DEFENSE NUCLEAR FACILITIES SAFETY BOARD

625 Indiana Avenue, NW, Suite 700 Washington, D.C. 20004-2901
(202) 694-7000

October 15, 2009

The Honorable Inés R. Triay
Assistant Secretary for Environmental Management
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585-0113

Dear Dr. Triay:

During the past several months, the staff of the Defense Nuclear Facilities Safety Board (Board) has reviewed the design, testing, and controls associated with the air pulse agitators for the Salt Waste Processing Facility (SWPF) at the Savannah River Site. The Board believes that, given appropriate controls and operational parameters, the air pulse agitators should fulfill the functions assumed in the safety basis. The selection of these controls and parameters must account for the limitations of the testing and modeling performed for these devices. Refinement or elimination of safety controls related to vessel agitation, currently under consideration by the SWPF project, needs to be based on conservative assumptions of the physical properties and the associated hydrogen retention and release mechanisms of the mixtures that may be present in SWPF process vessels. The enclosed report details the results of the staff's review and is provided for your information and use as appropriate.

Sincerely,

John E. Mansfield, Ph.D.
Vice Chairman

Enclosure

c: Mr. Jeffrey M. Allison
Mr. Mark B. Whitaker, Jr.

DEFENSE NUCLEAR FACILITIES SAFETY BOARD

Staff Issue Report

August 21, 2009

MEMORANDUM FOR: T. J. Dwyer, Technical Director

COPIES: Board Members

FROM: D. Eyler

SUBJECT: Air Pulse Agitator Controls, Salt Waste Processing Facility

This report documents a review by the staff of the Defense Nuclear Facilities Safety Board (Board) of the air pulse agitators for the Salt Waste Processing Facility (SWPF) at the Savannah River Site. Staff members D. Eyler and M. Duncan and outside expert L. Miller visited the site during the week of March 30, 2009, to review the design, testing, and safety-related controls associated with the air pulse agitators. This review included meetings with representatives from the Department of Energy-Savannah River Operations Office (DOE-SR) and Parsons, the engineering, procurement, and construction contractor. Subsequently, during April to July 2009, several discussions were held via telephone and on site regarding the need for safety controls related to the operation of the air pulse agitators.

Background. During a review performed in October 2008, the Board's staff noted that the waste acceptance criteria for SWPF did not specify particle size or hardness, and the staff raised questions about the potential for long-term accumulation of hydrogen-generating waste particles in low-flow areas. During subsequent discussions, the staff determined that the rheological characteristics of both the waste to be processed and the simulant used to test the design of the mixing system were not well documented, and that further exploration of the basis for the design and operation of this system was warranted.

Mixing System Description. SWPF will employ air pulse agitators to mix the contents of process vessels that are expected to accumulate solids. The purpose of the mixing is two-fold: (1) to limit the entrapment of hydrogen in the solids, and (2) to ensure effective sorption of actinides and strontium by monosodium titanate. The safety basis credits agitation with releasing hydrogen trapped in the solids that accumulate in process vessels. A Technical Safety Requirement in the Preliminary Documented Safety Analysis requires operation of the air pulse agitators when the contents of a process vessel could retain enough hydrogen that, if the hydrogen were released, the composite lower flammability limit would be exceeded in the vessel vapor space. Periods without agitation would be allowed based on projected hydrogen retention in the solids. Following certain accidents (i.e., a loss of power or a seismic event), sparging of the waste by forcing air through the air pulse agitators is credited with releasing trapped hydrogen.

The SWPF air pulse agitators consist of a central agitator surrounded by equally spaced circumferential agitators. During normal operation, the air pulse agitators mix process waste fluid by ejecting a portion of their internal volume downward from a pulse tube through a nozzle as they are pressurized with air; they then refill with waste as air pressure is lowered inside the tube to a slight vacuum. The air pulse agitators are cycled sequentially, resulting in intermittent operation of each agitator.

To sparge the waste, air flow can be provided using portable compressors connected to the air supply line for the air pulse agitators (a stub connection is provided for this purpose). The portion of the system from the stub connection to the pulse tubes inside the process vessels is functionally classified as safety-significant and will meet Performance Category (PC)-3 seismic requirements.

Design, Testing, and Analytical Issues. The review by the Board's staff identified several issues related to the assumptions, testing, and modeling supporting the design of the air pulse agitators.

Ambiguous Design Specifications—The rheological specifications for SWPF process fluid are unclear. The document that provides the design basis for the facility's process states that the process fluid is expected to behave as a Newtonian fluid below a total solids concentration of 5 weight percent, with some degree of non-Newtonian behavior possible above that concentration. However, the assumed design parameters are in the regime of non-Newtonian behavior, as explained in Attachment 1. Furthermore, the study that supported the development of the rheological specifications for SWPF process fluid indicated that non-Newtonian behavior can be expected. The testing and modeling conducted in support of the design fail to account for non-Newtonian behavior, as described below.

Insufficient Scaled Testing Rheological Measurements—Scaled simulant testing demonstrated that the simulant was eventually mixed by the air pulse agitators in both the normal and sparging modes of operation for selected configurations and operational parameters. However, the rheological properties of the simulants used in these tests were not adequately measured, as outlined in Attachment 2. Consequently, the limits of the validity of the testing cannot be determined, particularly with respect to the rheological characteristics assumed in the design.

Inadequacy of Air Pulse Agitator Design Models—The model of the performance of the air pulse agitators developed from scaled testing in support of the design neglected to account for several effects, including transient cavern formation, longer mixing times as a result of intermittent agitator operation, and the physical properties of the simulant used during testing and the waste to be processed. These shortcomings are outlined in Attachment 3. Furthermore, the model focused solely on normal operation of the air pulse agitators. No model was developed for the operation of the agitators in the sparging mode that accounts for the behavior of bubbles released from the air pulse agitator tubes into a non-Newtonian fluid and the effectiveness of these bubbles in releasing hydrogen trapped in the waste. Failure to account for transient behavior, physical properties of the process fluid, and the operational modes and characteristics of the air pulse agitators limits the utility of the model in predicting mixing performance under any conditions other than those that existed during testing.

Retention of Hydrogen in Process Vessels—SWPF has an open design item to determine through testing the significance of entrapment of hydrogen gas in the process mixture. If entrapment of hydrogen is determined to be insignificant, controls related to agitation could then be deleted. During the staff's on-site review, SWPF personnel stated that testing would not be performed; rather, this assessment will be made based on information regarding hydrogen retention and release from waste in the tank farms at the Savannah River Site. SWPF personnel further stated they are assuming that a "slight disturbance" of the solids in the process vessels would be sufficient to release any hydrogen trapped in the waste. This assumption was derived from two operational events in the tank farms. Based on this assumption, SWPF personnel believe that the air pulse agitators have a generous margin in their performance of the safety function to release trapped hydrogen.

The conclusion that only a "slight disturbance" would release hydrogen trapped in the solids is not justified by the two operational events cited by SWPF personnel, as discussed in Attachment 4. To support the hypothesis that SWPF waste will release its hydrogen when slightly disturbed, additional theory and supporting data need to be developed to show how hydrogen bubbles are captured in the waste, what amount of energy will release them, and why the hydrogen retention and release characteristics of the tank farm waste are similar to those of the fluid contained in SWPF process vessels. Furthermore, any assumption made about the ability of the air pulse agitators to release hydrogen in both the normal and sparging modes of operation needs to take into account the limitations of the models and testing discussed elsewhere in this report.

Subsequent to the staff's on-site review, SWPF conducted a preliminary analysis to demonstrate that release of hydrogen retained in the solids contained in the process vessels would not result in flammable concentrations, and therefore, safety controls related to mixing of the contents of process vessels would not be required. This analysis involved calculating the flammable gas concentration in the vapor space of the process vessels that would result from a release that takes place after process vessel ventilation, mixing, and cooling are lost for 10 days (e.g., following a seismic event).

- The analysis assumes that the hydrogen retained in the solids is released 10 days after mixing ceases. As discussed above, the retention and release behavior of hydrogen in accumulated solids in SWPF process vessels has not been characterized; consequently, assuming hydrogen release 10 days after mixing ceases cannot be shown to be conservative. Therefore, elimination of safety controls related to agitation based on this assumption cannot be justified.

- The analysis attempts to demonstrate that the temperature rise of the contents of the process vessels following a loss of cooling would be significantly less than previously calculated. Lower temperatures would result in less evaporation of the process solvent contained in the mixture, thereby reducing the solvent's contribution to the flammable gas content in the vapor space of the process vessels. The staff's review of this analysis revealed a number of questionable assumptions that lead to nonconservative results. Observations from the staff's review are discussed in Attachment 5.

Determination of Controls and Operational Parameters. Periods without agitation will be allowed based on projected hydrogen retention in the solids during normal facility operation. Sparging the waste is credited with releasing trapped hydrogen following certain accidents. For both modes of operation, the lack of rheological data from the testing, the limited range of configurations and operational parameters during the testing, and the inadequacy of the modeling make the development of operational requirements for the air pulse agitators problematic. Additionally, differences in particle size distribution between the simulant used during the testing and actual waste need to be considered in development of controls.

- The minimum number of air pulse agitators, bounds of operational parameters for the agitators (e.g., supply pressure), and permissible quiescent periods are not specified in the Technical Safety Requirement. For any condition not tested, an adequate physical model will be needed to develop operational parameters that ensure that the functional requirements are met. Determination of allowable quiescent periods will need to be based on conservative assumptions regarding retention of hydrogen within the process vessels.

- Since tank waste has considerably larger particles than the simulant used during testing, there may be greater accumulation of actual waste in low-flow areas, and longer times may be required to resuspend solids than were observed during testing. This effect requires consideration when the length of any quiescent period is being determined. Additionally, vessels may require inspection to determine whether solids are accumulating in low-flow areas.

- The parameters for sparging (e.g., minimum air flow rates, duration of sparge, simultaneous or sequential sparging) have not been determined. The scaled test of sparging that was performed showed that most solids were mixed over time when all perimeter pulse pots were simultaneously sparged with sufficient air pressure and flow. Sparging through only the central agitator was less effective. The lack of a physical model and test data pertaining to sequential sparging will make it difficult to select operational parameters for sparging.

Conclusion. The Board's staff concludes that the design of the air pulse agitators should enable gross mixing of solids from a settled state over a period of a few hours that would be sufficient to release trapped hydrogen. However, the following observations need to be considered in the development of controls and operational parameters for the facility:

- Because an adequate physical model has not been developed, mixing may be less effective than predicted in design calculations. The mixing performance assumed on the basis of the test results is valid to the extent that the simulants can be shown to have rheological properties similar to those of the waste to be processed by SWPF. The rheological characteristics of the simulants used during the scaled testing of the design of the air pulse agitators ought to be determined to validate the design's adequacy.

- Specific controls will be required to make certain that the rheological characteristics of the waste processed in SWPF are consistent with those that were assumed in the design and that existed during testing. Otherwise, the efficacy of the agitators cannot be ensured. These controls could potentially be implemented as limits on the total solids concentration in process vessels of concern. Any such controls will need to take into account the presence of larger particles in the actual waste stream and the potential for process upsets.

- Determination of the minimum number of air pulse agitators and the permissible length of time without agitation (i.e., specifics of the Technical Safety Requirement) needs to account for the limitations of the physical model and the testing performed, conservative assumptions regarding hydrogen retention in the process vessels, and differences in particle size distribution between the simulant and actual waste.

- Lacking an adequate physical model, operational parameters for sparging need to be based conservatively on the testing that was performed.

- Caution needs to be exercised in using the safety basis assumptions and operational information from the tank farms to determine safety basis requirements for agitation at SWPF. A comparison of the physical properties and hydrogen retention and release mechanisms in both the tank farms and SWPF process vessels ought to be performed to justify any elimination of the controls currently in the SWPF Preliminary Documented Safety Analysis based on analyses and experience associated with the tank farms.

- Calculation of flammable gas concentration in the vapor space of the process vessels in support of modification or elimination of controls ought to be based on conservative assumptions regarding hydrogen retention in the process fluids and modeling of the heat transfer from the process vessels.

Attachment 1

Rheological Specifications of the SWPF Design

The waste to be processed at SWPF is expected to be a mixture of supernate and sludge solids. Prior testing has demonstrated that some Savannah River Site waste slurries exhibit non-Newtonian fluid behavior at waste concentrations higher than a few weight percent. The waste to be processed at SWPF can be modeled as a type of non-Newtonian fluid known as a Bingham plastic, as outlined below:

Shear stress = yield stress + consistency × shear rate

Apparent viscosity = consistency + yield stress ÷ shear rate[1]

The document that provides the design basis for the facility's process states that the process fluid is expected to behave as a Newtonian fluid below a total solids concentration of 5 weight percent, with some degree of non-Newtonian behavior possible above that concentration. The document further states that since the facility does not normally operate above a total solids concentration of 5 weight percent, and the extent of non-Newtonian behavior of the process fluid is expected to be minimal, the fluid rheological characteristics are assumed to be Newtonian.[2]

The assumption that the process fluid exhibits minimal or no non-Newtonian behavior is flawed based on the rheological values prescribed in the design basis document. The rheological specifications for the design are based on an assumption of a maximum total solids concentration of 7 weight percent (which is approximately the concentration calculated in the process mass balance for some process vessels), and specify a maximum yield stress of 5 pascals (Pa) and a maximum viscosity (interpreted to be equivalent to consistency based on the source document for the rheological specifications) of 10 centipoise (cP).[3] As illustrated in Figure 1, a value of 5 Pa for yield stress results in a significant departure in the behavior of shear stress as a function of shear rate from that exhibited by a Newtonian fluid with a viscosity equivalent to the maximum consistency assumed for the process fluid in SWPF.

Previous measurements of the consistency of Savannah River Site waste have generally been less than 10 cP at concentrations of total solids greater than 10 weight percent. At this relatively low value, consistency is not the primary parameter controlling the performance of the air pulse agitators. Rather, yield stress is the key rheological parameter of interest. For the waste to be processed at SWPF, previous testing at the Savannah River Site revealed that a maximum value of 5 Pa for yield stress bounds most waste rheological samples when total solids concentrations do not exceed 7–8 weight percent. Should physical models for mixing be

---

[1] For a Newtonian fluid, yield stress = 0, consistency = viscosity, and shear stress = viscosity × shear rate.

[2] P-DB-J-00003, Revision 3, *Salt Waste Processing Facility Process Basis of Design*.

[3] The source document for the rheological specifications (Parsons memorandum 01-700-02041, Revision 1, *Review of Physical Property Data for SWPF Feed and MST/Sludge Streams*) notes that there is risk in characterizing the mixture of monosodium titanate and waste sludge as a Newtonian fluid since there is limited data available regarding the behavior of such mixtures, especially at solids concentrations above 5 weight percent.

developed for SWPF that account for the non-Newtonian behavior of the process fluid, assuming a yield stress of 5 Pa would be consistent with the previous testing, and therefore acceptable.

The design basis for the facility's process does not address the potential for a combination of waste sludge and monosodium titanate exhibiting thixotropic behavior after settling.[4] The potential for this behavior is described in a study of the rheological characteristics of mixtures of monosodium titanate and sludge simulant. Failure to consider the potential for thixotropic behavior in the design of the air pulse agitators could result in the inability to fully resuspend solids following periods without agitation.

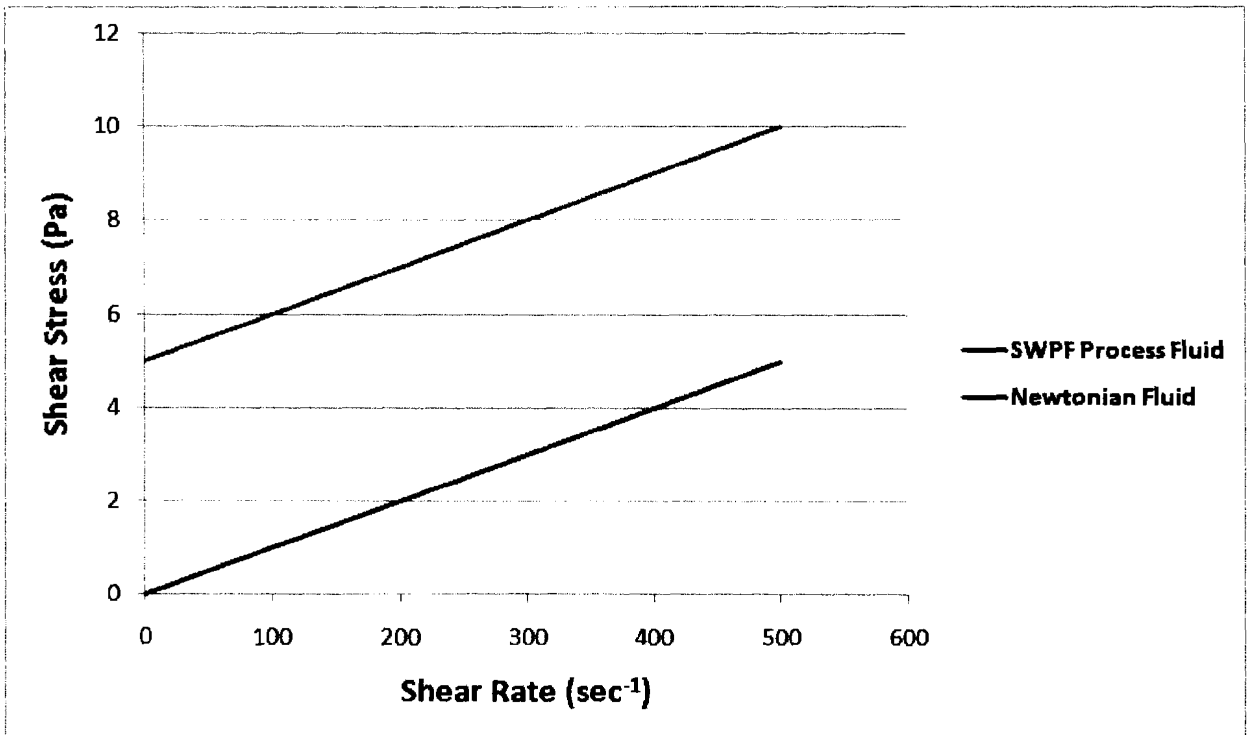

Figure 1

[4] Thixotropic behavior is a time-dependent phenomenon in which shear stress is reduced when a fluid experiences a strain rate. This behavior results in the fluid exhibiting the characteristic of yield strength, which is the amount of stress required to impart fluid motion. Once fluid motion commences, the amount of stress required to increase the strain rate will lower over time to the yield stress value.

Attachment 2

Scaled Testing of SWPF Air Pulse Agitators

Scaled simulant testing of the air pulse agitators was conducted at 1/3, 1/5, and 5/8 scales, using various nozzle configurations, diameters, velocities, nozzle drive times, air pressures, and vessel levels. Sparging was tested only as part of the 1/3 scale test. The rheological properties of the simulants used in these tests were not adequately measured:

- Rheological properties (yield stress and consistency) were not measured during the 1/3 scale testing. The simulant was a mixture of monosodium titanate and kaolin clay that had a total solids concentration of 7 weight percent.[1]

- The only rheological property measured during the 5/8 scale testing was viscosity (18 cP at an unspecified shear rate). Neither yield stress nor consistency was determined. The simulant consisted of a 5 weight percent total solids mixture of monosodium titanate, sludge simulant, and supernate simulant.

- Rheological properties for the 1/5 scale testing were not measured. An inference of viscosity (9 cP) was made from the 5/8 scale testing viscosity measurement, with an unexplained claim that Stokes' law provides a method for deriving the 1/5 scale viscosity.[2] The means by which this relationship was used to derive the 1/5 scale viscosity value was not explained in the test report.

A calculation of yield Reynolds number could provide a measure of the comparability of the various tests and the steady-state flow regimes that result from the design of the SWPF air pulse agitators.[3] However, since simulant yield stress was not measured during the scaled simulant testing, it is not possible to evaluate the applicability of the scaled simulant testing to the SWPF design by comparing yield Reynolds numbers. If the simulant used in the scaled testing has a yield stress comparable to the value assumed in the design, the steady-state flow regimes will be comparable since the fluid densities and nozzle velocities are comparable.

---

[1] Clay suspensions are often used to demonstrate the behavior of Bingham plastic fluids.

[2] Stokes' law relates fluid viscosity, particle density, fluid density, particle size, and particle settling velocity.

[3] Yield Reynolds number is a nondimensional value equal to (fluid density) × (nozzle velocity) ^{2} ÷ (yield stress).

Attachment 3

Design Model for SWPF Air Pulse Agitators

Typically, a pulse mixing jet in a non-Newtonian fluid will initially form a cavern of well-mixed turbulent flow adjacent to the jet exits beneath a region of unmixed fluid. This phenomenon occurs as a result of the dissipation of the fluid's ability to overcome the shear strength of the non-Newtonian material as the distance from the jet nozzle increases. During the scaled testing of the SWPF air pulse agitators, transient cavern formation can be inferred from measurements that show the time dependence of mixing within the vessels as a function of test parameters.

An additional consideration for the design of the air pulse agitators is the use of intermittent jets, which experimentation has shown to have cavern heights significantly lower than those of continuous jets with the same peak nozzle velocities. Reduction of cavern heights implies longer mixing times, and in the limit, incomplete mixing. Thus at SWPF, where jet flow from the nozzles is intermittent and variable, and nozzles are operated sequentially, calculations of the effectiveness of jet mixing need to take into account the transient nature of the jets.

Finally, the design needs to reflect the limitations of the simulant used in the testing. Knowledge of the rheological characteristics of the simulant used during the testing is limited. Additionally, it is known that tank waste at the Savannah River Site has considerably larger particles than those of the simulant used during testing. Consequently, greater flow than existed during testing will be required to put actual waste particles into suspension (this is true even if the process fluid exhibits Newtonian behavior).

The design of the air pulse agitators at SWPF is based on (1) a calculation of the "effective clearing radius," defined as the distance at which the shear stress from a steady jet impinging on a flat surface decays to the fluid yield stress; and (2) a dimensional parametric analysis to determine the sizing of the air pulse agitators, which is based on scaling up from the tank dimensions and nozzle velocities used during testing of the air pulse agitators. This approach neglects the above considerations and has the following deficiencies:

- The calculation of "effective clearing radius" concludes that the distance at which the fluid shear stress generated by the air pulse agitators will decay to a value below the yield stress is significantly greater than the radius of the vessel. The calculation assumes that the development of this shear stress at that radius is instantaneous. However, the mixing in the scaled testing did not occur instantaneously at a much smaller radius, indicating that the calculation does not adequately model the behavior observed. The results of scaled testing were not used to validate this calculation.

- The calculation of "effective clearing radius" assumes continuous jet operation instead of intermittent operation, which would be expected to result in weakened mixing.

- The dimensional parametric analysis for scaling up the design does not include a physical model based on the testing. Since the rheological parameters for the testing are unknown, the range of parameters over which the scaling analysis is valid cannot be determined. The fact that mixing did not occur for some lower nozzle velocities and nozzle diameter configurations during the scaled testing is not explained by the dimensional parametric analysis.

- The design does not take into account the possibility that simulant testing may not adequately represent the impact of the presence of larger waste particles on the effectiveness of mixing.

As a result of the shortcomings described above, the design model for the air pulse agitators is useful only to the extent that the conditions and parameters for operation of the air pulse agitators mirror those that existed during testing. Should SWPF personnel elect to develop a model that extends beyond the conditions that existed during testing, that model will need to be based on a physical modeling analysis that connects the scaled testing results to the full-scale design and be validated by scaled testing.

Attachment 4

Hydrogen Release Assumption

SWPF personnel are assuming that a "slight disturbance" of the solids in the process vessels would be sufficient to release any hydrogen trapped in the waste based on two operational events in the tank farms. In the first event, a slurry pump was run for 5 minutes in Tank 40; this evolution was followed by a release of hydrogen into the tank head space over a period of 8 hours. In the second event, a release of hydrogen was noted approximately 5 hours after a transfer of the waste in Tank 42 to another tank had begun. The above assumption is not supported by the documents cited by SWPF personnel that describe these events:

- For both events, the composition and rheological characteristics of the tank waste were not described or compared with those expected in SWPF process vessels after settling.

- For both events, the flow path and energy of the slurry movement within the tanks were not described. Additionally, the release of hydrogen occurred over an extended period during or after the events that are believed to have precipitated the release. Consequently, the mechanism by which the releases occurred cannot be conclusively determined.

An additional concern with the development of this assumption is it neglects to consider the effect of processing within the facility on the rheological characteristics of the waste (and therefore, hydrogen release).

Attachment 5

SWPF Personnel's Preliminary Analysis of Temperature Rise in Process Vessels

SWPF personnel conducted a preliminary analysis in an attempt to demonstrate that the temperature rise of the contents of the process vessels following a loss of cooling would be less than previously calculated. The staff's review of this preliminary analysis revealed several questionable assumptions that yield nonconservative results:

- The analysis assumes that the liquid in the tanks has no temperature profile, based on the reasoning that convective mixing of the fluid in the tanks will keep temperatures essentially uniform. Convective mixing to this degree is predicated on the process fluids exhibiting Newtonian behavior; this assumption is not valid for fluids with solids of the types and concentrations expected in the process vessels in question, as discussed elsewhere in this report. Non-Newtonian behavior of the process fluids would result in higher tank temperatures and headspace vapor pressures than those calculated by SWPF personnel.

- SWPF personnel's calculations show that the dominant heat transfer mechanism from the liquid in the vessels to the surrounding process cell is by conduction through the vessel support skirt into the concrete basemat. SWPF personnel model the vessel and all of its steel structural supports as being at a uniform temperature. The concrete basemat surface in contact with the vessel support is modeled as having the same temperature as the process vessel before a loss of cooling occurs. The basemat's lower surface that is in contact with the earth is modeled to be fixed at 65° F. This lower surface of the basemat is also modeled as having no heat transfer across it. This model raises three concerns:

  - The calculation of heat transfer by conduction from the skirt to the concrete basemat uses the value for thermal conductivity of stainless steel; considering that the temperature gradient as modeled exists only in the concrete, the value for thermal conductivity of concrete ought to be used instead. Use of the value for thermal conductivity of stainless steel results in overprediction of the amount of heat that would be transferred from the vessel skirt to the concrete by conduction.

  - The analysis does not provide a basis for assuming that the steel support skirt has a uniform temperature. Considering that the support skirts are several feet long, an appreciable temperature gradient along the skirt length could develop.

  - Modeling the lower surface of the basemat as adiabatic and as being at a constant temperature results in a temperature profile at the adiabatic boundary. This result does not reflect physical reality. Considering that the analysis assumes that the thickness of the basemat is much less than what actually exists in the facility design, it is unclear whether this modeling approach leads to nonconservative results.