feed activities. It is the same as the event tree for the LAW activities, except that "Bump Conditions @ > 350 Days" is replaced by "Bump Conditions @ X Days", where X is to be determined. In a series of parametric GOTH_SNF calculations, Crea et al. (2000) analyzed the thermal-hydraulic response of the AWF during retrieval operations. Tanks 241-AY-102 and 241-AZ-102 were considered and deemed bounding based on tank heat load and sludge inventory. For each DST, the first calculation was to predict the temperature at which the mixed waste heat loads, namely the mixer pump heat dissipation and decay heat, balance the ventilation system heat removal. Once this maximum temperature is attained, the mixer pumps are shut off, but the ventilation system continues to operate.

An example of predicted waste and supernatant temperatures for Tank 241-AZ-102 is shown here as Figure 3-5. Nomenclature is as follows: T1 is the initial supernatant temperature, T2 is the maximum waste temperature, T3 is the initial mixed-waste temperature, and T4 is the mixed waste temperature as a function of time. Figure 3-5 shows that after the mixer pumps start at 37 days, the waste temperature quickly approaches T3, initial mixed-waste temperature. Due to the mixer pump heat load, the mixed-waste temperature, T4, approaches its maximum after 32 days of mixer pump operation, which is about 69 days from time zero; this T4 designator in Figure 3-5 is placed at this maximum value. If the mixer pumps were to continue operating, the

Figure 3-4. AWF Feed Delivery Activity Tank Bump Event Tree.

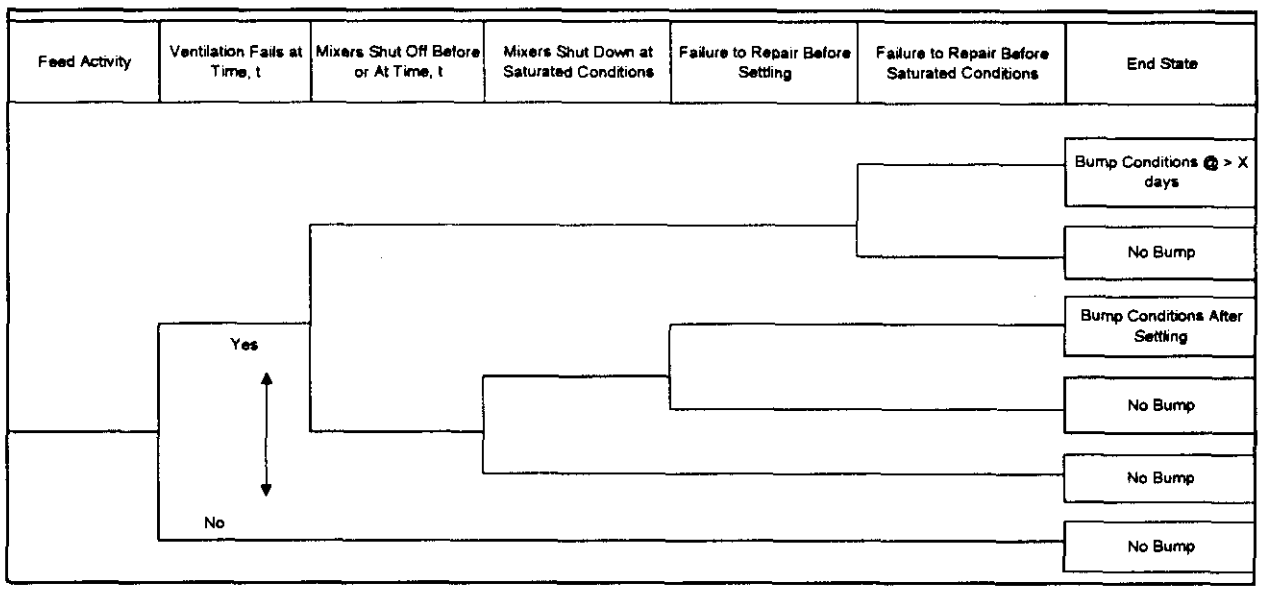
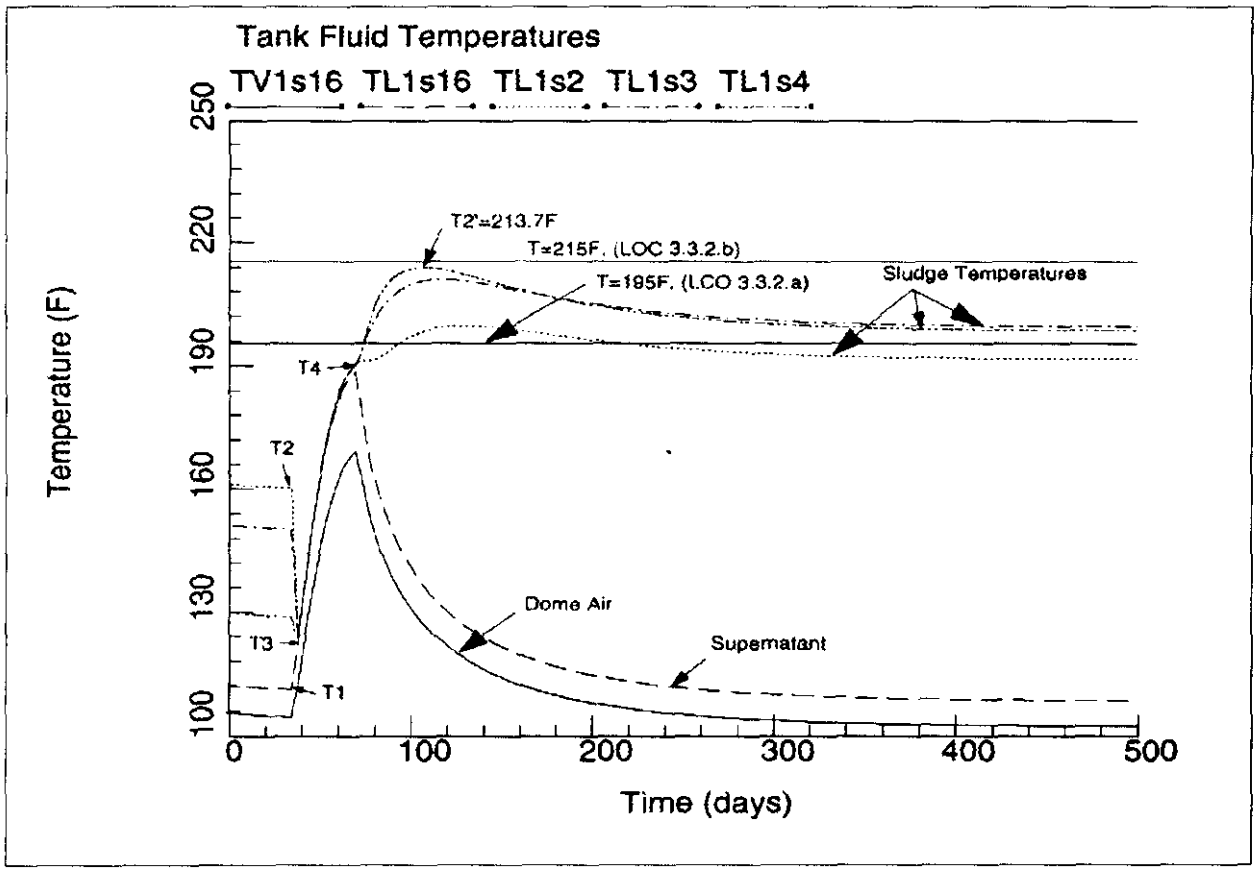


Figure 3-5. Tank 241-AZ-102 Case 2 Temperatures with 2,000 SCFM Annulus Flow and Chilled Air (Crea et al. 2000).



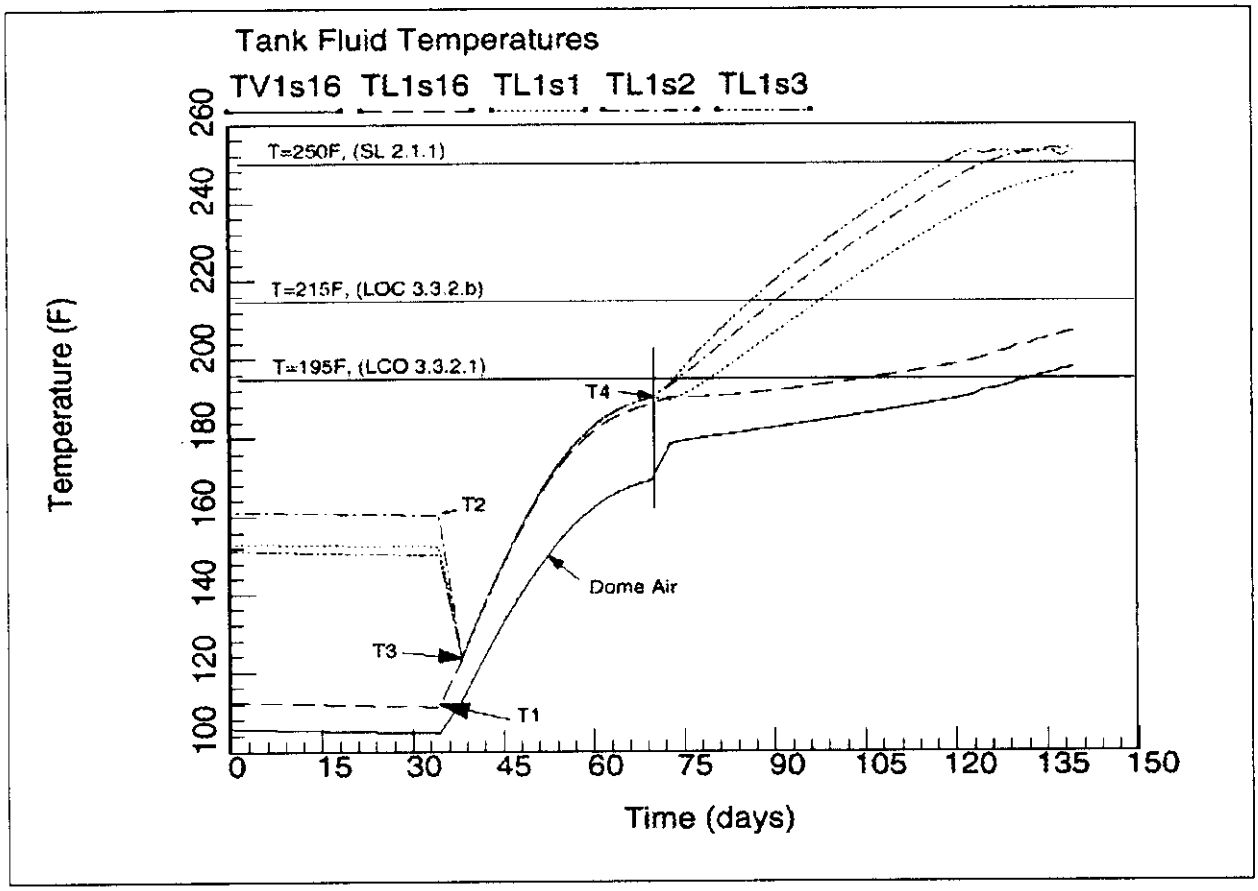
mixed waste temperature would remain at this value, which is just below LCO 3.3.2a. For the run shown in Figure 3-5, the mixer pumps are turned off when T4 reaches its maximum, and the waste begins to settle. The maximum temperature of post-settled waste, T2, is shown to be just under LCO 3.3.2.b. The fluffing factor value of 2.0 explains why T2 is so high. Fluffing increases sludge height and decreases thermal conductivity. Because of the continued operation of the ventilation system, supernatant temperature begins to decline after the mixer pumps are turned off and eventually approaches the condition at time zero.

GOTH_SNF calculations demonstrate several points gleaned indirectly from Figure 3-5. First, if the mixer pumps and ventilation system operate indefinitely, the waste is well-mixed and the temperature remains just below LCO 3.3.2a. In other words, T4 would be a flat line extending from 69 days on. This is the basis for assumptions 2, 3, and 4 in Section 3.3. The worst case then is to lose ventilation when T4 just reaches its maximum and the mixer pumps are shut off. If the ventilation and mixer pumps are lost/shut down after only a few days of operation, the time to bump conditions is not much different than either of the values listed in Table 6-4 of the safe storage accident analysis (Epstein et al. 2000), which shows values of over 100 days for self-heat to saturation for the current waste conditions.

Crea et al. (2000) have analyzed the loss of ventilation case for both Tanks 241-AY-102 and 241-AZ-102. Tank 241-AZ-102 is limiting in this regard, which is why results are shown in Figure 3-6 are for this tank. In fact, the loss of ventilation analysis for Tank 241-AY-102 shows that bump conditions are not reached after 100 days without ventilation. Figure 3-6 shows that the tank reaches bump conditions at about 120 days after time zero, which is about 50 days after the loss of ventilation and mixer pump shutdown. The maximum waste temperature flattens out at about 254°F, or 123°C, which is the local saturation temperature. (The safety limit SL2.1.1 set at 250°F is based on chemical reactivity concerns.) When sludge layer temperatures reach saturation, the supernatant is just over 200°F, or 94°C.

Partial mixing in the AWF is an unlikely event bounded by the scenario described in Figure 3-6 and the "Ventilation Fails at Time, t, Mixers Shut Off Before or At Time, t, and Failure to Repair Before Saturated Conditions" sequence shown in Figure 3-4. Tank 241-AZ-101 mixing tests (Carlson et al. 2000) demonstrate that even one pump at partial capacity is almost as effective as two pumps at full capacity. Partial mixing would occur only if a lone pump operated very briefly. Tank 241-AZ-101 tests show effective mixing took place in less than 19 hours. A partial mixing scenario leading to bump conditions would require mixer pump(s) failure during some brief interval with concurrent failure of the ventilation system. This partial mixing scenario is far less likely to occur than the one described in Figure 3-6. Moreover, because the mixer pumps fail after only a few hours, waste temperatures are still not much above initial safe, storage temperatures, which means that available recovery times would be very long.

Figure 3-6. Tank 241-AZ-102 Case 2 Temperatures for Loss of Ventilation and Mixer Pump Shut Off at Maximum Mixed Waste Temperature (Crea et al. 2000).



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4.0 TANK BUMP PHYSICAL MODELS AND CRITERIA

The previous section identified that the scenario of interest is as follows: ventilation fails at time t, mixers shut off at or before time t, and failure to repair before saturated conditions. This section develops a general tank bump criterion for this scenario and shows that a tank bump cannot occur for low heat load tanks (< 10 kW) regardless of the non-convective layer depth or partial mixing. For low heat load tanks, the time to repair is infinite, in effect.

A steam bump via gas release from the resettled non-convective layer becomes possible if the supernatant temperature increases after the mixer pump operation is stopped. Obviously if the decay heat production exceeds the heat losses to the surrounding soil, the waste temperature (and supernatant temperature) will increase. The maximum supernatant temperature will be achieved when heat production is completely balanced by heat losses to the surroundings, that is when steady-state is achieved. Thus the criterion we seek is one that ensures that the supernatant temperature remains below the critical temperature (≃ 90°C) for steam bumps at steady-state.

To obtain simple results from the time-independent analysis, we make the following basic assumptions:

A1. Because the thicknesses of the non-convective layer and the soil layer above the tank are small in comparison with the tank diameter, heat conduction in the horizontal direction can be ignored in these regions. Also, heat loss to the soil below the tank is given by the solution to the conduction equation with spatially uniform heat flux over the bottom of the tank into a semi-infinite medium (underlying soil).

A2. Owing to turbulent natural convection, the supernatant (convective layer) temperature is spatially uniform.

A3. Because of thermal radiation and natural convection the temperature drop in the vertical direction across the tank headspace may be ignored.

A4. Again because of natural convection, the resistance to heat exchange between the ground and the atmosphere may be ignored and the resistance to heat exchange between the non-convective layer and the convective layer may be ignored.

The conduction equation for the non-convective layer is expressed as

$$\frac{d^2 T}{d z^2} = -\frac{Q_{NCL}}{k_{NCL}} \tag{4-1}$$

where z is the vertical distance measured from the bottom of the non-convective layer to some arbitrary location within the layer, T is the layer temperature at elevation z, k_{NCL} is the thermal conductivity of the non-convective layer, and Q_{NCL} is the layer's volumetric decay-heat generation rate. At the tank floor (z = 0), equation (4-1) must satisfy the condition

$$-k_{NCL}\frac{dT}{dz}(0) = -\frac{k_{soil}}{R}\left[T(0) - T_{\infty}\right] \tag{4-2}$$

which equates the heat flux in the non-convective with the heat flux in the underlying soil at $z = 0$. In equation (4-2), k_{soil} is the thermal conductivity of the soil, R is the radius of the waste tank, and T_{∞} is the soil temperature far below the tank.

In accord with the assumptions listed earlier, the conduction heat flux at the top of the non-convective layer (at $z = H_{NCL}$) plus the upward heat flux from the convective layer must equal the conduction heat flux through the overlying soil layer (or soil "overburden") of thickness H_{soil}. This energy balance is represented mathematically as

$$-k_{NCL}\frac{dT}{dz}\left(H_{NCL}\right) + H_{CL}\,Q_{CL} = \frac{k_{soil}}{H_{soil}}\left(T_{CL} - T_a\right) \tag{4-3}$$

where H_{CL}, Q_{CL}, and T_{CL} are, respectively, the depth, volumetric heat generation rate, and uniform temperature of the convective layer; and T_a is the temperature of the atmosphere.

It is more convenient to work in terms of dimensionless variables and parameters:

$$\theta = \frac{k_{NCL}\left(T - T_{\infty}\right)}{Q_{NCL}\,H_{NCL}^2}, \qquad x = \frac{z}{H_{NCL}}, \qquad \theta_{CL} = \frac{k_{NCL}\left(T_{CL} - T_{\infty}\right)}{Q_{NCL}\,H_{NCL}^2}, \tag{4-4}$$

$$B_1 = \frac{k_{soil}\,H_{NCL}}{k_{NCL}\,H_{soil}}, \qquad B_2 = \frac{k_{soil}\,H_{NCL}}{k_{NCL}\,R}, \tag{4-5}$$

$$\Lambda = \frac{k_{NCL}\left(T_{\infty} - T_a\right)}{Q_{NCL}\,H_{NCL}^2}, \qquad q = \frac{H_{CL}\,Q_{CL}}{H_{NCL}\,Q_{NCL}}. \tag{4-6}$$

Inserting these dimensionless quantities into equations (4-1), (4-2), and (4-3), the differential equation becomes

$$\frac{d^2\theta}{dx^2} = -1 \tag{4-7}$$

with boundary conditions

$$\frac{d\theta}{dx}(0) = B_2\,\theta(0) \tag{4-8}$$

$$\frac{d\theta}{dx}(1) = q - B_1\left(\theta_{CL} + \Lambda\right) \tag{4-9}$$

where θ_{CL} is the dimensionless, spatially uniform convective layer temperature.

Integrating equation (4-7) twice with respect to z gives

$$\frac{d\theta}{dx} = -x + C_1 \tag{4-10}$$

$$\theta = -\frac{x^2}{2} + C_1 x + C_2 \tag{4-11}$$

The constants C_1 and C_2 are determined by the boundary conditions, equations (4-8) and (4-9), and the fact that $\theta(1) = \theta_{CL}$ at $z = H_{NCL}$ or, equivalently, at $x = 1$. The results are

$$C_1 = B_2\,\theta(0) \tag{4-12}$$

$$C_2 = \theta(0) \tag{4-13}$$

$$\theta(0) = \frac{q + 1 + B_1\left(\frac{1}{2} - \Lambda\right)}{B_1 + B_1 B_2 + B_2} \tag{4-14}$$

$$\theta_{CL} = \frac{(1 + B_2)\left[q + 1 + B_1\left(\frac{1}{2} - \Lambda\right)\right]}{B_1 + B_1 B_2 + B_2} - \frac{1}{2} \tag{4-15}$$

For a sufficiently thick non-convective layer and/or a sufficiently large volumetric heat generation rate within the non-convective layer, the temperature T (or θ) will exhibit a maximum. The maximum value θ_{max} and the elevation x_{max} at which it occurs can be found by letting $(d\theta)/(dx) = 0$ in equation (4-10) and solving the result for x_{max}. This gives (see equations (4-12) and (4-14))

$$x_{max} = B_2\,\theta(0) = \frac{B_2\left[q + 1 + B_1\left(\frac{1}{2} - \Lambda\right)\right]}{B_1 + B_1 B_2 + B_2} \tag{4-16}$$

From equation (4-11)

$$\theta_{max} = \theta(0)\left[1 + \frac{1}{2} B_2\,\theta(0)\right] \tag{4-17}$$

Equation (4-17) yields physical values of θ_{max} only when these values occur within the non-convective layer, that is only when the following inequality is satisfied:

$$0 < x_{max} \leq 1.0 \tag{4-18}$$

Steam bumps become possible when the supernatant temperature is close to its saturation temperature at atmospheric pressure. A rather conservative value for the critical supernatant temperature T_{crit} below which steam bumps are impossible is 90°C (Epstein et al. 2000). Thus the limits of the non-bumping and bumping regimes can be found by setting the convective layer temperature T_{CL} in equation (4-15) equal to T_{crit}. This leads to the relation (see also equations (4-4) and (4-6))

$$\frac{k_{NCL}\,(T_{crit} - T_\infty)}{Q_{NCL}\,H_{NCL}^2} = \frac{1+B_2}{B_1 + B_1\,B_2 + B_2}\left\{\frac{H_{CL}\,Q_{CL}}{H_{NCL}\,Q_{NCL}} + 1 + B_1\left[\frac{1}{2} - \frac{k_{NCL}\,(T_a - T_\infty)}{Q_{NCL}\,H_{NCL}^2}\right]\right\} - \frac{1}{2} \tag{4-19}$$

Equation (4-19) can be used to construct the Q_{CL} - Q_{NCL} locus which separates the non-bumping and bumping regimes. Alternatively, the volumetric generation rates may be converted to power W via the definitions

$$W_{NCL} = A\,H_{NCL}\,Q_{NCL} \tag{4-20}$$

$$W_{CL} = A\,H_{CL}\,Q_{CL} \tag{4-21}$$

where A is the tank cross-sectional area (411 m^2). The "boundary" for steam bumps in power parameter space is then

$$W_{CL} = \frac{B_1\,A\,k_{NCL}\,(T_\infty - T_a)}{H_{NCL}} + \left(\frac{B_1 + B_1\,B_2 + B_2}{1+B_2}\right)\frac{A\,k_{NCL}\,(T_{crit} - T_\infty)}{H_{NCL}} - \frac{1}{2}\left(\frac{2+B_2}{1+B_2}\right)W_{NCL} \tag{4-22}$$

Since the parameters k_{NCL}, k_{soil}, R, T_∞, and T_a are nearly the same for all the tanks, the possibility of steam bumps as determined from equation (4-22) depends mainly on the values of W_{CL}, W_{NCL}, and H_{NCL}. However, a careful examination of equation (4-22) reveals that the power conditions for a steam bump are remarkably insensitive to the depth H_{NCL} of the non-convective layer. Figure 4-1 shows a convective layer power versus non-convective layer power map for steam bump conditions when H_{NCL} = 3.5 m. The fixed input parameters for the calculations are given in Table 4-1. The calculations show that the boundary in the figure translates by only ± 5.0% for H_{NCL} values as low as 0.5 m and as high as 6.0 m. Thus, the map shown in Figure 4-1 may be regarded as a universal map for the possibility of steam bumps. Also shown in Figure 4-1 is the region in which boiling occurs in the non-convective layer when the temperature of the convective layer is below T_{crit} = 90°C. The lower boundary of this region is defined by the condition $T_{max} = T_{bp}$, which, from equation (4-17), leads to an explicit relation

Figure 4-1. Convective Layer Power - Non-Convective Layer Power Map for the Possible Occurrence of Steam Bumps; T_{crit} = 90°C.

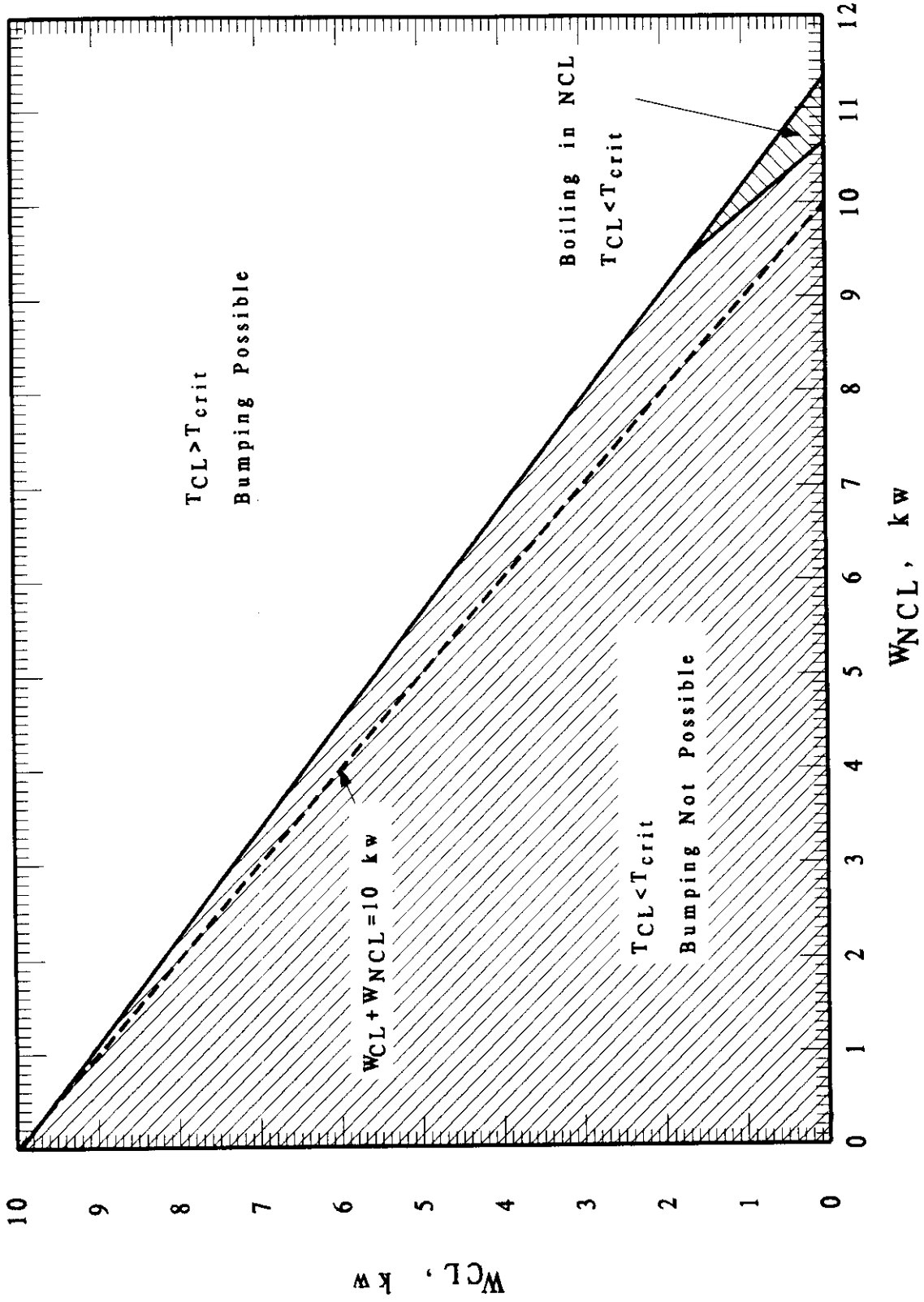

Table 4-1. Parameter Values for Steam Bump Condition Calculations.

Soil thermal conductivity	$k_{soil} = 1.0\ W\ m^{-1}\ K^{-1}$
Non-convective layer thermal conductivity	$k_{NCL} = 1.0\ W\ m^{-1}\ K^{-1}$
Tank radius	$R = 11.0\ m$
Soil Overburden	$H_{soil} = 4.0\ m$
Average Hanford air temperature	$T_a = 14°C$
Average Hanford soil temperature	$T_\infty = 14°C$

between W_{CL} and W_{NCL}. The parameter T_{bp} is the local boiling temperature at the mid-plane of the non-convective layer. The pure conduction theory presented here does not account for boiling in this layer so that the steam bump boundary is not precisely located at high W_{NCL} values. Nevertheless, given the small parameter space occupied by the non-convective-layer boiling region, more refined calculations are probably not justified. The present analysis should provide a useful first approximation to the steam bump-boundary when boiling occurs in the non-convective layer.

The dashed curve in Figure 4-1 is an approximate and conservative alternative to the steam bump boundary arrived at by the formal analysis presented in the foregoing. This boundary is represented by the formula

$$W_{CL} + W_{NCL} = 10\ kW \tag{4-23}$$

and provides the simple rule of thumb that steam bumps are not possible in tanks with total power levels less than 10 kW. If T_a is taken to be as high as 28°C, the predicted boundary is lowered by 15%. In this case, the conservative rule of thumb is $W_{CL} + W_{NCL} = 8.5$ kW. Since the criterion presented here for steam bumps is insensitive to the depth of the non-convective layer, the criterion is also insensitive to the degree to which the non-convective layer settles to its original volume (i.e., the fluffing factor) or to the degree to which the non-convective layer depth is rendered non-uniform by prior mixing operations.

To defend the conclusion regarding non-uniformity, consider the overall tank energy balance

$$W_{NCL} + W_{CL} = \frac{A\,k_{soil}}{R}\left[T(0) - T_\infty\right] + \frac{A\,k_{soil}}{H_{soil}}\left(T_{CL} - T_\infty\right) \tag{4-24}$$

which states that the total tank power is divided between downward heat conduction into the underlying soil and upward heat conduction through the soil overburden. Substituting $T_{CL} = 90°C$ into equation (4-24) should provide a formula for the steam bump boundary that is identical in form to equation (4-23), provided that the as yet unknown temperature T(0) at the bottom of the tank can be determined. Owing to multi-dimensional conduction effects in a non-

uniform, non-convective layer and possible boiling of the interstitial liquid, the quantity T(0) can not be accurately estimated without resorting to a numerical approach. However, a useful lower bound to T(0) may be obtained by writing an energy balance which equates the vertical conduction heat flux through the thickest portion of the non-convective layer (where $H_{NCL} = H_{NCL,max}$) with the heat flux through the underlying soil; namely,

$$\frac{k_{NCL}\left[T_{CL} - T(0)\right]}{H_{NCL,max}} = \frac{k_{soil}\left[T(0) - T_{\infty}\right]}{R} \tag{4-25}$$

Solving this relation for T(0) gives

$$T(0) = T_{\infty} + \frac{T_{CL} - T_{\infty}}{1 + B_{2,max}} \tag{4-26}$$

$$\text{where } B_{2,max} = \frac{k_{soil}\, H_{NCL,max}}{R\, k_{NCL}} \tag{4-27}$$

In deriving equation (4-26), we have neglected decay heat, boiling, and lateral heat conduction. All of these effects would tend to increase the effective value of T(0) at the bottom of the tank, either by increasing T(0) itself or decreasing the effective depth of the non-convective layer from the local, peak depth $H_{NCL,max}$.

It is not likely that a ridge of mixer-blown non-convective material would achieve a depth that exceeds the radius of the tank. Thus $B_{2,max}$ in equation (4-27) should not be greater than unity and, therefore, T(0) in equation (4-26) should not be smaller than the arithmetic average $(T_{\infty} + T_{CL}) / 2$. Thus, from equation (4-24), a rather conservative steam bump boundary for a tank with a non-uniform layer of non-convective material is

$$W_{NCL} + W_{CL} = \left(1 + \frac{H_{soil}}{2\,R}\right)\frac{\left(T_{CL} - T_{\infty}\right) A\, k_{soil}}{H_{soil}} = 9.23\ \text{kW} \tag{4-28}$$

The above equation is not too different from equation (4-23) that was derived for a uniform non-convective layer.

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5.0 WASTE FEED DELIVERY TANK BUMP SCENARIO QUANTIFICATION

The purpose of this section is to estimate the frequency of tank bumps caused by a single waste feed delivery (WFD) operation that involves mixer pump operation. Per the discussion in Section 3.0, the only scenario that needs evaluation is as follows: ventilation fails at time t, mixers shut off at or before time t, and failure to repair before saturated conditions. The event tree shown in Figure 3-4 is stylized in the sense that it applies for only one ventilation failure time t, when in fact, there are an infinite number of times at which the ventilation system could fail. The final calculation for tank bump must account for the fact that the time to ventilation failure is a continuous random variable. Only the first batches from Tanks 241-AZ-101 and 241-AZ-102 need consideration.

5.1 FREQUENCY OF BUMP CONDITIONS FOR THE ANALYZED SCENARIO

For some mixer pump operation time in the interval between t and $t + \Delta t$, an expression for the frequency of this scenario F_{WFD}, is given by:

$$d\,F_{WFD}(t) = p_f(t)\,P_{nr}(t)\,dt \tag{5-1}$$

where $p_f(t)$ is the ventilation system failure probability density as a function of t, and $P_{nr}(t)$ is the conditional probability that ventilation cannot be recovered as a function of the failure at time t. Probability density $p_f(t)$ has units of 1/hr or 1/day, and $P_{nr}(t)$ has units of 1/demand (1/d), as does F_{WFD}. In writing this equation, an assumption is that the mixer pumps are shut off at the same time the ventilation system fails. The total frequency over the entire operation time is then simply:

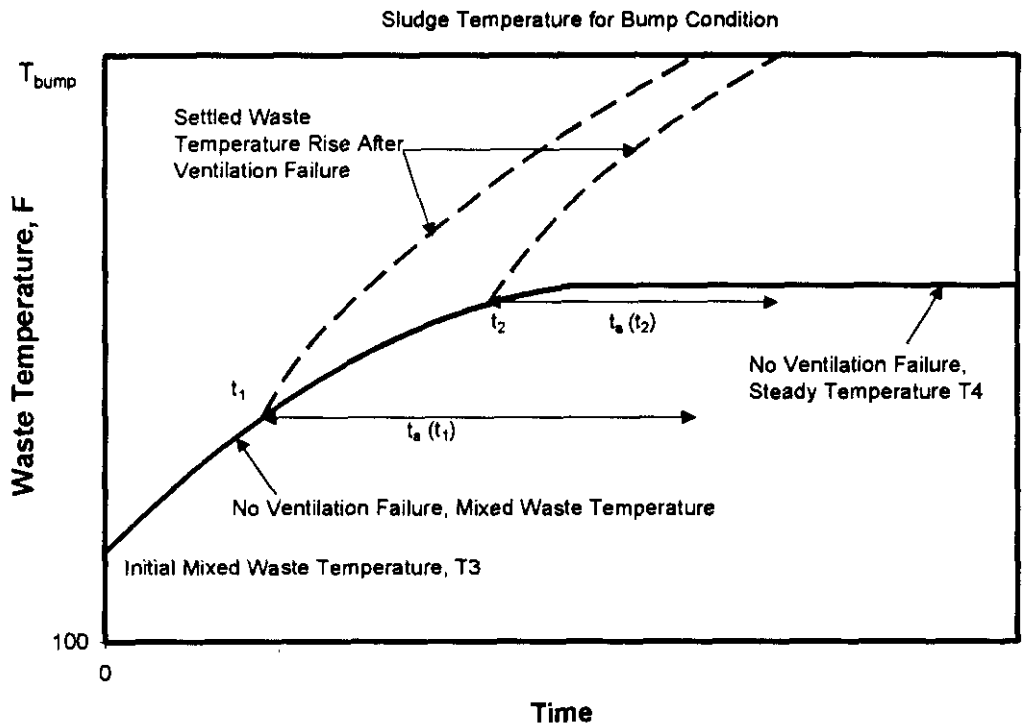
$$F_{WFD} = \int_0^{t_{op}} p_f(t)\,P_{nr}(t)\,dt \tag{5-2}$$

where equation (5-1) is integrated over time that the ventilation system must run concurrently with the mixer pumps.

Figure 5-1 illustrates how equations (5-1) and (5-2) arise. If ventilation is lost at a mixer pump operation time t and recovery actions are never taken, the waste will self-heat until the settled waste temperature reaches the bump condition temperature. The time-to-bump conditions (or available recovery time) is determined by the difference between the mixed waste temperature, T4, at time t and the settled waste temperature criterion of 240°F. (This 240°F value is in keeping with LCO limits, where 25 degrees were subtracted from the sludge saturation temperature (HNF-SD-WM-TSR-006 2000).)

Figure 5-1 shows that the time to bump conditions, t_a, is a function of t, is very long if t is only a few days, and becomes constant after the mixed waste temperature reaches steady-state. A ventilation failure early in the operation, as shown in Figure 5-1 by the designator t_1, results in

Figure 5-1. Illustration of Time to Tank Bump Conditions as a Function of Ventilation System Failure Time During Mixer Pump Operation.



t_a (t_1), which is longer than the available recovery time t_a (t_2) for a ventilation failure later in the operation. Once the mixed waste temperature reaches steady-state, t_a is constant. Figure 3-6 shows that if the ventilation system fails anytime after about 35 days of mixer operation, the available time for recovery is a constant, but the available time is much greater if the ventilation system fails after, say, 10 or 15 days of mixer pump operation. In principle, the calculation shown in Figure 3-6 can be repeated for each possible ventilation failure time, t, and the available recovery time approximated by the following function:

$$\text{If } (t < 35 \text{ days}) \qquad t_a = \frac{[T_{bump} - T4(t)]}{\alpha} \qquad (5\text{-}3)$$

$$\text{else} \qquad t_a = \text{constant}$$

where α is the temperature rate-of-change in °F/day, T_{bump} is the temperature defined for bump conditions, and T4(t) is the mixed waste temperature from Figure 3-6. This function is evaluated numerically in the next sub-section.

Because there is no conspicuous choice for t_{op}, it will be treated parametrically. The best-estimate is that the mixer pumps will operate for only a few days, in which case the retrieval tank bump accident frequency analysis is academic. Consider Figure 3-6 and assume that the ventilation system fails and mixer pumps are shut off at 45 days with respect to time zero, or about 8 days of mixer pump operation. Figure 3-6 shows that if the ventilation system fails and the mixer pumps are shut down at the peak temperature, T4, 40 days must pass before bump conditions (240°F) are reached. If the accident sequence starts at 45 days from time zero, however, the time-to-bump conditions is much greater than 40 days because the initial temperature is only 150°F, or 66°C. Assuming that the heat up rate is (240°F – 191°F) / 40 days, which equals 1.2°F/day, the time to heat up to bump condition from 150°F would be about 75 days.

The preceding approximation shows that if the mixer pumps operate briefly, the time-to-bump conditions after a retrieval accident scenario is comparable to the time-to-bump conditions calculated for a safe storage scenario with the current conditions. The safe storage analysis shows that for the current conditions, annual tank bump frequency is beyond extremely unlikely. Moreover, the ventilation system failure frequency depends directly on the mission time for mixer pump operation: the smaller the mixer pump operation time, the smaller the probability of ventilation system failure during mixer pump operation. If the mixer pumps operate for only several days, both the probability of ventilation failure and the probability of recovery failure prior to bump conditions are so small that the accident frequency is beyond extremely unlikely for any one operation.

Another assumption is that a lengthy mixer pump interval is possible because it will not violate LCO 3.3.2 as long as the ventilation system functions. Operator errors or schedule delays may cause mixer pump operations to exceed the expected duration. For this reason, the mixer pump mission time will be studied parametrically.

5.2 VENTILATION SYSTEM FAILURE RATE

The probability of a ventilation system failure during the feed activity is considered here. Only random equipment failures are quantified, as failures due to external events have been shown to be unimportant by comparison (Epstein et al. 2000). Loss of off-site power (LOSP) events long enough to initiate bump conditions were judged beyond extremely unlikely as an initiating event. Seismic events of sufficient magnitude to cause ventilation system failure are not incredible, but such events in and of themselves pose greater risk to the site than do tank bumps. Note that severe weather events were considered as part of the WFD RAM (Carlson 1999a and 1999b), but are neglected here. The WFD RAM considered high winds, extreme temperatures, thunderstorms, and precipitation as a source of schedule delays, but not necessarily as a source of ventilation system failure. For example, the WFD RAM considered low temperatures that would make working conditions unbearable as a cause for a schedule delay.

The success criteria defined in Section 3.3 state that both the annulus and primary ventilation systems must operate. Schematic diagrams of the primary and annulus ventilation systems are shown in Figures 5-2 and 5-3, respectively. Simplifying assumptions which allow Figure 3-6 to be applied here are that the two systems are independent of each other and that a failure of either system leads to a complete loss of active heat removal. The probability density function for ventilation system failure during the feed activity is then:

$$p_f = \lambda_p + \lambda_{ann} \tag{5-4}$$

where λ_p is the primary system failure rate per unit time and λ_{ann} is the annulus ventilation system failure rate per unit time.

Primary system failure rate was estimated in the safe storage accident analysis (Epstein et al. 2000) to have an expected failure rate of 0.04/yr, but distributed log-uniformly between 0.01 and 0.1/yr. This estimate was based on limited data for exhaust fan availability and assumes that primary ventilation system failure rate is the same as the failure rate of a sub-system of two exhaust fans. This assumption is reasonable given the operating history and waste temperature surveillance. The safe storage primary ventilation failure rate is in reasonable agreement with the generic failure rate for two motor-driven fans or blowers with one in standby, taking into account common cause failures by the simple beta-factor method. This failure rate is listed as 3E-5/hr (0.26/yr) with an error factor of 3 (Carlson 1999a) and a generic beta-factor for common cause failure is 0.13 for fans (Mosleh et al. 1988). For a system with two fans, one in standby, the annual failure rate of primary ventilation system would be roughly $0.26 \times 0.13 / yr$, or 0.03/yr, with an error band of 0.09 to 0.01/yr.

For the waste feed delivery operation, the primary ventilation system failure rate will be conservatively evaluated using generic failure rate data for the major components shown in Figure 5-2. The failure rate for the primary ventilation system is then:

$$\lambda_p = \lambda_{HEME} + \lambda_{CH} + \lambda_{CCFFANS} \tag{5-5}$$

Figure 5-2. Schematic Diagram of the Primary Ventilation System for AZ/AY DSTs.

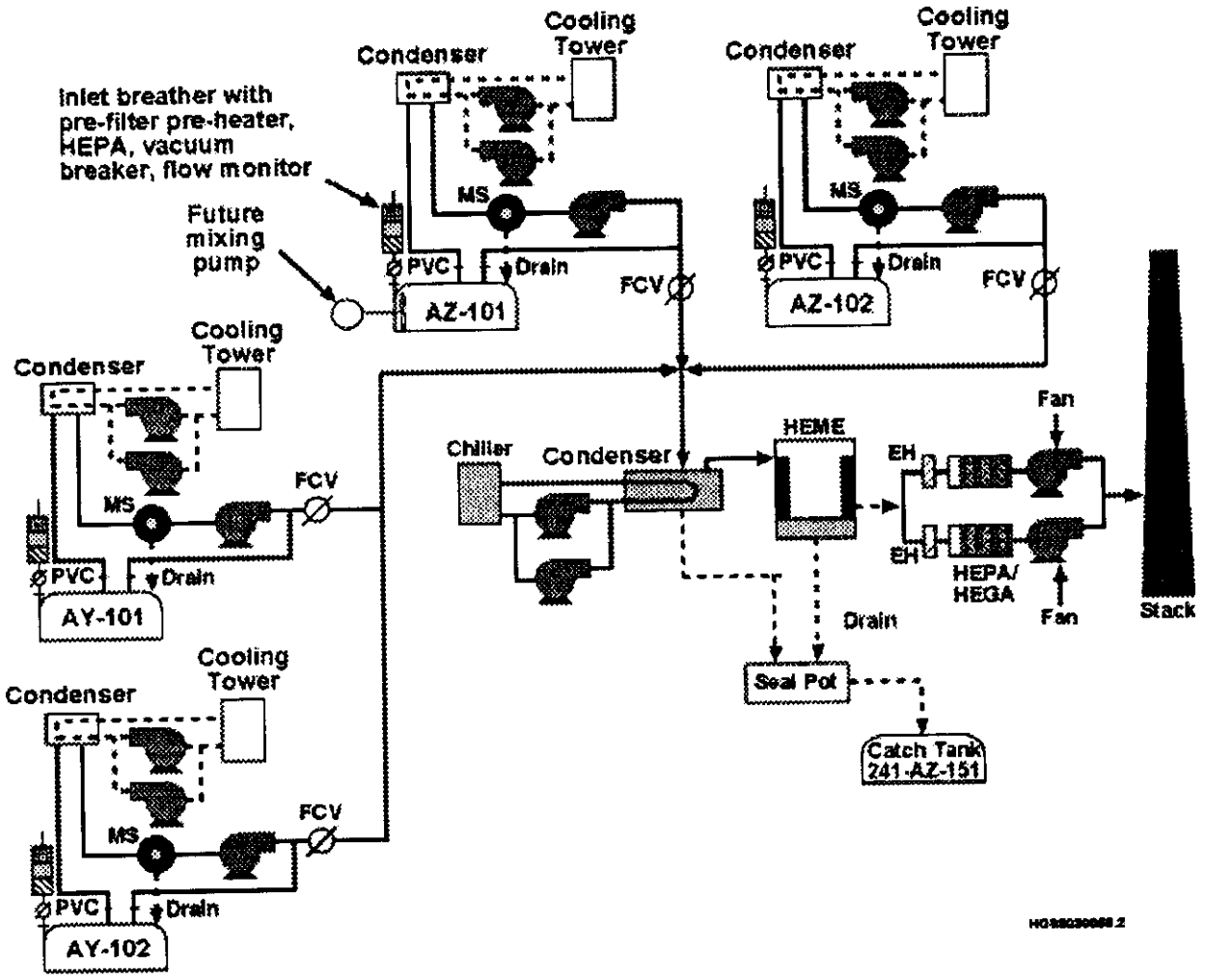
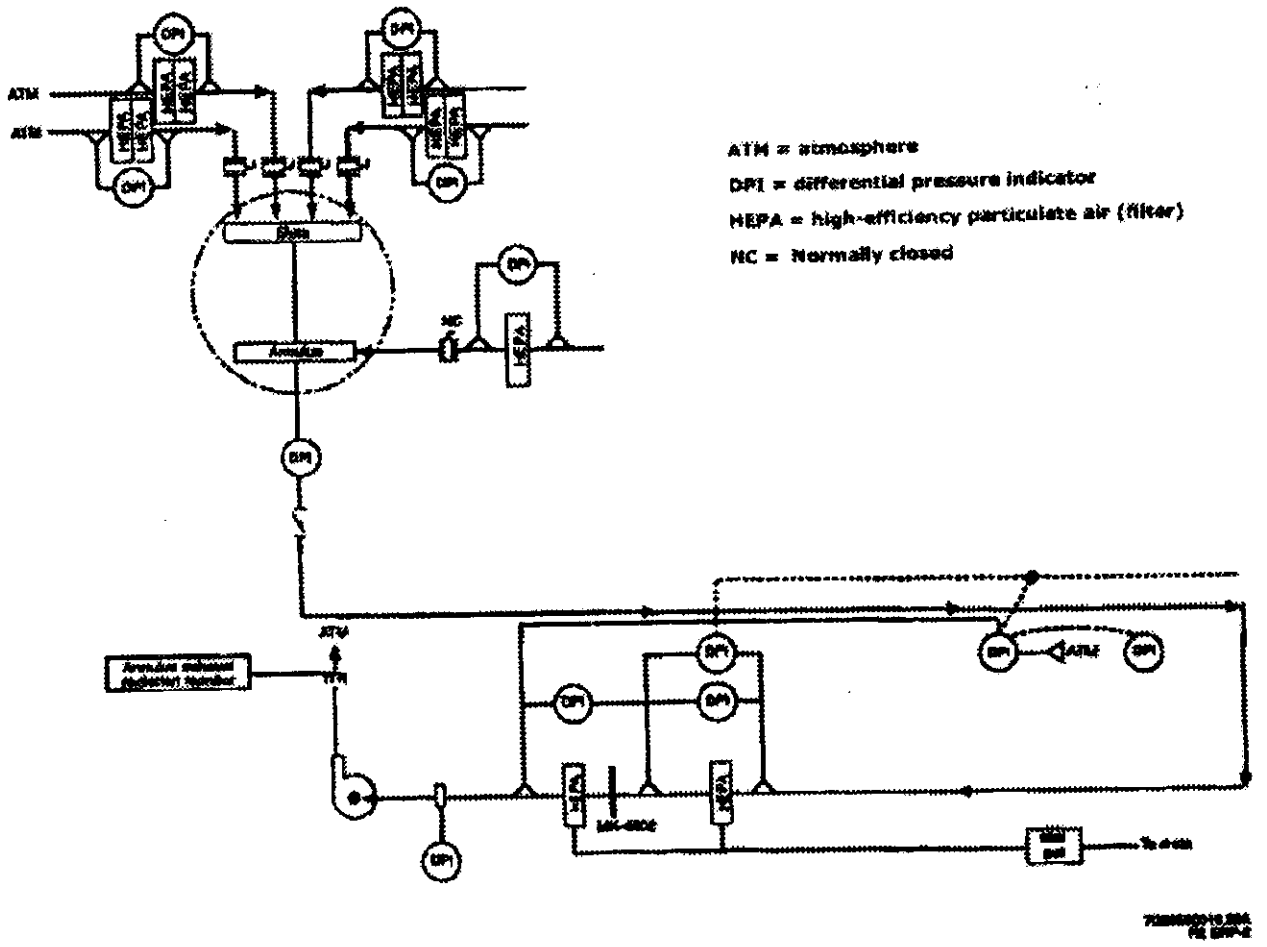


Figure 5-3. Schematic Diagram of Tank 241-AZ-102 Annulus Ventilation System.



where λ is the hourly failure rate, subscript HEME denotes the failure rate for high efficiency mist eliminator, CH denotes the failure rate for the heat exchanger unit (chiller and condenser), and CCFFANS is the failure rate for the sub-system of exhaust fans, which has already been calculated at 4.5E-6/hr. This equation neglects HEPA filters, dampers, and instrumentation sub-components that have very low failure rates or are not vital to heat removal. The ventilation condenser cooling system, which circulates some air back to the tank headspace, is neglected on the basis of WFD RAM results showing that the number of off-normal events for the ventilation condenser cooling system is much less than the number of off-normal events for either the primary ventilation or annulus ventilation system. The same can be said for support systems, namely electric power, service water, and instrument air. The WFD RAM shows that the number of off-normal events per transfer due to any one of the support systems is two orders of magnitude smaller than the number due to either the primary or annulus ventilation systems.

Figure 5-3 shows that the annulus system is much simpler. By making the same assumptions made for the primary ventilation systems (neglect support systems and HEPA filters), the failure rate for the annulus ventilation system is just the generic failure rate for a motor-driven fan, which is 3E-5/hr. That is, $\lambda_{ann} = \lambda_{FAN}$, where $\lambda_{FAN} = 3E\text{-}5/hr$.

An expression for ventilation system failure rate is then:

$$p_f = \lambda_{HEME} + \lambda_{CH} + \lambda_{CCFFANS} + \lambda_{FAN} \tag{5-6}$$

Data from the WFD RAM are as follows:

- HEME failure rate has a mean of 1E-4/hr with an error factor of 10,
- Heat exchanger failure rate has a mean of 4E-5/hr with an error factor of 10, and
- Annulus fan failure rate has a mean of 3E-5/hr with an error factor of 3.

To consider the uncertainty in the ventilation failure rate, a simulation was performed with the following input distributions:

- HEME failure rate is log-uniform on the interval 1E-5/hr to 1E-3/hr,
- Heat exchanger failure rate is log-uniform on the interval 4E-6/hr to 4E-4/hr,
- Annulus fan failure rate is log-uniform on the interval 1E-5/hr to 9E-5/hr, and
- Exhaust fans failure rate is log-uniform on the interval 1.5E-6/hr to 4.5E-6/hr.

To describe the output distribution, thirty random deviates for ventilation failure rate were used for curve fitting. The Chi-square goodness-of-fit test showed that a log-normal distribution with

log-mean equal to –8.37 and log-standard deviation equal to 0.806 was a reasonable fit (p value = 0.57). This distribution has a mean of 3.2E-4/hr and standard deviation of 3.1E-4/hr.

5.3 FAILURE TO RECOVER PROBABILITY

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 (CM) function.

Failure to recover probability is considered in the safe storage accident analysis (Epstein et al. 2000) and only important results are repeated here. The probability that ventilation is not recovered in the available time is then:

$$P_{nr} = \left(1 - x_{rs}\right) \sum_{n=1}^{N} x_n \left[1 - \text{log-normal}\left(t_a, \alpha_n, \beta_n\right)\right] \tag{5-7}$$

where N is the number of corrective maintenance activities, x is the fraction of all CM activities for the nth CM 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 CM activity. This expression assumes that restoration activities succeed during the available time, which is justifiable because the restoration time is one week at most while the available time is somewhere beyond 40 days. This expression states that the probability that CM fails is the sum of the probabilities that individual CM activities fail. The probability that an individual CM 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 CM activity is weighted by the relative frequency of each CM activity.

The available time t_a is taken to be the time to heatup to saturated conditions. Restoration or corrective maintenance activities should begin immediately because late waste feed deliveries will result in penalties. Now the time available, t_a, is a function of the time that the ventilation system fails and the mixer pumps are shut off, t. Figure 3-6 shows that if the ventilation system fails anytime after about 35 days of mixer operation, the available time for recovery is 40 days, but the available time is much greater if the ventilation system fails after 10 or 15 days of mixer pump operation. In principle, the calculation shown in Figure 3-6 should be repeated for each possible ventilation failure time, t. This is accomplished in Appendices A and B, and the available recovery time is approximated by the following function:

$$\begin{aligned} &\text{If } (t < 35 \text{ days}) \qquad t_a = \frac{[240°F - T4\,(t)]}{\alpha} \\ &\text{else} \qquad t_a = 40 \text{ days} \end{aligned} \tag{5-8}$$

where α is the temperature rate-of-change in F/day and T4(t) is the mixed waste temperature from Figure 3-6. Temperature rate-of-change, α, is 1.2°F/day, based on the results in Appendix B. T4(t) is found based on a curve fit to the data from Figure 3-6, using the data points between 37 days (T3, the initial mixed waste temperature) and 72 days (peak T4). This data is shown in Table 5-1.

Table 5-1. Mixed Waste Temperature as a Function of Time (see Figure 3-6).

Time (Days)		Mixed Waste Temperature, T4, (°F)
Relative to Zero	Minus 37 Days	
37	0	124
45	8	148
48	11	158
51	14	166
54	17	173
57	20	180
60	23	184
66	29	189
72	35	191

A good curve fit ($R^2 = 0.997$) is given by $T4 = 123. + 3.9\,t - 0.055\,t^2$°F, where t is days minus 37. The expression for time available before bump conditions is then:

$$\text{If } (t < 35 \text{ days}) \qquad t_a = \frac{\left[240°\text{F} - \left(123 + 3.9\,t - 0.055\,t^2°\text{F}\right)\right]}{\alpha} \tag{5-9}$$

$$\text{else} \qquad t_a = 40 \text{ days}$$

Equation (5-2) can now be rewritten as:

$$F_{WFD} = \left[\lambda_p + \lambda_{ann}\right] \int_0^{t_{op}} \left(1 - x_{rs}\right) \sum_{n=1}^{N} x_n \left[1 - \text{log-normal}\left(t_a, \alpha_n, \beta_n\right)\right] dt \tag{5-10}$$

with t_a as specified just above in equation (5-9). This expression is lengthy but is easily evaluated numerically for various mission times t_{op}. Baseline inputs shown in Table 5-2 are taken from the safe storage accident analysis (Epstein et al. 2000).

Corrective maintenance activities are defined as follows: TCNEL refers to Tank Farm (Radiological) Area Access, Non-intrusive, Moderate to Extensive Planning, Long Lead; TCIEL refers to Tank Farm (Radiological) Area Access, Contact Handled/Intrusive, Moderate to Extensive Planning, Long Lead; "3" refers to heaters, and "5" refers to fans and filters.

Table 5-2. Baseline Inputs for Tank Bump Frequency Evaluation as a Function of Time.

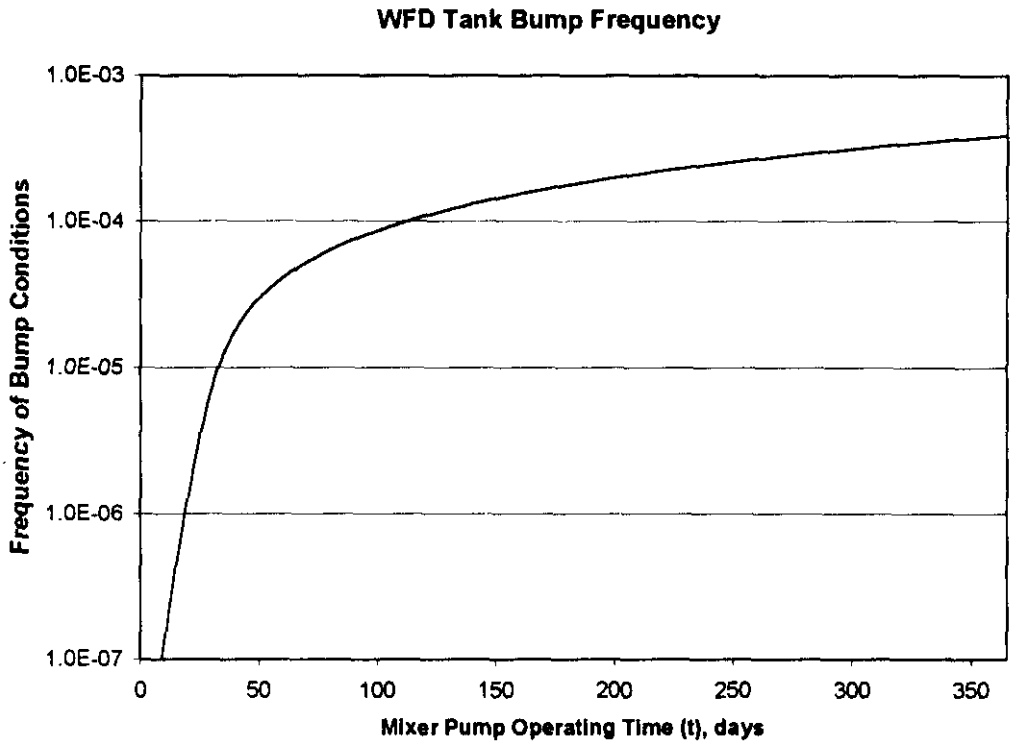
Symbol	Definition	Value
None Here.	Ventilation Failure Rate	0.0077 / day
x_{rs}	Restoration Activity Fraction	0.8
x_1	Corrective Maintenance Activity Fraction for 3TCNEL	0.485
x_2	Corrective Maintenance Activity Fraction for 5TCIEL	0.030
x_3	Corrective Maintenance Activity Fraction for 5TCNEL	0.485
α_1	Log-Mean of CM Activity 3TCNEL Distribution	5.08
α_2	Log-Mean of CM Activity 5TCIEL Distribution	5.56
α_3	Log-Mean of CM Activity 5TCNEL Distribution	4.89
β_1	Log-St. Dev. Of CM Activity 3TCNEL Distribution	0.56
β_2	Log-St. Dev. Of CM Activity 5TCIEL Distribution	0.56
β_3	Log-St. Dev. Of CM Activity 5TCNEL Distribution	0.56

Results of numerical integration of equation (5-10) are shown in Figure 5-4, which shows tank bump conditions frequency as a function of mixer pump operation time. Appendix C contains computation details. As expected, the curve approaches zero risk for zero operation time, and shows tiny values for mixer pump operation times on the order of a few days. Figure 5-4 shows that tank bump frequency during feed delivery becomes not incredible only after 19 days of continuous mixer pump operation. This greatly exceeds the expected mixer pump operating times mentioned in Section 3.3.

Figure 5-2 also suggests that an interesting risk metric for waste feed delivery activities is the number of mixer pump operation days need to result in a credible frequency of bump conditions per demand (greater than 1×10^{-6}/d). This metric can be considered with respect to the planned operations to gauge the level of risk involved in a waste activity. To solve for this metric, F_{WFD} is set to 1×10^{-6} and the right-hand side of equation (5-10) is integrated over various t_{op} until the equality is satisfied. This has been accomplished as part of an uncertainty analysis which proceeds as follows:

- Generate respective random samples for $\lambda_p + \lambda_{ann}$, x_{rs}, and x_n,
- Iterate on t_{op} until equation (5-10) is satisfied with $F_{WFD} = 1 \times 10^{-6}$,
- Record t_{op} is the result of one trial, and
- Repeat for many trials and express results as a probability density function or cumulative distribution function.

Figure 5-4. Base Case Tank Bump Conditions Frequency as a Function of Mixer Pump Operation.



The following distributions were used for the Monte Carlo simulation of the risk metric: the sum $\lambda_p + \lambda_{ann}$ is log-normally distributed on mean equal to 3.21E-4/hr and standard deviation equal to 3.07E-4/hr, x_{rs} is uniformly distributed between 50% and 80%, and x_2, the corrective maintenance activity fraction for 5TCIEL, is uniformly distributed between 1% and 10%. Distributions for the ventilation failure rate and x_2 reflect an error factor of roughly 3 about the mean.

Results of the simulation are shown in Figure 5-5. Out of 1000 trials, 7 days is the minimum value and 17 days is the median. These values exceed the planned mixer pump operation times and demonstrate margin for schedule delays.

5.4 THE LIKELIHOOD OF TANK BUMP GIVEN SATURATED CONDITIONS AND FLUFFED WASTE PROPERTIES

Up to this point, we have simply determined the frequency of bump conditions based on non-convective layer and/or supernatant temperature relative to local saturation temperature. As in the safe storage accident analysis (Epstein et al. 2000), tank bump might not occur despite bump conditions, if neutral buoyancy cannot be attained in the non-convective layer through buildup of noncondensible gases. Meyer and Wells (2000) derived criteria that must be satisfied in order for buoyant displacements to occur. These models are evaluated for the fluffed conditions to determine the likelihood of retrieval bumps given saturated conditions in the sludge.

Meyer and Wells (2000) 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

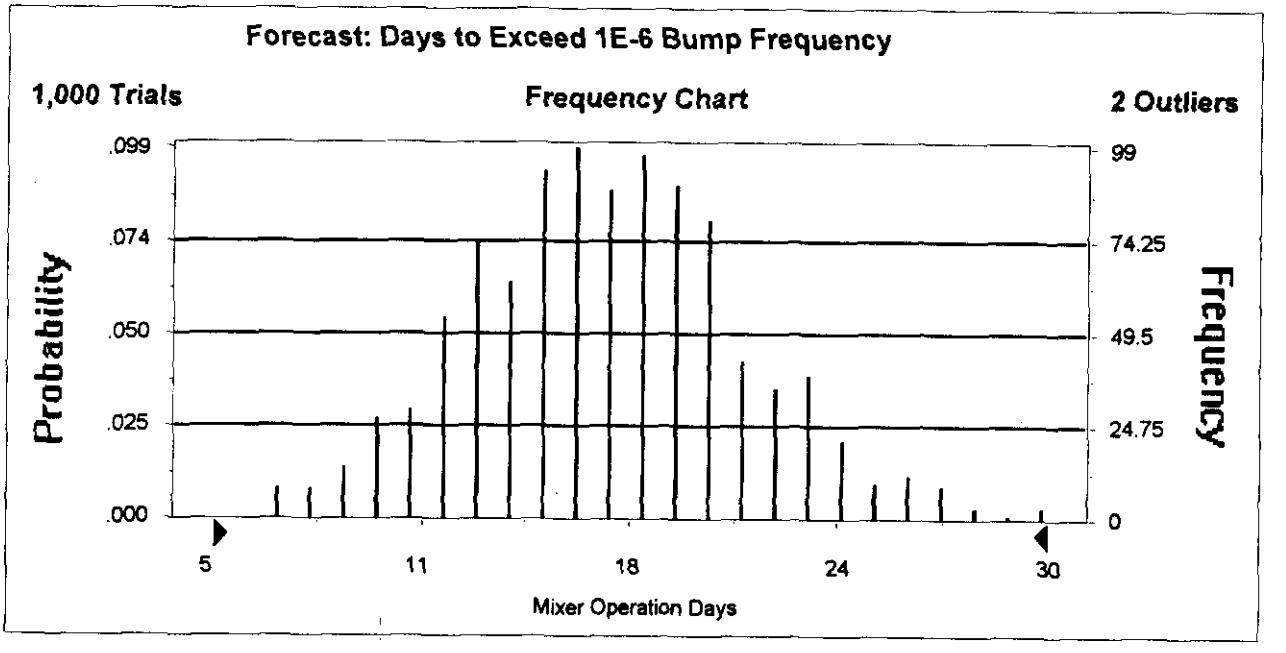
$$\frac{C_1 \, h_{NCL}^2}{\rho_{NCL} - \rho_{CL}} \left(\frac{G\,T}{P_{NCL}} \right)^{1/3} > 1 \qquad (5\text{-}11)$$

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

$$\frac{C_2}{\rho_{NCL} - \rho_{CL}} \left(\frac{\rho_{NCL}^2 \, h_{NCL}^2 \, G\,T}{P_{NCL}} \right)^{1/3} > 1 \qquad (5\text{-}12)$$

for an assumed bubble flux at the lower boundary and zero internal nucleation rate. In equations (5-11) and (5-12), 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), 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

Figure 5-5. Uncertainty Analysis for the Mixer Pump Operation Day where Tank Bump Conditions Frequency Becomes Credible.



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 (5-11) and (5-12).

Equation (5-11) yields a better representation of double-shell tank buoyant displacement behavior (Stewart 2000) and is chosen here for application to Tank 241-AZ-102. The value of the constant in equation (5-11) based on the most recent tank data is $C_1 = 18.5$ (Stewart 2000).

It is of interest to evaluate equation (5-11) when G is based on noncondensable gas generation only. The noncondensable gas generation rate at some temperature T is obtained by using the Arrhenius equation to extrapolate the known gas generation rate at the current non-convective layer temperature T_o to its value at T:

$$G_g(T) = G_g(T_o)\exp\left(-\frac{T_{act}}{T} + \frac{T_{act}}{T_o}\right) \tag{5-13}$$

where the activation temperature T_{act} (= E / R) is 1.074×10^4 (Hu 1999). For simplicity and conservatism, T is taken to be the non-convective layer maximum temperature.

Gas generation rate $G_g(T_o)$ for Tank 241-AZ-102 is known for the current conditions (Epstein et al. 2000), but the fluffed conditions are of interest here. A general expression for noncondensable gas generation is not available, but Hu et al. (2000) gives empirical expressions for hydrogen generation rates due to thermolysis and radiolysis. These expressions show that both thermolytic and radiolytic hydrogen generation are directly proportional to liquid wt. fraction and occur mainly in the liquid phase. Fluffing increases sludge liquid wt. fraction.

The Tank 241-AZ-102 sludge has an initial liquid wt. fraction of 58% and initial solids volume fraction of 17% (Crea et al. 2000). A fluffing factor of two cuts the solids volume fraction in half and increases the liquid wt. fraction to 76%. This suggests that for a given temperature, fluffing increases hydrogen generation in the sludge by up to 30%. Current noncondensable gas generation rate is multiplied by 1.3 to account for this possibility. Results are relatively insensitive to this uncertainty because the gas generation rate is raised to the 1/3 power.

Equation (5-11) was evaluated with the following Tank 241-AZ-102 inputs:

- Particle density, $\rho_s = 3.8$ gm/ml (Crea et al. 2000),
- Liquid density, $\rho_l = 1.1$ gm/ml (Crea et al. 2000),
- Fluffing factor, f = 1.4 and 1.7, by assumption,
- Initial sludge depth, $h_{NCL0} = 96$ cm,
- Initial supernatant depth, $h_{sup0} = 761$ cm,
- Mixed-waste average density, $\rho_w = 1.14$ gm/ml (Hu et al. 2000),

- Current temperature = 355 K (Epstein et al. 2000),
- Current noncondensable gas generation = 1.3 x 1.26 x 10^{-2} mole/m^3-day (Epstein et al. 2000), and
- Waste temperature, T_{max} = 396 K (254°F from Figure 3-6).

Auxiliary relationships needed are:

$$\alpha_s = \frac{\left(h_{NCL0} + h_{sup0}\right)\left(\rho_w - \rho_l\right)}{f\, h_{NCL0}\left(\rho_s - \rho_l\right)} \tag{5-14}$$

$$\rho_{NCL} = \alpha_s\, \rho_s + \left(1 - \alpha_s\right)\rho_l \tag{5-15}$$

$$P_{NCL} = \frac{101350 + \rho_{CL}\, g\left(h_{NCL0} + h_{sup0} - f\, h_{NCL0}\right) + \frac{1}{2}\left(\rho_{NCL}\, g\, f\, h_{NCL0}\right)}{101350} \tag{5-16}$$

where α_s is the solids volume fraction.

Evaluation of equation (5-11) with f = 1.4 yields 0.6 for the left-hand side, but evaluation with f = 1.7 yields 1.0 for the left-hand side. Table 5-3 shows inputs, intermediate values, and results.

The likelihood of tank bump, given bump conditions, is then roughly the likelihood that the fluffing factor exceeds 1.7. This work begins by identifying 2.0 as a very conservative, perhaps bounding, value used by Crea et al. (2000) and adopted here for consistency. Based on laboratory settling data used for the Project W-320 waste transfer into Tank 241-AY-102, 1.4 is a best-estimate value and 1.8 is a two standard-deviation upper bound (Numatec 1998). Tank 241-SY-101 settling data provide a best-estimate fluffing factor of 1.5 and bounding value of 1.75.

A fluffing factor greater than 1.7 can be characterized as unlikely, but not incredible, and the same can be said for the probability of a bump given bump conditions. In principle, equation (5-1) could be modified to reflect this. This right-hand side of the equation could be multiplied by the probability of fluffing factor exceeding 1.7 to obtain the frequency of a bump rather than merely bump conditions.

5.5 CONCLUSIONS

The frequency analysis above shows that a tank bump induced by the planned retrieval operations is beyond extremely unlikely. Available recovery times would be very long relative to the time needed for corrective maintenance activities. Given bump conditions, a bump in Tank 241-AZ-102 could only occur if the fluffing factor greatly exceeds the expected value.

Table 5-3: Evaluation of Meyer and Wells (2000) Criterion for Two Fluffing Factors of 1.4 and 1.7.

Particle Density	Liquid Density	Fluffing Factor	Initial Sludge Depth	Initial Supernatant Depth	Average Density	Fluffed Alpha
3800	1100	1.4	0.96	7.61	1140	0.094466
Const	**Sludge Depth, m**	**Sludge Density**	**Supernatant Density**	**Hydrostatic Pressure, atm**		
18.5	1.344	1355	1100	1.86		
G_g0	**T_{act}, K**	**T_0, K**	**G_g**	**T, K**		
1.64E-02	1.07E+04	355	0.38	396		
LHS	**Bump?**					
0.56491	0					

Particle Density	Liquid Density	Fluffing Factor	Initial Sludge Depth	Initial Supernatant Depth	Average Density	Fluffed Alpha
3800	1100	1.7	0.96	7.61	1140	0.077796
Const	**Sludge Depth, m**	**Sludge Density**	**Supernatant Density**	**Hydrostatic Pressure, atm**		
18.5	1.632	1310	1100	1.84		
G_g0	**T_{act}, K**	**T_0, K**	**G_g**	**T, K**		
1.64E-02	1.07E+04	355	0.38	396		
LHS	**Bump?**					
1.014242	1					

Tank bump conditions brought on by retrieval operations become credible only after extended mixer pump operation for, say, 20 days. This result means that if mixer pump operation time can be doubled or tripled if need be, yet still pose a tank bump frequency less than 1×10^{-6}/d. This result also shows that input and underlying assumptions used by Crea et al. (2000) are very conservative. In particular, the demand that peak (or steady-state) temperature not exceed the LCO 3.3.2 temperature is a stringent one.

6.0 WASTE FEED DELIVERY TANK BUMP CONSEQUENCE ANALYSIS

The scenario described in Sections 3.0 and 5.0 is evaluated for consequences even though there is high confidence that the planned operations result in a tank bump frequency that is beyond extremely unlikely. A first step is to compare the post-mixing tank bump conditions to the current safe storage tank bump conditions. The respective tank bump conditions for the post-mixing and safe storage cases define a crucial initial condition: the volume of gas released to the headspace during a buoyant displacement. Because post-mixing waste properties are uncertain, a single retrieval tank bump is studied parametrically to determine the range of expected headspace overpressures, bubble expansion ratios, and aerosol generation values. From the results of the parametric study, a bounding case for the worst combination of initial gas volume and supernatant temperature is identified. Source term and radiological/toxicological doses are presented for this bounding case.

6.1 BUBBLE AND WASTE ASCENT MODEL

An important initial condition in the waste ascent model described in the safe storage accident analysis (Epstein et al. 2000) is the volume of gas released to the headspace during a buoyant displacement. Meyer et al. (1997) recommend the following dimensional formula:

$$V_b(0) = 750 \frac{\alpha_{NB}\, h_{NCL}\, \tau_y}{P_{NCL}\, \rho_{CL}} \tag{6-1}$$

where α_{NB} is the neutral buoyant void fraction, h_{NCL} is the non-convective layer height in meters, P_{NCL} is the hydrostatic pressure in the non-convective layer in atm, τ_y is the yield stress of the non-convective layer in Pa, and ρ_{CL} is the convective layer density in kg/m^3. For Tank 241-AZ-102, this equation was evaluated for the safe storage scenario using the following values: P_{NCL} = 2 atm, α_{NB} = 0.262, h_{NCL} = 96 cm, ρ_{CL} = 1100 kg/m^3, and τ_y = 100 Pa. These values result in $V_b(0)$ = 8 m^3.

The post-mixed scenario value of $V_b(0)$ is now found for Tank 241-AZ-102. From Crea et al. (2000) the non-convective layer has a "fluffing factor" of about 2.0 for post-mixed conditions; i.e., after mixing stops, the waste settles so that in the short term, the non-convective layer is twice its initial height. This means that the post-mixing non-convective layer density is less than the current value, as is the neutral buoyant fraction. Relative to the current conditions, the post-mixing non-convective layer (NCL) has a higher liquid volume fraction, L_f, owing to the fluffing factor.

An expression for the liquid volume fraction as a function of NCL height can be found by using the definition of waste density averaged over the entire height of waste:

$$L_f = \frac{h_w\, \rho_{avg} - h_{NCL}\, \rho_s - h_{CL}\, \rho_l}{h_{NCL}\, \rho_l - h_{NCL}\, \rho_s} \tag{6-2}$$

where h is height, ρ is density, subscript w denotes the total waste height, NCL denotes the fluffed NCL height, avg denotes an average over the entire waste height (h_w), s denotes solid, l denotes liquid supernatant, and CL denotes post-mixed convective layer. For Tank 241-AZ-102, the following values are taken from Crea et al. (2000): solid density = 3.8 gm/cm^3, liquid density = 1.1 gm/cm^3, and fluffed NCL height = 192 cm (2.0 · 96 cm). From Hu et al (2000), total waste height is 8.57 m and waste average density is 1.14 gm/cm^3. Post-mixed convective layer height is then 6.65 m (8.57 – 1.92 m). Substituting these values into equation (6-2) gives L_f = 93.4%.

Fluffed NCL density is given by,

$$\rho'_{NCL} = \frac{1}{F}\left(\rho_{NCL} + (F-1)\,\rho_L\right) \tag{6-3}$$

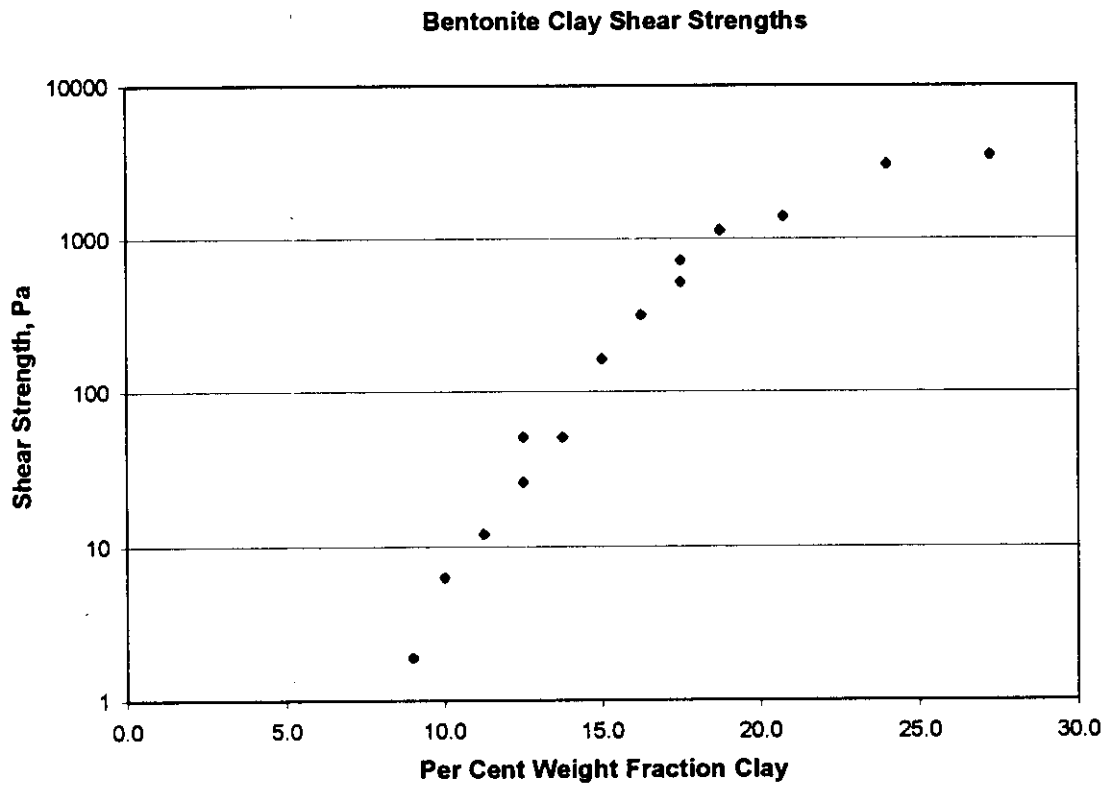
where F is the fluffing factor, ρ'_{NCL} is the fluffed non-convective layer density, and ρ_{NCL} is the non-convective layer density before mixing. From Hu et al. (2000), the initial non-convective layer density is 1.49 gm/cm^3. The fluffed non-convective layer density is then 1.3 gm/cm^3. Post-mixed neutral buoyant fraction, α_{NB}, is then 15% (1 – 1.1 / 1.3).

Equation (6-1) can now be considered to see how $V_b(0)$ changes between the current and post-mixed states. Although the NCL height increases by a factor of two, the neutral buoyant fraction is almost halved and the product $\alpha_{NB}\, h_{NCL}$ does not change much. In the denominator, ρ_{CL} remains unchanged and P_{NCL} changes only slightly because the NCL density decreases while the NCL height increases. Yield strength decreases, however, in response to the increased void fraction, which means that $V_b(0)$ in the post-mixed case is somewhat less than $V_b(0)$ for the safe storage case.

Gauglitz et al. (1996) measured the yield strength of bentonite-clay simulants as a function of clay/water ratio and reported order of magnitude decreases in shear strength for modest decreases in the clay weight fraction. Data plotted here as Figure 6-1 show that in decreasing clay weight fraction from 20% to 15%, measured shear strength falls from about 1300 Pa to a little less than 200 Pa. For Tank 241-AZ-102, the solid wt. fraction in the NCL is now 38%, but would be 18% in the post-mixed scenario. Figure 6-1 cannot be directly applied to the Tank 241-AZ-102 waste. Nevertheless, fluffed shear strength must be regarded as less than current waste shear strength because the trends shown in Figure 6-1 have been observed in waste simulants. An absolute change in solids weight fraction of a few percentage points can change shear strength by an order of magnitude.

Clearly, a tank bump occurring under fluffed conditions is likely to be weaker than a tank bump emanating from safe storage conditions. Yield strength under fluffed conditions is a fraction of the current yield strength, which means that the post-mixing scenario $V_b(0)$ is less than the safe storage $V_b(0)$. In addition, for Tank 241-AZ-102, the convective layer height is reduced by a meter or so, which also reduces the strength of the post-mixed bump. Yield strength as a function of solids mass fraction is not available for the DST waste. For the retrieval scenario, the consequences of a single tank bump are studied parametrically in the next section.

Figure 6-1. Bentonite Clay Shear Strengths.



6.2 PARAMETRIC HADCRT ANALYSIS OF A RETRIEVAL TANK BUMP FOR HEADSPACE PRESSURE AND AEROSOL GENERATION

The discussion in the previous section qualitatively described the differences between a safe storage tank bump and a retrieval tank bump. Using the HADCRT code, this section parametrically considers the peak headspace pressure and aerosol generation resulting from a single retrieval bump. The HADCRT code and base case inputs for the safe storage bump are described in Epstein et al. (2000) and the details are not repeated here.

Tank 241-AZ-102 is again selected for analysis with two sets of inputs. The first set has a bounding supernatant temperature of 100°C, with $V_b(0) = 8\ m^3$, $4\ m^3$, and $1\ m^3$; a second set has supernatant temperature equal to 94°C, with $V_b(0) = 8\ m^3$, $4\ m^3$, and $1\ m^3$. For the sake of comparison, the cases with $V_b(0) = 8\ m^3$ use a fluffing factor of 1.0 and represent the safe storage scenario. The previous section showed that $V_b(0)$ is directly proportional to the sludge shear strength. The two cases presented here assume that the fluffed sludge yield strength is somewhere between ½ the original value and $1/8^{th}$ the original value. A supernatant temperature of 100°C is bounding for pure water properties and 94°C is the best-estimate value from Figure 3-6. To bound uncertainties in headspace pressurization, the closed, adiabatic case is considered. Headspace overpressure can also be compared to the HEPA failure overpressure (5 psig or 35,600 Pa) to show that weak bumps will not cause failure. Relative to the safe storage case, the convective layer depth is reduced by 1 m (from 7.6 to 6.6 m) to account for fluffing. Table 6-1 summarizes inputs for the eight cases. Appendix D contains HADCRT input decks.

In each case, only one bump event was considered. Headspace overpressure, gas volume expansion ratio, and the mass of aerosol generated are reported in Table 6-2. Case 8FF1-100, the first row in this table, essentially reproduces the results from the safe storage accident analysis (Epstein et al. 2000). For Case 4FF2-100, the initial mass of liquid is about the same as in Case 8FF1-100 because neutral buoyancy is now about half the non-fluffed value of 0.26; this offsets the fact that $V_b(0)$ decreases to $4\ m^3$ from $8\ m^3$. The initial liquid mass is found from Epstein et al. (2000):

$$m_\ell(0) = \rho_{NCL}\, V_b(0) \left[\frac{1}{\alpha_{NB}} - 1 \right] \tag{6-4}$$

For Case 1FF2-100 (or Case 1FF2-94), the initial mass of liquid is reduced relative to the initial mass for Case 4FF2-100 (or 4FF2-94) in direct proportion to the reduction in $V_b(0)$.

Cases 8FF1-100 and 4FF2-100 produce similar results for overpressure and aerosol generation per bump, with the reduction in initial gas volume offset by an increased expansion ratio for Case 4FF2-100. Although Case 4FF2-100 should result in roughly twice the number of bumps as Case 8FF1-100 (assuming the run is continued for several hours), Case 4FF2-100 also has about one-half the solids fraction in the non-convective layer that Case 8FF1-100 does.

Table 6-1. Parameter Values for Tank 241-AZ-102 Headspace Overpressure Analysis.

A. Waste and Headspace Parameters	
$V_b(0) = 6.54 \times 10^{-8}\ m^3$	Initial volume of representative bubble based on 5.0 mm bubble diameter.
$V_b(0) = 8, 4,$ or $1.0\ m^3$	Initial total volume of bubbles released from sludge and used in ratio $V_b / V_b(0)$, parameter variation.
$V_\ell = 2712\ m^3$	Volume of convective layer.
$V_{hs}(0) = 1800\ m^3$	Initial volume of headspace.
$H(0) = 6.6$ m	Initial depth of convective layer.
$M_\ell(0) = 34{,}000, 30{,}000,$ and $7{,}500$ kg	Initial non-convective layer mass in parcel.
$T_\ell(0) = 115°C$	Initial parcel temperature.
$P_{hs}(0) = 1.012 \times 10^5$ Pa	Initial headspace pressure.
$T_{CL}(0) = 100$ or $94°C$	Supernatant temperature.
$X_{st}(0) = 95\%$	Headspace steam mole fraction.
B. Flow Path Parameters	
$A_{in} = 0.00\ m^2$	Neglect 8" inlet line.
$A_{out} = 0.00\ m^2$	Neglect 20" outlet line.
$A_{leak} = 0.00\ m^2$	Neglect leakage around 42" risers.
$\Delta P_{HEPA} = 35{,}600$ Pa	HEPA failure ΔP, crediting vent path pressure losses.
$C_e = 0.5$	Flow coefficient for inlet and outlet paths.
$V_{pit} = 4 \times 10\ m^3 + 1 \times 20\ m^3$	Sluice pit and center pit volumes.
$T_{pit}(0) = 75°C$	Pit initial temperature.
$P_{pit}(0) = 1.012 \times 10^5$ Pa	Pit initial pressure.
C. Property Values	
$\rho_{CL} = 1100\ kg\ m^{-3}$	Density of convective layer.
$\mu_g = 1.2 \times 10^{-5}\ kg\ m^{-1}\ s^{-1}$	Viscosity of bubble gas (vapor).
$\rho_g = 0.6\ kg\ m^{-3}$	Density of bubble gas (vapor).
$\sigma = 0.059\ kg\ s^{-2}$	Surface tension of supernatant.
$D = 9.2 \times 10^{-5}\ m^2\ s^{-1}$	Bubble gas/water vapor diffusion coefficient.

Table 6-2 shows that only Cases 8FF1-100 and 4FF2-100 conceivably threaten HEPA filter integrity by way of overpressure. Cases 8FF1-100 and 4FF2-100 result in an overpressure of about 2.5 psig, which is still less than the 5 psig value for failure. The balance of the cases result in smaller overpressures.

Table 6-2. Results of Parametric Analysis of a Single Retrieval Bump in Tank 241-AZ-102.

Case ID	Initial Gas Volume, m^3	Initial Liquid Mass, kg	Fluffing Factor	Supernatant Temperature, °C	Expansion Ratio	Overpressure, kPa	Mass of Aerosol Generated, kg
8FF1-100	8	34,000	1	100	23	17.4	1.24
4FF2-100	4	30,000	2	100	43	16.9	1.15
1FF2-100	1	7,500	2	100	100	8.9	0.44
8FF1-94	8	34,000	1	94	9.5	6.4	0.31
4FF2-94	4	30,000	2	94	16	5.5	0.23
1FF2-94	1	7,500	2	94	3	0.1	2.0×10^{-3}

For a given initial gas volume and liquid mass, the 94°C supernatant temperature cases result in a smaller overpressure and aerosol generation. This is because the bubble expansion ratio is very sensitive to the amount of supernatant sub-cooling. For the 94°C case with weak non-convective layer (Case 1FF2-94), overpressure and aerosol generation are small. In this case, even a large number of bumps will result in source term and radiological/toxicological doses that are small relative to those for the safe storage scenario. HEPA filter failure is unlikely, although the aerosol loading could be much larger than design values.

In summary, parametric calculations show that the best-estimate position is that the retrieval tank bump scenario is likely to result in much smaller source terms and radiological/toxicological doses than the safe storage bump scenario. This conclusion is supported by the results shown in Table 6-2 of the 94°C case. A best-estimate position is that HEPA filter failure would not be expected on overpressure, although aerosol loading could exceed design values. A bounding analysis view states that in light of the results for Case 4FF2-100, the retrieval tank bump scenario could result in consequences similar to those of the safe storage scenario. As a result, Case 4FF2-100 is considered in further detail below. In particular, the entire series of tank bump transients is evaluated, rather than just a single bump.

6.3 HADCRT INPUT FOR THE BOUNDING TANK 241-AZ-102 TANK BUMP SCENARIO

Case 4FF2-100 is evaluated for source term and radiological/toxicological consequences. The tank configuration is the same as that used in Epstein et al. (2000) for the safe storage scenario. 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 flowpaths between the environment and the headspace are the filtered 8" diameter inlet and the filtered 20" diameter. Sluice pit covers lift at a pressure differential of 13.8 kPa and pump pit covers lift at a pressure differential of 17 kPa. Other inputs are shown in Table 6-3. HEPA filters are not credited.

Other parameters important to consequences are the initial mass of liquid in the buoyant parcel, the time between bumps, and the number of bumps. With the volume of gas assumed to be 4 m^3, a non-convective layer density of 1300 kg/m^3 and neutral buoyancy fraction of 0.15, the initial amount of liquid plus suspended solids in the buoyant parcel is 30,000 kg $(1300 \bullet 4 \bullet [1 / 0.15 - 1])$. Average time between bumps is given by Epstein et al. (2000):

$$t_{BD} = \frac{V_b(0)}{G_g \, A_T \, h_{NCL}} \tag{6-5}$$

With G_g = 0.38 mole/m^3/day, or 0.007 m^3/m^3/day, (see Table 5-3), A_T = 411 m^2, and h_{NCL} = 1.92 m, t_{BD} = 1100 minutes (18 hrs). The total number of bumps is equal to the total amount of gas in the non-convective layer divided by the volume of gas in one bump:

$$N_{BD} = \frac{\alpha_{NB} \, A_T \, h_{NCL}}{V_b(0)} \tag{6-6}$$

which is 29 for α_{NB} = 0.15.

Results of the Tank 241-AZ-102 tank bump calculation are shown in Figures 6-2 and 6-3, which provide short- and long-term histories for headspace temperature and pressure, and the aerosol distribution. Figure 6-2 shows the short-term response for one bump. Figure 6-3 shows the response during the interval between the first and second bump, which is 1100 minutes or 66,000 seconds.

Peak overpressure and temperature are 17,000 Pa and 122°C, respectively. Headspace temperature and pressure return to the initial conditions of 100°C and 1 atmosphere after roughly 1000 seconds. The first bump generates 1.22 kg of aerosol, which is slightly higher than the 1.15 kg reported in Table 6-2. The slight difference can be explained by the fact that Table 6-2 was generated using a closed headspace.

Figure 6-3 shows that about 0.42 kg are removed by natural circulation during the interval between bumps. The temperature difference between the tank headspace and the environment creates a flow pattern whereby ambient air enters through the 8" diameter inlet line and headspace gas leaves through the 20" diameter outlet line. Airborne aerosols leak out the headspace in this manner. Figure 6-3 also shows that there is practically no airborne aerosol in the tank after about 40,000 seconds. About 0.8 kg are deposited at that point and 0.42 kg have escaped. Time constant for aerosol settling in the DST headspace is ten hours at most, which is consistent with experimental data such as the AB-5 test (Hilliard et al. 1983), as compared to the time between bumps of 18 hours. This means that the interval between bumps is long enough

Table 6-3. Parameter Values for Tank 241-AZ-102 Bounding Consequence Analysis.

A. Waste and Headspace Parameters	
$V_b(0) = 6.54 \times 10^{-8}\ m^3$	Initial volume of representative bubble based on 5.0 mm bubble diameter.
$V_b(0) = 4\ m^3$	Initial total volume of bubbles released from sludge and used in ratio V_b / V_b (0), parameter variation.
$V_\ell = 2712\ m^3$	Volume of convective layer.
$V_{hs}(0) = 1800\ m^3$	Initial volume of headspace.
$H(0) = 6.6\ m$	Initial depth of convective layer.
$m_\ell(0) = 30{,}000\ kg$	Initial non-convective layer mass in parcel.
$T_\ell(0) = 115°C$	Initial parcel temperature.
$P_{hs}(0) = 1.012 \times 10^5\ Pa$	Initial headspace pressure.
$T_{CL}(0) = 100°C$	Supernatant temperature.
$X_{st}(0) = 95\%$	Headspace steam mole fraction.
B. Flow Path Parameters	
$A_{in} = 0.03\ m^2$	Neglect 8" inlet line.
$A_{out} = 0.20\ m^2$	Neglect 20" outlet line.
$A_{leak} = 5 \times 0.00133\ m^2$	Neglect leakage around 42" risers.
$\Delta P_{HEPA} = 35{,}600\ Pa$	HEPA failure ΔP, crediting vent path pressure losses.
$C_e = 0.5$	Flow coefficient for inlet and outlet paths.
$V_{pit} = 4 \times 10\ m^3 + 1 \times 20\ m^3$	Sluice pit and center pit volumes.
$T_{pit}(0) = 75°C$	Pit initial temperature.
$P_{pit}(0) = 1.012 \times 10^5\ Pa$	Pit initial pressure.
C. Property Values	
$\rho_{CL} = 1100\ kg\ m^{-3}$	Density of convective layer.
$\mu_g = 1.2 \times 10^{-5}\ kg\ m^{-1}\ s^{-1}$	Viscosity of bubble gas (vapor).
$\rho_g = 0.6\ kg\ m^{-3}$	Density of bubble gas (vapor).
$\sigma = 0.059\ kg\ s^{-2}$	Surface tension of supernatant.
$D = 9.2 \times 10^{-5}\ m^2\ s^{-1}$	Bubble gas/water vapor diffusion coefficient.

Figure 6-2. Tank 241-AZ-102 Retrieval Bump Short-Term Results.

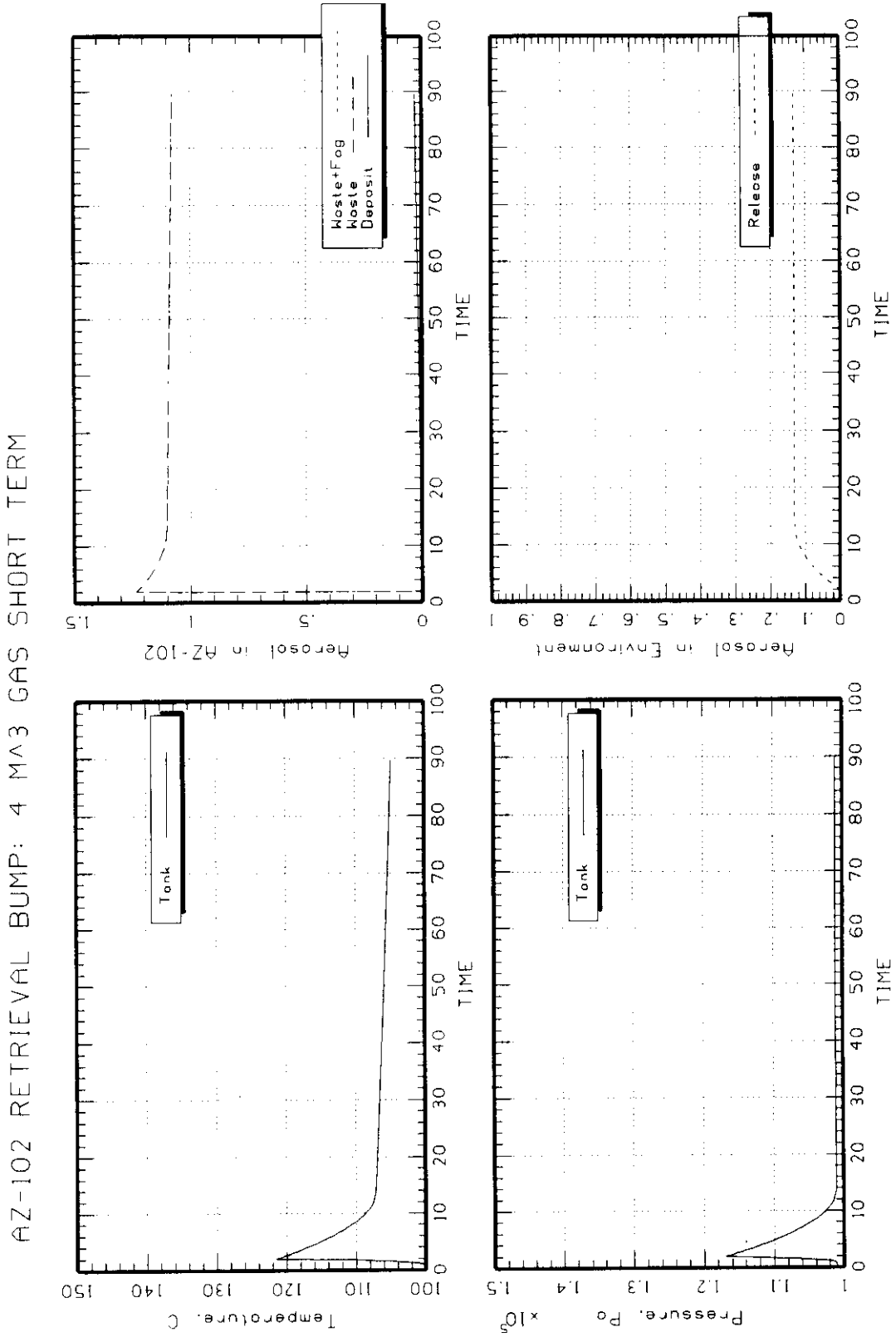
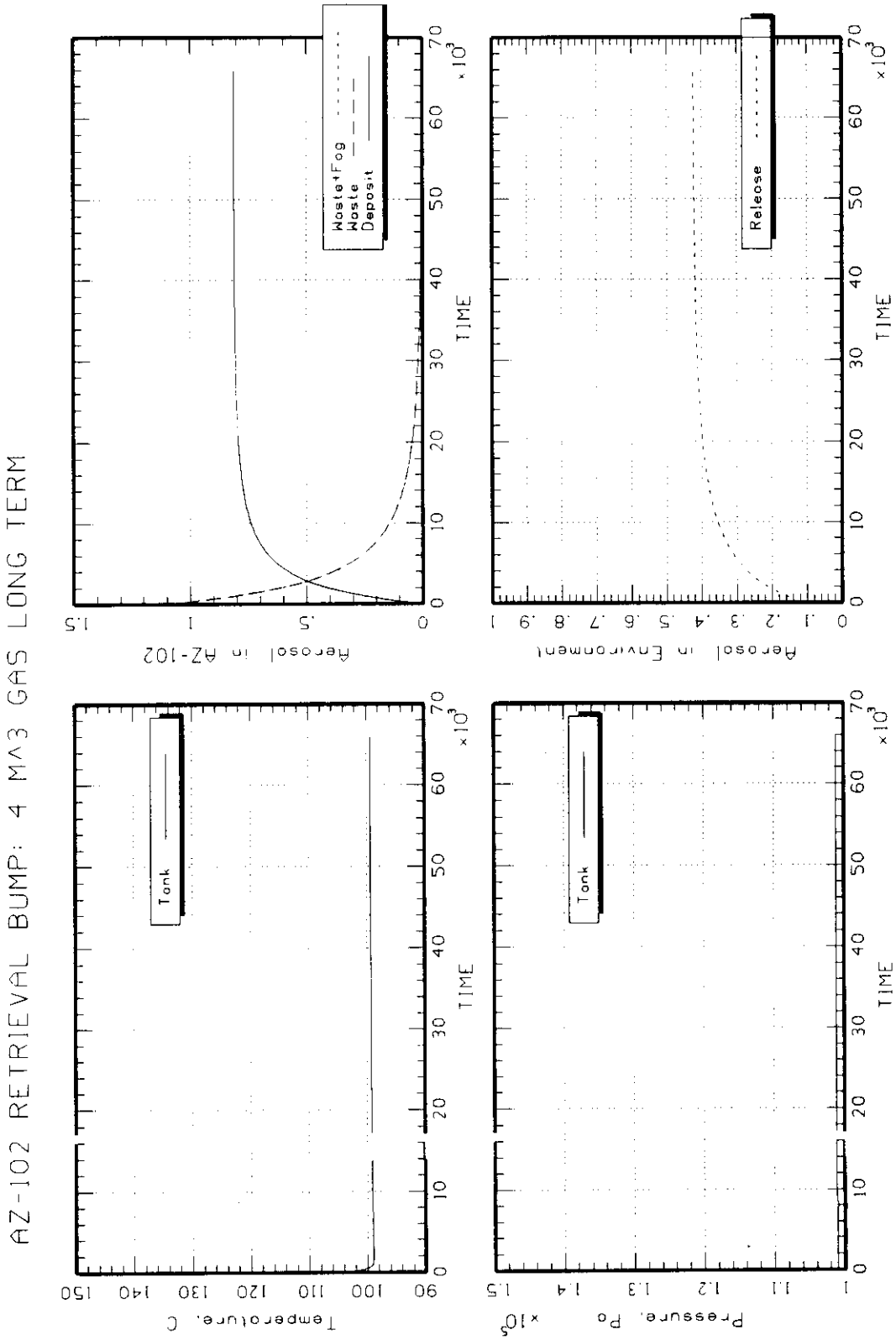


Figure 6-3. Tank 241-AZ-102 Retrieval Bump Long-Term Results.



that each successive bump knows nothing about the one before it. An integral analysis for many bumps is not necessary. The consequences of *n* bumps are simply *n* times the consequences of one bump.

The present calculation considers one sequence of bumps that eventually displaces all non-convective material. Sedimentation, noncondensable 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.

6.4 TANK 241-AZ-102 RETRIEVAL TANK BUMP BOUNDING RADIOLOGICAL AND TOXIC CHEMICAL CONSEQUENCES

Mass of entrained material is converted to dose using the following method from Cowley et al. (2000):

$$D = (Q)(ULD)\left(\frac{X}{Q}\right)(BR) \tag{6-7}$$

where D = Dose, Sv,

Q = Released quantity, L,

ULD = Unit Liter Dose, Sv/L,

X / Q = Atmospheric dispersion coefficient, s/m^3, and

BR = Breathing rate, m^3/s.

The released mass, kg, calculated above can be converted into volume, L, for waste solids and liquids. Then, parameter values from Cowley et al. (2000) as summarized in Table 6-4 may be applied.

Table 6-4. Radiological Consequence Factors (Cowley et al. 2000).

Factor	On-Site	Off-Site
ULD, Sv/L		
DST Solids	1.07×10^5	1.84×10^5
DST Liquids	7.97×10^2	8.45×10^2
X / Q, s/m^3	5.58×10^{-3}	8×10^{-6} (1)
BR, m^3/s	3.33×10^{-4}	3.33×10^{-4}
(1) Calculated in equation (6-8).		

For on-site dose, worker exposure at 100 m is taken for an 8-hour shift, so the X / Q value of 5.58×10^{-3} s/m^3 from Section 5.2.3 of Cowley et al. (2000) applies. Similarly, the breathing rate is specified in Section 3.7 of the reference for light work.

For off-site dose, the methods of Section 5.2.3 of Cowley et al. (2000) are applied using values from Table 5-2 of the reference and approximating the release as an 8-hour event because nearly all of the release occurs over an 8-hour interval. Performing this evaluation,

$$\frac{\log\left(1.74 \times 10^{-5}\right) - \log\left(X/Q\ 8\ \text{hrs.}\right)}{\log\left(1.74 \times 10^{-5}\right) - \log\left(1.47 \times 10^{-7}\right)} = \frac{\log\left(2\ \text{hrs.}\right) - \log\left(8\ \text{hrs.}\right)}{\log\left(2\ \text{hrs.}\right) - \log\left(8{,}760\ \text{hrs.}\right)} \tag{6-8}$$

yielding $X / Q = 8 \times 10^{-6}$ s/m^3. The light work breathing rate also applies off-site due to the short release duration.

Next, liters of solid and liquids released must be derived. In the first bump, non-convective solids are substantially diluted by supernatant: an initial release of 30,000 kg (liquid + solid) is increased to about 115,000 kg total in the rising parcel after entrainment (a calculation detail not plotted). But in later bumps, some solids now present in the supernatant are entrained as well, so that in the last bump of the series, the tank mixed-mean solid fraction applies. From Section 6-2, waste properties are:

	Density (kg/m^3)	**Volume (kL)**	**H_2O (wt. %)**
Convective	1.10	2,712	84%
Non-Convective	1.30	789	

where dissolved salts are responsible for an $H_2O\% < 100\%$ in the convective layer. From the results in Section 6-2, the solids fraction in the fluffed non-convective layer is 6.6%. Thus, the overall mixed mean solids volume fraction is (6.6) (789) / (789 + 2712) = 1.5%. Noting that the released non-convective volume is 30,000 kg / 1.3 (kg/L) = 23.1 kL and the entrained volume is 85,000 kg / (1.1 kg/L) = 77 kL, the maximum fraction of entrained solids at the final bump is approximately

$$\frac{(1.5)\,(77) + (6.6)\,(23.1)}{77 + 23.1} = 2.7\% \tag{6-9}$$

The average density of released material is simply (30,000 + 85,000) / (26,800 + 74,000) = 1.14 kg/L, which is precisely the waste average density noted in Hu et al. (2000). Therefore, the 0.42 kg release is equivalent to 0.37 L total, of which 2.7% or 0.01 L are solid, and 0.36 L are liquid. Note that exact volume fractions and densities could be derived for conversions above, but the amount of solids entrained varies with each bump, so a somewhat conservative approach was taken.

The overall Q * ULD for waste is found by weighting Table 6-4 values by the volume released,

On-Site $\quad Q * ULD = (1.07 \times 10^5)\,(0.01) + (797)\,(0.36) = 1{,}357$ Sv

Off-Site $\quad Q * ULD = (1.84 \times 10^5)\,(0.01) + (845)\,(0.36) = 2{,}144$ Sv

Therefore, total on-site worker dose is

On-Site $D = (1{,}357\ Sv)(5.58 \times 10^{-3}\ s/m^3)(3.33 \times 10^{-4}\ m^3/s) = 0.003\ Sv$

and off-site receiver dose is:

Off-Site $D = (2{,}144\ Sv)(8.0 \times 10^{-6}\ s/m^3)(3.33 \times 10^{-4}\ m^3/s) = 6.0 \times 10^{-6}\ Sv$

Toxic chemical consequences are found using the methods of WHC-SD-WM-SARR-011 (1996). Table 3-8 of the reference provides the toxic limit sum-of-fractions for toxic chemical dose relative to allowed thresholds. Pertinent sum-of-fraction data from Table 3-8 of the reference are summarized in Table 6-5. Values are given for continuous release consistent with the radiological evaluation.

Table 6-5. Sum-of-Fraction of Risk Guidelines for a Unit Release of Chemicals (WHC-SD-WM-SARR-011 1996).

Continuous Release, units s/L			
Waste Type	**Receptor Location**	**Accident Frequency 1/yr.**	
		10^{-2} to 10^{-4}	**10^{-4} to 10^{-6}**
DST Liquids	On-Site	750	210
DST Solids	On-Site	3300	630
DST Liquids	Off-Site	8.4	0.62
DST Solids	Off-Site	15	2.8

When viewed as a continuous release, values in the table are applied to the released volumes of 0.01 L solid and 0.36 L liquid over a duration of 28,800 seconds. A puff evaluation is made for a single release, with a duration of 60 seconds per Cowley et al. (2000). This means the puff release result is a factor of 28,800/60 = 480 times larger than the continuous release result. The puff evaluation is made because the release history for the tank bump accident presented earlier has aspects of both a continuous and a puff release, and because toxic chemical consequences are sensitive to peak concentration. An evaluation is made for frequency bins of 10^{-2}/yr to 10^{-4}/yr and 10^{-4}/yr to 10^{-6}/yr. A release duration of 28,800 s and volumes of 0.01 L solid and 0.36 L liquid are applied for both the puff and continuous release. The result of the evaluation is given in Table 6-6.

Table 6-6. Toxic Consequence Evaluation Results for a Single Retrieval Scenario Bump.

Releases	**Receptor Location**	**Accident Frequency 1/yr = 10^{-2} to 10^{-4}**	**Accident Frequency 1/yr = 10^{-4} to 10^{-6}**
Continuous	On-Site	1.05×10^{-2}	2.84×10^{-3}
	Off-Site	1.10×10^{-4}	8.72×10^{-6}
Puff	On-Site	5.1	1.4
	Off-Site	5.29×10^{-2}	4.19×10^{-3}

Continuous release results are within guidelines, but puff releases are not.

6.5 TANK 241-AZ-102 RETRIEVAL TANK BUMP BOUNDING RADIOLOGICAL AND TOXIC CHEMICAL CONSEQUENCES: 12-HOUR ON-SITE EXPOSURE AND 24-HOUR OFF-SITE EXPOSURE

The calculations in Section 6.4 were repeated using the standard practice of a 12-hour exposure to on-site receptor and a 24-hour exposure to the off-site receptor.

Consider the 12-hour on-site radiological exposure first. The atmospheric dispersion coefficient, X / Q, must be calculated anew because the 8-hour values no longer apply. For an on-site receptor (Cowley et al. 2000):

$$\frac{\log\left(9.40 \times 10^{-3}\right) - \log\left(X/Q\ 12\ \text{hrs.}\right)}{\log\left(9.40 \times 10^{-3}\right) - \log\left(4.03 \times 10^{-4}\right)} = \frac{\log\left(2\ \text{hrs.}\right) - \log\left(12\ \text{hrs.}\right)}{\log\left(2\ \text{hrs.}\right) - \log\left(8{,}760\ \text{hrs.}\right)} \qquad (6\text{-}10)$$

which yields X / Q = 4.8×10^{-3} s/m^3, which is only slightly different than the value shown in Table 6-4 (5.6×10^{-3} s/m^3). ULD and breathing rate do not change. Figure 6-3 shows that releases between the period of 8-hours (28,800 seconds) and 12-hours (43,200 seconds) are negligible. Therefore, the 0.003 Sv value calculated in Section 6.4 applies here as well.

Consider the 24-hour off-site radiological exposure next. Two bumps occur during a 24-hour period, so doubling the value reported in Section 6.4 (6×10^{-6} Sv) is appropriate. Total radiological dose is then 1.2×10^{-5} Sv for a 24-hour off-site receptor.

Similarly, the on-site values listed in Table 6-6 are valid for a 12-hour duration, and the off-site values must be doubled. The general conclusion remains unchanged: continuous release calculations are within guidelines, puff release calculations are not.

7.0 REFERENCES

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A.0 QUANTITATIVE TREATMENT OF TRANSIENT CONDUCTION WITHIN THE NON-CONVECTIVE LAYER DURING SETTLING

To predict the thermal behavior of a growing non-convective waste layer during settling, a time-dependent conduction analysis is required. Again, conduction in the horizontal direction is ignored (see Assumption A1 in Section 4.0). In keeping with our objective of developing an accurate but simple mathematical representation of waste self-heat accident scenarios during retrieval activities, we sidestep a direct numerical attack of the partial differential equation of heat conduction. Instead, we exploit the integral profile method. Rather than demanding that the temperature T (z, t) satisfy the transient heat conduction equation everywhere (locally), we only impose the global conservation condition:

$$\rho_{NCL}\, c_{NCL} \frac{d}{dt} \int_0^{H_{NCL}(t)} T(z,t)\, dz - \rho_{NCL}\, c_{NCL}\, T\left(H_{NCL}, t\right) \frac{d\, H_{NCL}}{dt} = k_{NCL} \frac{\partial T}{\partial z}\left(H_{NCL}, t\right) - k_{NCL} \frac{\partial T}{\partial z}(0, t) + Q_{NCL}\, H_{NCL}(t) \tag{A-1}$$

where H_{NCL} (t) is the instantaneous thickness of the non-convective layer, t is time, z is vertical distance measured from the bottom of the tank, Q_{NCL} is the volumetric decay heat rate, and ρ_{NCL}, c_{NCL}, k_{NCL} are, respectively, the density, specific heat, and thermal conductivity of the non-convective layer.

At the bottom of the tank equation (A-1) is subject to the heat loss condition

$$k_{NCL} \frac{\partial T}{\partial z}(0, t) = h_{av}\left[T(0, t) - T_{av}\right] + h_{soil}\left[T(0, t) - T_{\infty}\right] \tag{A-2}$$

where h_{av} is the coefficient of heat transport to the annulus ventilation system at temperature T_{av} and h_{soil} is the coefficient of heat transport to the soil (k_{soil} / R, see equation (4-2)) at temperature T_{∞}. Note that quasi-steady heat conduction is assumed to be a reasonable approximation within the underlying soil. At the top of the non-convective layer, the upward conduction heat flux is equal to the natural convection heat transport rate at the bottom of the convective layer

$$-k_{NCL} \frac{\partial T}{\partial z}\left(H_{NCL}, t\right) = h_{CL}\left[T\left(H_{NCL}, t\right) - T_{CL}(t)\right] \tag{A-3}$$

where T_{CL} (t) is the instantaneous temperature of the convective layer and h_{CL} is the coefficient for turbulent natural convection heat transfer off the top of the non-convective layer.

The instantaneous average temperature $\overline{T}(t)$ of the non-convective layer is

$$\overline{T}(t) = \frac{1}{H_{NCL}(t)} \int_0^{H_{NCL}(t)} T(z, t)\, dz \tag{A-4}$$

Substituting equations (A-2) to (A-4) into equation (A-1) yields

$$\begin{aligned} & \rho_{NCL}\, c_{NCL}\, H_{NCL}(t) \frac{d\overline{T}}{dt} \\ = & -\rho_{NCL}\, c_{NCL} \left[\overline{T}(t) - T\left(H_{NCL}, t\right)\right] \frac{d\, H_{NCL}}{dt} - h_{CL}\left[T\left(H_{NCL}, t\right) - T_{CL}(t)\right] \\ & - h_{av}\left[T(0, t) - T_{av}\right] - h_{soil}\left[T(0, t) - T_{\infty}\right] + Q\, H_{NCL}(t) \end{aligned} \tag{A-5}$$

To close the problem, it remains to relate the two dependent variables $T(H_{NCL}, t)$ and $T(0, t)$ to the average temperature $\overline{T}$. The thickness (depth) of the non-convective layer is obtained from a separate analysis of the waste solids settling process. Here it is assumed that $H_{NCL}(t)$ is a known function of time. A reasonable functional form for the temperature profile in the non-convective layer is now postulated. The following second-degree polynomial is chosen because it provides the exact solution of the problem in the limit of steady-state heat transfer:

$$\frac{T(z, t) - T(0, t)}{T\left(H_{NCL}, t\right) - T(0, t)} = \frac{z}{H_{NCL}}[1 - x(t)] + x(t)\left(\frac{z}{H_{NCL}}\right)^2 \tag{A-6}$$

where $x(t)$ is a time-dependent profile shape factor. Substituting equation (A-6) into equations (A-2), (A-3), and (A-4) yields the algebraic system

$$\frac{(1 - x)\, k_{NCL}}{H_{NCL}}\left[T\left(H_{NCL}, t\right) - T(0, t)\right] = h_{av}\left[T(0, t) - T_{av}\right] + h_{soil}\left[T(0, t) - T_{\infty}\right] \tag{A-7}$$

$$-\frac{(1 + x)\, k_{NCL}}{H_{NCL}}\left[T\left(H_{NCL}, t\right) - T(0, t)\right] = h_{CL}\left[T\left(H_{NCL}, t\right) - T_{CL}(t)\right] \tag{A-8}$$

$$\overline{T}(t) = T(0, t) + \frac{1}{6}(3 - x)\left[T\left(H_{NCL}, t\right) - T(0, t)\right] \tag{A-9}$$

After some lengthy algebra, equations (A-7), (A-8), and (A-9) yield the following solutions for the three unknowns $T(0, t)$, $T(H_{NCL}, t)$, and $x(t)$:

$$T(0,t) = T_{av} + \frac{3\left(2+B_{CL}\right)\left[\bar{T}(t)-T_{av}\right] - B_{CL}\left[T_{CL}(t)-T_{av}\right] - \frac{1}{2}B_{soil}\left(B_{CL}+4\right)\left(T_{av}-T_{\infty}\right)}{6+2\left(B_{av}+B_{CL}+B_{soil}\right)+\frac{1}{2}B_{CL}\left(B_{av}+B_{soil}\right)} \quad \text{(A-10)}$$

$$T\left(H_{NCL},t\right) = T_{av} + \frac{2+B_{av}+B_{soil}}{2+B_{CL}}\left[T(0,t)-T_{av}\right] + \frac{B_{soil}}{2+B_{CL}}\left(T_{av}-T_{\infty}\right) + \frac{B_{CL}}{2+B_{CL}}\left[T_{CL}(t)-T_{av}\right] \quad \text{(A-11)}$$

$$x(t) = B_{CL}\,\frac{T\left(H_{NCL},t\right)-T_{CL}(t)}{T(0,t)-T\left(H_{NCL},t\right)} - 1 \quad \text{(A-12)}$$

where the B parameters are time-varying Biot numbers defined as

$$B_{av} = \frac{h_{av}\,H_{NCL}(t)}{k_{NCL}}, \qquad B_{CL} = \frac{h_{CL}\,H_{NCL}(t)}{k_{NCL}}, \qquad B_{soil} = \frac{h_{soil}\,H_{NCL}(t)}{k_{NCL}} \quad \text{(A-13)}$$

Under certain conditions the vertical temperature profile in the non-convective layer will exhibit a maximum. The location z_{max} of the peak temperature is found by differentiating equation (A-6) and setting the result equal to zero to obtain

$$z_{max}(t) = \frac{H_{NCL}(t)}{2}\left[1-\frac{1}{x(t)}\right] \quad \text{(A-14)}$$

Substituting this result into equation (A-6) gives the maximum temperature

$$\frac{T_{max}(t)-T(0,t)}{T\left(H_{NCL},t\right)-T(0,t)} = \frac{1}{4}\left[2-x(t)-\frac{1}{x(t)}\right] \quad \text{(A-15)}$$

A physical maximum temperature occurs only when z_{max} lies within the interval

$$0 < z_{max} < H_{NCL}(t) \quad \text{(A-16)}$$

Equations (A-5), (A-10) to (A-12), and (A-15) are sufficient to determine the temperature histories at the bottom and top of the non-convective layers.

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B.0 TRANSIENT TEMPERATURE CALCULATIONS FOR OFF-NORMAL RETRIEVAL SCENARIOS

The model described in Appendix A was used to develop a code for calculating temperature transients during postulated off-normal retrieval scenarios. In particular, the code was used to calculate five temperatures during loss of ventilation scenarios: supernatant temperature, non-convective layer (NCL) (or sludge) average temperature, NCL maximum temperature, NCL top temperature, and NCL bottom temperature. The RETRIEVAL code was written in the Visual Basic for Applications language and is executed as a macro in an Excel 7.0 spreadsheet.

B.1 CODE DESCRIPTION

The integral profile method described in Appendix A requires a model for NCL height during mixing and settling. Since the mixing process is not important to the scenarios of interest, RETRIEVAL simply ramps the NCL thickness to zero in two timesteps and imposes a supernatant and average NCL temperature equal to the waste instantaneous mixing temperature. In the case of $H_{NCL} \rightarrow 0$,

- B_{CL}, B_{av}, and B_{soil} approach zero (equation (A-13)),
- $x(t) = -1$ (equation (A-12)),
- $z_{max}(t) = H_{NCL}(t)$ (equation (A-14)),
- $T_{max}(t) = T(H_{NCL}, t)$ (equation (A-15)), and
- $T(0, t) = T(H_{NCL}, t)$ (equation (A-11)).

which shows that the model approaches the expected uniform temperature profile for a thin NCL.

The settling model is simply:

$$H_{NCL}(t) = H_{NCL}(0)\, F\left[1 - \exp(-t/\tau)\right] \qquad \text{(B-1)}$$

where $H_{NCL}(0)$ is the initial NCL (sludge) height, F is the fluffing factor (2.0 here), and τ is the waste settling time in days. Results plotted for Tank 241-AY-102 show that 5 days is a reasonable estimate for settling time constant (Sathyanarayana 2000). RETRIEVAL tracks NCL thickness based on the settling model above and calculates fluffed properties of density, specific heat, and thermal conductivity.

Sludge properties are calculated by determining appropriate mass and/or volume fractions and then weighting the individual values for liquid and solid constituents to find mixture values. Initial sludge particle volume fraction is an input. The initial particle volume fraction, solid properties, and liquid properties are from Crea et al. (2000) for Tank 241-AZ-102, and are

presented below. Based on fluffing factor, input for mixer pump operation, and settling time, the code calculates the appropriate mass and volume fractions for the sludge in the fluffed state. Equation (6-2) is used to find the volume fraction. Sludge density is then the volume-weighted average of solid and liquid (supernatant) densities. Sludge-specific heat is the mass fraction-weighted average of solid- and liquid- (supernatant) specific heat values. Thermal conductivity is calculated by the Maxwell model, as in Sathyanarayana (2000), and uses sludge liquid volume fraction as an input.

While the mixer pumps are operating, there is only one equation for the temperature rate-of-change and all waste is said to be a convective layer. This equation reflects the overall energy balance at the waste boundaries and ignores interfacial heat transfer. Once the convective layer temperature rate-of-change is calculated, it is assigned to be sludge temperature rate-of-change, which must always be tracked. The individual terms for heat losses and sources are described in Appendix A for the bottom surface, and in the discussion below of supernatant temperature rate-of-change.

Mixer pump heat is distributed uniformly throughout the waste. During mixing, the waste density is just the total mass waste divided by total initial volume. Waste heat capacity is assumed to be the liquid (supernatant) capacity and the solids heat capacity is ignored. While the mixer pumps are operating, thermal conductivity is irrelevant because there is no sludge layer.

Supernatant temperature can be described by a single value because convection ensures a uniform temperature distribution. The supernatant temperature rate-of-change includes the following sources and losses:

- Decay heat as calculated from the transient supernatant height,
- Heat transfer from the sludge top surface,
- Evaporation from the supernatant surface,
- Reflux of primary ventilation condensate,
- Conduction through the top and sides, and
- Annulus ventilation system.

Supernatant decay heat depends on the volume of the supernatant. The code assumes that the total waste height remains constant and that the height of the supernatant is just the height of the waste minus the height of the sludge. Sludge height during settling is given by equation (B-1).

The rate-of-change of supernatant temperature and/or sludge temperature proves to be insensitive to assumptions about the heat transfer coefficient between the sludge top surface and the supernatant. The sludge top surface temperature is always within a degree or so of the supernatant temperature. Heat transfer coefficient between the sludge and the supernatant is representative of natural convection of water overlying a hot surface:

$$h_{sup} = 100\left[T\left(H_{NCL}, t\right) - T_{CL}(t)\right]^{1/3} \frac{W}{m^2 - K} \tag{B-2}$$

where T (H_{NCL}, t) is the temperature at the top of the sludge and T_{CL} (t) is the supernatant temperature.

Evaporation from the supernatant is predicted by a simple model that assumes evaporation is only effective if primary ventilation is operating. If primary ventilation is operating, headspace properties are assumed to be that for pure air. Vapor suppression by dissolved salt means that vapor pressure is 85% that of pure water (Crea et al. 2000). Evaporation is expressed as:

$$W_{ev} = h_m \left(Y_s - Y_{atm}\right)^{4/3} \tag{B-3}$$

where W_{ev} is the evaporation rate in kg/s, h_m is a mass transfer coefficient, Y is vapor mass fraction, subscript s denotes the supernatant surface, and subscript atm denotes headspace atmosphere. Vapor mass fraction at the surface, Y_s, is found from the steam partial pressure at the surface accounting for vapor suppression by salts. Mass transfer coefficient, h_m, is based on the heat-mass transfer analogy. Vapor mass fraction in the atmosphere is found by a Newton's method solution to the mass balance for the amount of steam in the headspace:

$$\frac{Y_{atm}}{1 - Y_{atm}} = \frac{h_m \left(Y_s - Y_{atm}\right)^{4/3}}{\rho_g \, Q_v} \tag{B-4}$$

where Q_v is the primary ventilation volumetric flowrate and ρ_g is the gas density.

Condensate is returned to the supernatant with some user-defined split fraction and temperature. The usual assumption is that all the condensate returns to the supernatant.

Conduction through the soil overburden is simply one-dimensional, steady-state conduction through a slab with one end at the ambient air temperature and the other at the supernatant temperature. Sideward conduction is defined to be 33% of upward conduction, based on Kummerer (1994), and apportioned between sludge and supernatant based on height.

Annulus ventilation removes heat based on the supernatant temperature, the sideward heat transfer area of the DST (perimeter times supernatant height), the annulus ventilation inlet temperature, and some user-defined heat transfer coefficient.

B.2 VALIDATION

The coding was validated against the loss of ventilation results presented in Figure 3-6. This plot shows the following:

- The transient starts from a mixed waste temperature of 190°F (88°C),

- The NCL maximum temperature reaches saturation after 50 (119 – 69) days, and
- Supernatant temperature reaches 209°F, or 98.3°C, after 69 (138 – 69) days.

For Tank 241-AZ-102, RETRIEVAL input was taken from Appendix B of Crea et al. (2000), and is as shown in Table B-1.

This input reproduces the GOTH run shown in Figure 3-6. Results are shown in Figure B-1. The first 34 days are simply to allow the waste temperatures to reach steady-state. The user-defined annulus ventilation heat transfer coefficient was chosen to keep the supernatant temperature constant at roughly 113°F. A comparison of Figure B-1 and Figure 3-6 shows that the RETRIEVAL code does a reasonable job of predicting the peak sludge temperature. Mixing then occurs between 34 and 69 days, at which time the mixer pumps and ventilation systems are shut off.

RETRIEVAL results show reasonable agreement with GOTH results shown in Figure 3-6:

- The transient starts from a mixed waste temperature of 193°F (89.7°C),
- The NCL maximum temperature reaches saturation (254°F) after 42 (111 – 69) days, and
- Supernatant temperature reaches 209°F, or 98.3°C, after 73 (142 - 69) days.

The RETRIEVAL supernatant temperature curve is not in precise agreement with the GOTH curve because evaporative cooling is not accounted for in RETRIEVAL. After the mixer pumps are turned off, evaporative cooling will still be effective for a time.

This calculation was repeated with mixer pump shut off and ventilation failure occurring at various times other than 69 days. In all instances, the maximum sludge temperature rate-of-change was about the same.

B.3 SUCCESS CRITERIA RUN

To determine if primary ventilation alone can prevent a bump, the previous case was revised to assume that primary ventilation does not fail at 69 days (time of mixer pump shut down) but annulus ventilation fails. Input is shown in Table B-2.

Results are shown in Figure B-2. The figure indicates that the sludge would still reach saturated conditions after about 55 (124 – 69) days, but the supernatant would be highly sub-cooled. This would prevent bumps, but not lead to a stable state. Figure B-2 confirms that a valid, conservative success criterion is that both primary and annulus ventilation are required.

Table B-1. RETRIEVAL Validation Input.

DST Thermalhydraulic Analysis Inputs: Tank 241-AZ-102					
Waste Properties			**Timing**		
Supernatant Liquid Density	kg/m^3	1100	Length	days	150
Supernatant Heat Capacity	J/kg/C	4200	Time Step	days	0.05
Supernatant Themal Conductivity	W/m/K	0.61	Plot Interval	days	2
Vapor Suppression	%	85			
Particle Size	microns	10			
Particle Density	kg/m^3	3800			
Particle Heat Capacity	J/kg/C	840			
Particle Thermal Conductivity	W/m/K	8.6			
Particle Volume Fraction	-	0.17			
Settling Time Constant	days	5			
Sludge Depth	m	0.96			
Supernatant Depth	m	7.65			
Sludge Volume	m^3	360			
Supernatant Volume	m^3	3234			
Initial Supernatant Temperature	C	45			
Initial Sludge Temperature	C	63.6			
Heat Loads					
Supernatant Liquid	W	19638			
Sludge	W	38894			
Liquid Generation Rate	W/kg	0.0058			
Solids Generation Rate	W/kg	0.1644			
Mixer Pumps	W	447,000			
Ambient Conditions					
Air Temperature	C	28			
Soil Temperature	C	10			
Relative Humidity	%	50			
Soil Overburden Thickness	m	4			
Tank Radius	m	11.4			
Soil Thermal Conductivity	W/m/K	1			
Ventilation System					
Primary Flow	m^3/s	0.235			
Annulus Flow	m^3/s	0.46			
Annulus Heat Transfer Coefficient	$W/m^2/K$	0.55			
Annulus Flow Inlet Temp.	C	4.4			
Recirculation Fraction	--	1			
Recirculation Temperature	C	4.4			
Scenario Description					
Time Mixer Pumps Start	days	34			
Time Mixer Pumps Stop	days	69			
Fluffing Factor	--	2.0			
Time Primary Ventilation Starts	days	0			
Time Primary Ventilation Stops	days	69			
Time Annular Ventilation Starts	days	0			
Time Annular Ventilation Stops	days	69			

Figure B-1. RETRIEVAL Validation Results.

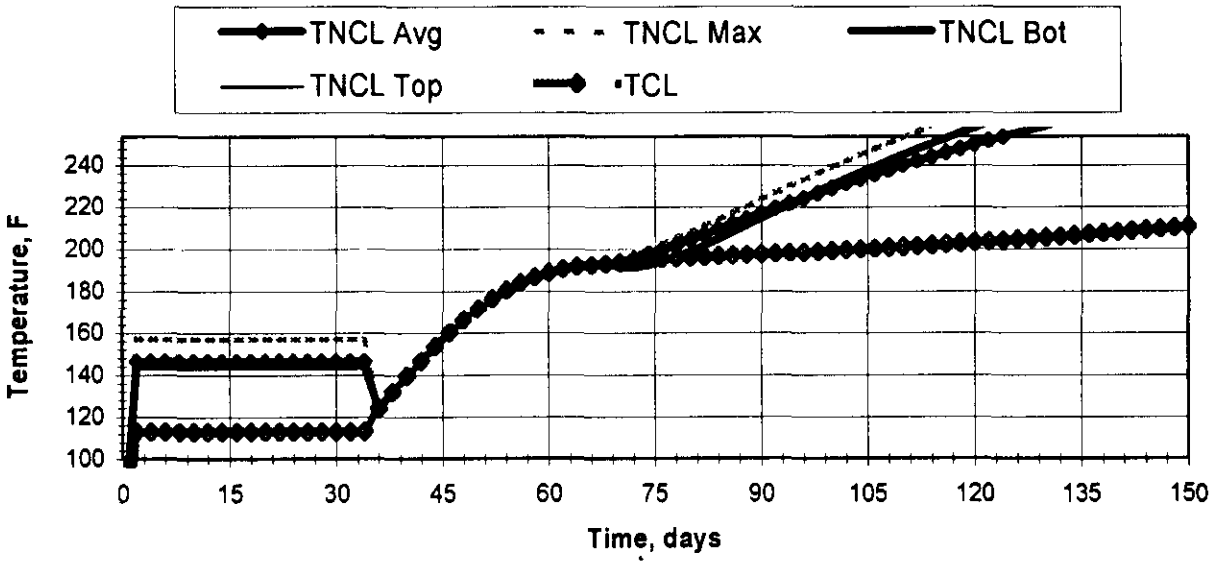
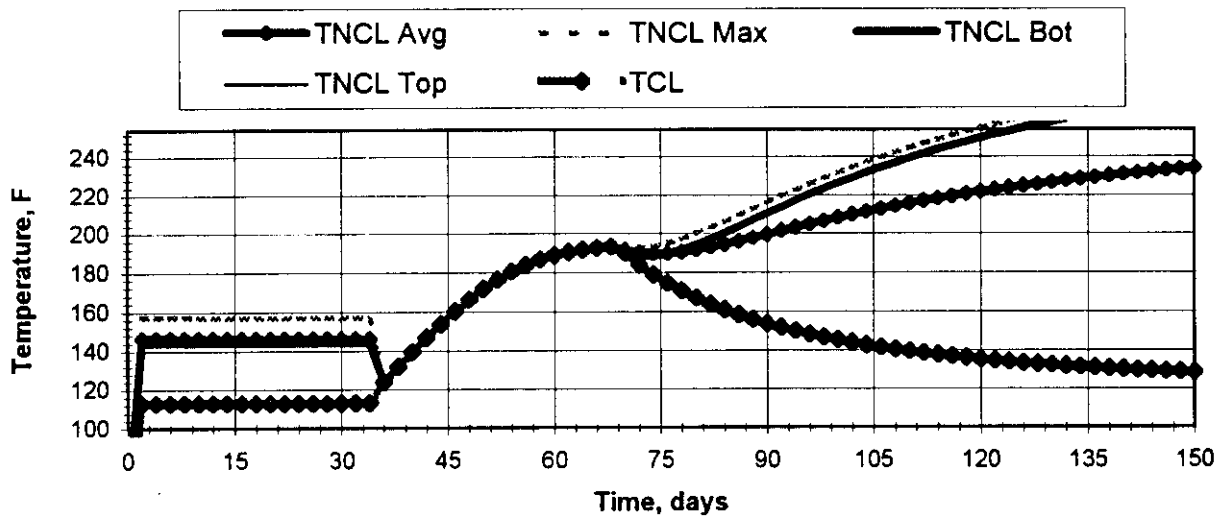


Table B-2. Inputs for Case with Primary Ventilation but No Annulus Ventilation.

DST Thermalhydraulic Analysis Inputs: Tank 241-AZ-102					
Waste Properties			**Timing**		
Supernatant Liquid Density	kg/m^3	1100	Length	days	150
Supernatant Heat Capacity	J/kg/C	4200	Time Step	days	0.05
Supernatant Thermal Conductivity	W/m/K	0.61	Plot Interval	days	2
Vapor Suppression	%	85			
Particle Size	microns	10			
Particle Density	kg/m^3	3800			
Particle Heat Capacity	J/kg/C	840			
Particle Thermal Conductivity	W/m/K	8.6			
Particle Volume Fraction	-	0.17			
Settling Time Constant	days	5			
Sludge Depth	m	0.96			
Supernatant Depth	m	7.65			
Sludge Volume	m^3	360			
Supernatant Volume	m^3	3234			
Initial Supernatant Temperature	C	45			
Initial Sludge Temperature	C	63.6			
Heat Loads					
Supernatant Liquid	W	19638			
Sludge	W	38894			
Liquid Generation Rate	W/kg	0.0058			
Solids Generation Rate	W/kg	0.1644			
Mixer Pumps	W	447,000			
Ambient Conditions					
Air Temperature	C	28			
Soil Temperature	C	10			
Relative Humidity	%	50			
Soil Overburden Thickness	m	4			
Tank Radius	m	11.4			
Soil Thermal Conductivity	W/m/K	1			
Ventilation System					
Primary Flow	m^3/s	0.235			
Annulus Flow	m^3/s	0.46			
Annulus Heat Transfer Coefficient	$W/m^2/K$	0.55			
Annulus Flow Inlet Temp.	C	4.4			
Recirculation Fraction	--	1			
Recirculation Temperature	C	4.4			
Scenario Description					
Time Mixer Pumps Start	days	34			
Time Mixer Pumps Stop	days	69			
Fluffing Factor	--	2.0			
Time Primary Ventilation Starts	days	0			
Time Primary Ventilation Stops	days	1000			
Time Annular Ventilation Starts	days	0			
Time Annular Ventilation Stops	days	69			

Figure B-2. Results of Case with Primary Ventilation but No Annulus Ventilation.



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APPENDIX C

SPREADSHEETS FOR ACCIDENT FREQUENCY CALCULATION

C.1 SPREADSHEET CALCULATIONS FOR FREQUENCY OF TANK BUMP CONDITIONS

This spreadsheet evaluates retrieval tank bump conditions frequency, F_{WFD}. See Section 5 of this report. Symbols are defined in the symbol table.

Differential equation for probability of tank bump conditions

$$d\,F_{WFD}(t) = p_f(t)\,P_{nr}(t)\,dt$$

Integrate over mixer operation time, t_{op}

$$F_{WFD} = \int_0^{t_{op}} p_f(t)\,P_{nr}(t)\,dt$$

Function Definitions: Ventilation System Failure and Probability of No Recovery

$$p_f = \lambda_p + \lambda_{ann}$$

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

Time Available Function: Heatup rate = 1.2 F/day

If (t < 35 days) $t_a = \dfrac{\left[240°F - \left(123 + 3.9\,t - 0.055\,t^2\,°F\right)\right]}{\alpha}$

else $t_a = 40$ days

Long Form of the Equation

$$F_{WFD} = \left[\lambda_p + \lambda_{ann}\right] \int_0^{t_{op}} \left(1 - x_{rs}\right) \sum_{n=1}^{N} x_n \left[1 - \text{log-normal}\left(t_a, \alpha_n, \beta_n\right)\right] dt$$

Definition of Exceedance Probability for CM Activity 1; log-normal is the cumulative log-normal distribution

$$\text{Exceed. Prob 1} = \left[1 - \text{log-normal}\left(t_a, \alpha_1, \beta_1\right)\right], \text{ etc.}$$

Symbol Table

Symbol	Definition	Value
$\lambda_p + \lambda_{am}$	Ventilation Failure Rate	0.0077/day
x_{rs}	Restoration Activity Fraction	0.8
x_1	Corrective Maintenance Activity Fraction for 3TCNEL	0.485
x_2	CM Activity Fraction for 5TCIEL	0.030
x_3	CM Activity Fraction for 5TCNEL	0.485
α_1	Log-Mean of CM Activity 3TCNEL	5.08
α_2	Log-Mean of CM Activity 5TCIEL	5.56
α_3	Log-Mean of CM Activity 5TCNEL	4.89
β_1	Log-St. Dev. of CM Activity 3TCNEL	0.56
β_2	Log-St. Dev. of CM Activity 5TCIEL	0.56
β_3	Log-St. Dev.of CM Activity 5TCNEL	0.56

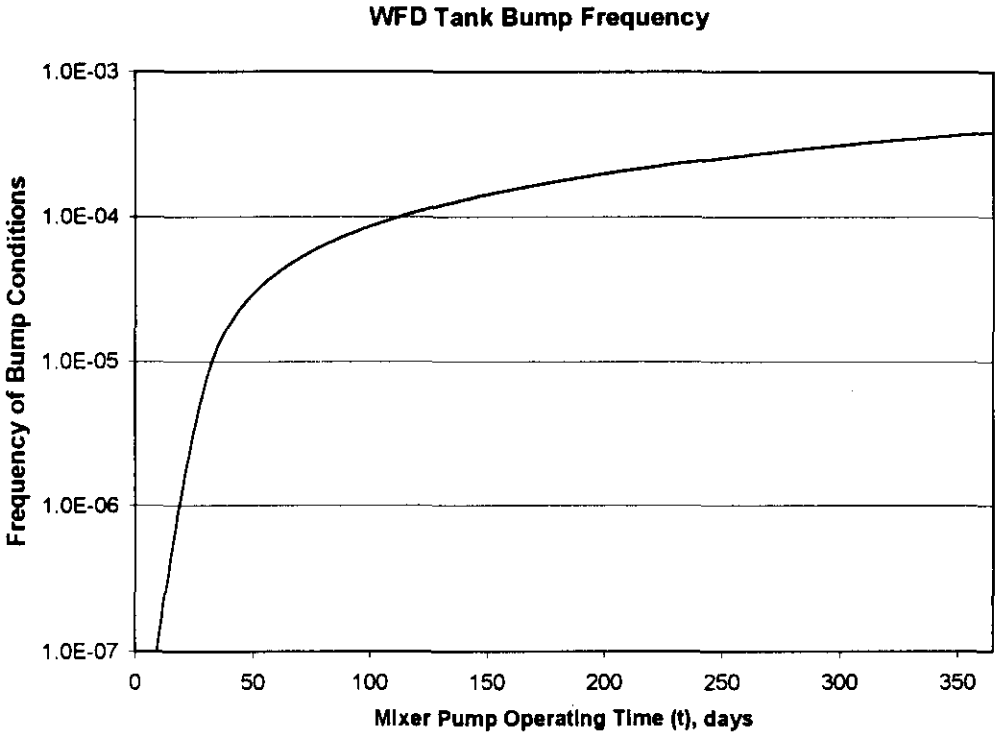
Corrective Maintenance Distributions

CM Activity	5TH	95TH	Log-Mean	Log St. Dev	CM Activity Fraction	CM No.	
3TCNEL	64	400	5.08	0.56	0.485	1	
5TCIEL	102	638	5.56	0.56	0.03	2	
5TCNEL	53	331	4.89	0.56	0.485	3	

Integration Table: Column Headings "Time Available", "Exceed. Prob.", "P_{nr}", "p_f", "F_{WFD}" defined on Pages B - 1 and B-2.

	Ventilation Failure Rate = p_f	Restoration Activity Fraction						Day that F_{WFD} > 1e-6
	1/day	-						19
	7.70E-03	0.8						
Mixer Operation Time, t_{op}	Time Available, t_a	Exceed. Prob 1	Exceed. Prob 2	Exceed. Prob 3	P_{nr}	p_f*P_{nr}	dF_{WFD}	F_{WFD}
days	days	-	-	-				
0	97.5	8.69E-07	4.34E-05	1.52E-07	3.60E-07	2.77E-09	0.00E+00	0.00E+00
1	94.3	1.17E-06	5.55E-05	2.08E-07	4.67E-07	3.59E-09	3.18E-09	3.18E-09
2	91.2	1.56E-06	7.09E-05	2.85E-07	6.05E-07	4.66E-09	4.12E-09	7.30E-09
3	88.2	2.09E-06	9.02E-05	3.88E-07	7.82E-07	6.02E-09	5.34E-09	1.26E-08
4	85.2	2.79E-06	1.15E-04	5.28E-07	1.01E-06	7.77E-09	6.89E-09	1.95E-08
5	82.4	3.71E-06	1.45E-04	7.16E-07	1.30E-06	1.00E-08	8.89E-09	2.84E-08
6	79.7	4.92E-06	1.83E-04	9.68E-07	1.67E-06	1.28E-08	1.14E-08	3.98E-08
7	77.0	6.50E-06	2.30E-04	1.30E-06	2.14E-06	1.64E-08	1.46E-08	5.45E-08
8	74.4	8.55E-06	2.88E-04	1.75E-06	2.73E-06	2.10E-08	1.87E-08	7.32E-08
9	72.0	1.12E-05	3.59E-04	2.34E-06	3.47E-06	2.67E-08	2.39E-08	9.71E-08
10	69.6	1.46E-05	4.46E-04	3.11E-06	4.40E-06	3.38E-08	3.03E-08	1.27E-07
11	67.3	1.90E-05	5.52E-04	4.12E-06	5.55E-06	4.27E-08	3.83E-08	1.66E-07
12	65.1	2.45E-05	6.79E-04	5.42E-06	6.97E-06	5.37E-08	4.82E-08	2.14E-07
13	63.0	3.14E-05	8.31E-04	7.09E-06	8.72E-06	6.71E-08	6.04E-08	2.74E-07
14	61.0	4.01E-05	1.01E-03	9.21E-06	1.08E-05	8.35E-08	7.53E-08	3.50E-07
15	59.1	5.08E-05	1.22E-03	1.19E-05	1.34E-05	1.03E-07	9.35E-08	4.43E-07
16	57.2	6.39E-05	1.47E-03	1.52E-05	1.65E-05	1.27E-07	1.15E-07	5.58E-07
17	55.5	7.98E-05	1.76E-03	1.94E-05	2.02E-05	1.55E-07	1.41E-07	7.00E-07
18	53.9	9.89E-05	2.09E-03	2.44E-05	2.45E-05	1.89E-07	1.72E-07	8.71E-07
19	52.3	1.22E-04	2.46E-03	3.05E-05	2.95E-05	2.27E-07	2.08E-07	1.08E-06
20	50.8	1.48E-04	2.87E-03	3.78E-05	3.53E-05	2.72E-07	2.49E-07	1.33E-06
21	49.5	1.78E-04	3.33E-03	4.63E-05	4.18E-05	3.22E-07	2.97E-07	1.63E-06
22	48.2	2.13E-04	3.84E-03	5.61E-05	4.91E-05	3.78E-07	3.50E-07	1.98E-06
23	47.0	2.52E-04	4.38E-03	6.73E-05	5.72E-05	4.41E-07	4.09E-07	2.38E-06
24	45.9	2.95E-04	4.95E-03	7.97E-05	6.60E-05	5.08E-07	4.74E-07	2.86E-06
25	44.9	3.41E-04	5.54E-03	9.34E-05	7.53E-05	5.80E-07	5.44E-07	3.40E-06
26	44.0	3.89E-04	6.15E-03	1.08E-04	8.51E-05	6.55E-07	6.18E-07	4.02E-06
27	43.2	4.39E-04	6.76E-03	1.23E-04	9.51E-05	7.32E-07	6.94E-07	4.71E-06
28	42.4	4.90E-04	7.38E-03	1.39E-04	1.05E-04	8.09E-07	7.71E-07	5.49E-06
29	41.8	5.39E-04	7.93E-03	1.54E-04	1.15E-04	8.84E-07	8.47E-07	6.33E-06
30	41.3	5.85E-04	8.45E-03	1.68E-04	1.24E-04	9.54E-07	9.19E-07	7.25E-06
31	40.8	6.27E-04	8.92E-03	1.82E-04	1.32E-04	1.02E-06	9.85E-07	8.24E-06
32	40.4	6.63E-04	9.31E-03	1.93E-04	1.39E-04	1.07E-06	1.04E-06	9.28E-06
33	40.2	6.92E-04	9.61E-03	2.02E-04	1.44E-04	1.11E-06	1.09E-06	1.04E-05
34	40.0	7.09E-04	9.80E-03	2.08E-04	1.48E-04	1.14E-06	1.12E-06	1.15E-05
35	40.0	7.09E-04	9.80E-03	2.08E-04	1.48E-04	1.14E-06	1.14E-06	1.26E-05

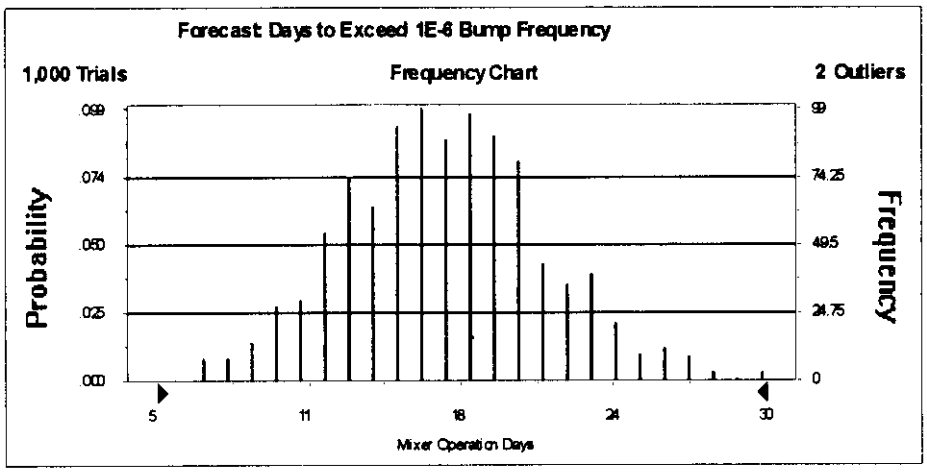
Values for times larger than 35 days are plotted below.


WFD Tank Bump Frequency
Frequency of Bump Conditions
1.0E-03
1.0E-04
1.0E-05
1.0E-06
1.0E-07
0
50
100
150
200
250
300
350
Mixer Pump Operating Time (t), days

C.2 UNCERTAINTY ANALYSIS FOR FREQUENCY OF TANK BUMP CONDITIONS

Crystal Ball Report
Simulation started on 7/21/00 at 13:09:58
Simulation stopped on 7/21/00 at 13:12:23

Forecast: Days to Exceed 1E-6 Bump Frequency



Percentiles:

Percentile	Mixer Operation Days
0.0%	7
2.5%	9
5.0%	10
50.0%	17
95.0%	24
97.5%	26
100.0%	32

End of Forecast

Assumptions

Assumption: Relative Frequency of 5TCIEL

Uniform distribution with parameters:

Minimum	0.01
Maximum	0.10

Mean value in simulation was 0.05

Assumption: Recovery Fraction = 1 - CM Fraction

Uniform distribution with parameters:

Minimum	0.50
Maximum	0.80

Mean value in simulation was 0.65

Assumption: Ventilation Failure Rate, 1/hr

Lognormal distribution with parameters:

Mean	3.21E-04
Standard Dev.	3.07E-04

Selected range is from 0.00E+0 to +Infinity
Mean value in simulation was 3.14E-4

End of Assumptions

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APPENDIX D

HADCRT INPUTS FOR TANK BUMP CONSEQUENCE ANALYSIS

D.1 Input File for Tank 241-AZ-102 Bounding Consequence Analysis: AZ102R.DAT

```
*****************************************************************
*   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   66000.   !  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
     0.0  0.01
     1.0  0.01
    10.0  0.1
    100.  1.0
   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
     0.0  0.1
     1.0  0.1
    10.0  1.0
    100.  10.0
   1000.  100.0
   DTPRIN           !  PRINT INTERVAL (Seconds)
     0.0  0.25
     1.0  0.25
     2.0  0.25
     3.0  0.25
     4.0  0.25
     0.0  0.25
     1.0  2.0
    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
     0.0  0.01
     1.0  0.1
    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
     0.0  0.1
     1.0  1.0
    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
 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
*
*
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       1800.       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     1        ! 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
*
 IGEOM        1
 RHO        1200.00
 KHS          0.6
 CPHS         1.E10
 QV         0.0
 XRI           0.0
 XRO           1.0
 AHS          1000.
 TIINIT       100.00
 TOINIT       100.00
 IMSLAB         10
 IREGI           1
 TIHS          100.0
 IREGO           0
 TOHS          100.0
 XLHS           10.0
 EHSI           1.0
 EHSO           1.0
 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      2.0      2.0      2.0      2.0
 DFJN     1.0      1.0      1.0      1.0
 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.
*
    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
 Z1JN     0.6      0.6
 Z2JN     0.0      0.0
 CJN      2.0      2.0
 DFJN     1.0      1.0
 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.
*
END JUNCTIONS   ! JUNCTIONS is a comment.
*
*-----------------------------------------------------------------------
BUMP! Input Section for "DCRT.For" Model
*-----------------------------------------------------------------------
TANK
  IRBUMP      1          ! BUMP region index
  HEIGHT_CL   6.6        ! Conv layer height
  T_WASTE     387.0      ! Non-Conv Waste temp, K
  T_SUPER     373.0      ! Supernatant Temp.
  VOLUME_CL   2712.      ! Conv layer volume, m^3
  GAS_VOL     4.0        ! Volume of released gas, m^3
  MASS_LIQ    30.E3      ! Mass of liquid in cluster
  NBMAX        1.E0      ! Number of total bumps
END TANK
*
*.......................................................................
WASTE
  DENSITY_CL  1100.      ! 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   66000.E0       ! Time between bumps
  TBUMP     200.         ! Development use only
END MODEL
*
*.......................................................................
*
END DCRT
*
```

D.2 Input File Comparison: 8FF1-100.DAT vs. AZ102R.DAT

```
12c12
<       AZ 102 RETRIEVAL TANK BUMP: NO FLOW, JUST GET PEAK PRESSURE
---
>       AZ 102 TANK BUMP
20c20
<    TLAST  10.   !  END TIME
---
>    TLAST   66000.  !  END TIME
44,50c44,50
<      0.0  1.0
<      1.0  1.0
<      2.0  1.0
<      3.0  1.0
<      4.0  1.0
<      5.0  1.0
<      6.0  2.0
---
>      0.0  0.25
>      1.0  0.25
>      2.0  0.25
>      3.0  0.25
>      4.0  0.25
>      0.0  0.25
>      1.0  2.0
143,145c143,145
<   IJUNC   0    ! Junction flow model
<   ICCFLW  0    ! Counter-current flow model
<   IHSINK  0    ! Heat sinks
---
>   IJUNC   1    ! Junction flow model
>   ICCFLW  1    ! Counter-current flow model
>   IHSINK  1    ! Heat sinks
313c313
<  AJN      0.000   0.000   0.000    0.000
---
>  AJN      0.030   0.200   0.053    0.00133
316c316
<  CJN      4.0     4.0     2.0      2.0
---
>  CJN      2.0     2.0     2.0      2.0
334c334
<  AJN      0.00     0.00
---
>  AJN      0.32     0.08
359,360c359,360
<   GAS_VOL     8.0        ! Volume of released gas, m^3
<   MASS_LIQ    34.E3      ! Mass of liquid in cluster
---
>   GAS_VOL     4.0        ! Volume of released gas, m^3
>   MASS_LIQ    30.E3      ! Mass of liquid in cluster
375c375
<   TINTB    1800.E0       ! Time between bumps
---
>   TINTB   66000.E0       ! Time between bumps
```

D.3 Input File Comparison: 8FF1-100.DAT vs. 4FF2-100.DAT

```
44,49c44,49
<      0.0  1.0
<      1.0  1.0
<      2.0  1.0
<      3.0  1.0
<      4.0  1.0
<      5.0  1.0
---
>      0.0  1.00
>      1.0  1.00
>      2.0  1.00
>      3.0  1.00
>      4.0  1.00
>      5.0  1.00
359,360c359,360
<   GAS_VOL     8.0        ! Volume of released gas, m^3
<   MASS_LIQ    34.E3      ! Mass of liquid in cluster
---
>   GAS_VOL     4.0        ! Volume of released gas, m^3
>   MASS_LIQ    30.E3    ! Mass of liquid in cluster
```

D.4 Input File Comparison: 8FF1-100.DAT vs. 1FF2-100.DAT

```
44,50c44,50
<      0.0  1.0
<      1.0  1.0
<      2.0  1.0
<      3.0  1.0
<      4.0  1.0
<      5.0  1.0
<      6.0  2.0
---
>      0.0  0.25
>      1.0  0.25
>      2.0  0.25
>      3.0  0.25
```

```
>       4.0  0.25
>       0.0  0.25
>       1.0  2.0
359,360c359,360
<   GAS_VOL     8.0        ! Volume of released gas, m^3
<   MASS_LIQ    34.E3      ! Mass of liquid in cluster
---
>   GAS_VOL     1.0        ! Volume of released gas, m^3
>   MASS_LIQ    7.5E3      ! Mass of liquid in cluster
```

D.5 Input File Comparison: 8FF1-100.DAT vs. 8F1-94.DAT

```
357c357
<   T_SUPER     373.0      ! Supernatant Temp.
---
>   T_SUPER     367.0      ! Supernatant Temp.
```

D.6 Input File Comparison: 8FF1-100.DAT vs. 4FF2-94.DAT

```
44,49c44,49
<       0.0  1.0
<       1.0  1.0
<       2.0  1.0
<       3.0  1.0
<       4.0  1.0
<       5.0  1.0
---
>       0.0  1.00
>       1.0  1.00
>       2.0  1.00
>       3.0  1.00
>       4.0  1.00
>       5.0  1.00
357c357
<   T_SUPER     373.0      ! Supernatant Temp.
---
>   T_SUPER     367.0      ! Supernatant Temp.
359,360c359,360
<   GAS_VOL     8.0        ! Volume of released gas, m^3
<   MASS_LIQ    34.E3      ! Mass of liquid in cluster
---
>   GAS_VOL     4.0        ! Volume of released gas, m^3
>   MASS_LIQ    30.E3     ! Mass of liquid in cluster
```

D.7 Input File Comparison: 8FF1-100.DAT vs. 1FF2-94.DAT

```
44,50c44,50
<       0.0  1.0
<       1.0  1.0
<       2.0  1.0
<       3.0  1.0
<       4.0  1.0
<       5.0  1.0
<       6.0  2.0
---
>       0.0  0.25
>       1.0  0.25
>       2.0  0.25
>       3.0  0.25
>       4.0  0.25
>       0.0  0.25
>       1.0  2.0
357c357
<   T_SUPER     373.0      ! Supernatant Temp.
---
>   T_SUPER     367.0      ! Supernatant Temp.
359,360c359,360
<   GAS_VOL     8.0        ! Volume of released gas, m^3
<   MASS_LIQ    34.E3      ! Mass of liquid in cluster
---
>   GAS_VOL     1.0        ! Volume of released gas, m^3
>   MASS_LIQ    7.5E3      ! Mass of liquid in cluster
```

APPENDIX E
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 E-2

Calc-Note Number FAI/00-52 Revision Number 0

Title Tank Bump Accident Potential and Consequences During Waste Retrieval

Project Nuclear Safety & Licensing Project No. or Shop Order CHG01C

Purpose: Extend the waste tank bump analysis to retrieval operations.

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
Boro Malinovic	Boro Malinovic	8/29/00
Michael Epstein	Michael Epstein	8/29/00
Martin Plys	Martin Plys	8/29/00

SECTION TO BE COMPLETED BY VERIFIER(S):

Verifier(s): Name (Print or Type)	Signature	Completion Date
Boro Malinovic	Boro Malinovic	8/29/00
Michael Epstein	Michael Epstein	8/29/00
Martin Plys	Martin Plys	8/29/00

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	Martin Plys	8/29/00

Section	Author	Reviewer
1	Martin G. Plys	Boro Malinovic
2	Boro Malinovic	Martin G. Plys
3	Boro Malinovic	Martin G. Plys
4	Michael Epstein	Boro Malinovic
5	Boro Malinovic	Martin G. Plys
6	Boro Malinovic	Michael Epstein
7	Boro Malinovic	Martin G. Plys
App. A	Michael Epstein	Boro Malinovic
App. B	Boro Malinovic	Martin G. Plys
App. C	Boro Malinovic	Martin G. Plys
App. D	Boro Malinovic	Martin G. Plys
App. E	N/A	N/A
App. F	N/A	N/A

CALC NOTE NUMBER FAI/00-52 REV. 0 PAGE E-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 F

CHECKLISTS FOR TECHNICAL PEER REVIEW

CHECKLIST FOR TECHNICAL PEER REVIEW

Document Reviewed: RPP-6654 draft, *Tank Bump Accident Potential and Consequences During Waste Retrieval*

Scope of Review: Gas retention and release behavior and modeling; tank thermal behavior and modeling

Yes	No	NA	
[x]	[ ]	[ ]	Previous reviews are complete and cover the analysis, up to the scope of this review, with no gaps.
[x]	[ ]	[ ]	Problem is completely defined.
[x]	[ ]	[ ]	Accident scenarios are developed in a clear and logical manner.
[x]	[ ]	[ ]	Necessary assumptions are explicitly stated and supported.
[ ]	[ ]	[x]	Computer codes and data files are documented.
[x]	[ ]	[ ]	Data used in calculations are explicitly stated.
[x]	[ ]	[ ]	Data were checked for consistency with original source information as applicable.
[ ]	[x]	[ ]	Mathematical derivations were checked including dimensional consistency of results. [most, but not all derivations were checked - CWS 8/22/00]
[x]	[ ]	[ ]	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]	Spreadsheet results and all hand calculations were verified.
[ ]	[ ]	[x]	Software input is correct and consistent with the document reviewed.
[ ]	[ ]	[x]	Software output is consistent with the input and with the results reported in the document reviewed.
[ ]	[ ]	[x]	Limits/criteria/guidelines applied to the analysis results are appropriate and referenced. Limits/criteria/guidelines were checked against references.
[ ]	[ ]	[x]	Safety margins are consistent with good engineering practices.
[x]	[ ]	[ ]	Conclusions are consistent with analytical results and applicable limits.
[x]	[ ]	[ ]	Results and conclusions address all points in the purpose.
[ ]	[ ]	[x]	The document was prepared in accordance with HNF-2353, Section 4.3, Attachment B, "Calculation Note Format and Preparation Instructions".

[x] [ ] [ ] Concurrence

Reviewer [signature] Date: 8/22/00

CHECKLIST FOR TECHNICAL PEER REVIEW

Document Reviewed: RPP-6654

Scope of Review: The review consisted participation in a series of several meeting in which FAI presented their work and a review of the subject report. Items identified as NA below were not included in this review.

Yes	No	NA	
[ ]	[ ]	[x]	Previous reviews are complete and cover the analysis, up to the scope of this review, with no gaps.
[x]	[ ]	[ ]	Problem is completely defined.
[x]	[ ]	[ ]	Accident scenarios are developed in a clear and logical manner.
[x]	[ ]	[ ]	Necessary assumptions are explicitly stated and supported.
[x]	[ ]	[ ]	Computer codes and data files are documented.
[x]	[ ]	[ ]	Data used in calculations are explicitly stated.
[ ]	[ ]	[x]	Data were checked for consistency with original source information as applicable.
[ ]	[ ]	[x]	Mathematical derivations were checked including dimensional consistency of results.
[x][1]	[ ]	[ ]	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]	Spreadsheet results and all hand calculations were verified.
[ ]	[ ]	[x]	Software input is correct and consistent with the document reviewed.
[ ]	[ ]	[x]	Software output is consistent with the input and with the results reported in the document reviewed.
[x]	[ ]	[ ]	Limits/criteria/guidelines applied to the analysis results are appropriate and referenced. Limits/criteria/guidelines were checked against references.
[ ]	[ ]	[x]	Safety margins are consistent with good engineering practices.
[x]	[ ]	[ ]	Conclusions are consistent with analytical results and applicable limits.
[x]	[ ]	[ ]	Results and conclusions address all points in the purpose.
[ ]	[ ]	[x]	The document was prepared in accordance with HNF-2353, Section 4.3, Attachment B, "Calculation Note Format and Preparation Instructions".
[x]	[ ]	[ ]	**Concurrence**

Reviewer (Donald M Ogden) *Date 8/28/00*

D.M. Ogden by 8/28/00
DS Bartl VIA
APPROVAL BY EMAIL

[1] Reviews conducted by John Marvin, Inc JMI for related document RPP-6213 identified some areas of concern relative to the applicability of the models. A consensus was not reached. The JMI RCR comments for RPP-6213 document the areas of disagreement. These issues also apply to RPP-6654.

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