John E. Mansfield, Vice Chairman
Joseph F. Bader
Larry W. Brown
Peter S. Winokur

DEFENSE NUCLEAR FACILITIES SAFETY BOARD

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

January 6, 2010

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:

The Defense Nuclear Facilities Safety Board (Board) recently reviewed the design and testing of the pulse jet mixing technology being deployed in the Pretreatment Facility at the Waste Treatment and Immobilization Plant (WTP) at the Hanford Site. The Board found deficiencies in the functional requirements for mixing and transport systems; specifically, the requirements do not adequately bound the properties of waste to be processed. As currently designed, the pulse jet mixers lack sufficient power to adequately mix and transport the most rapidly settling particles expected to be present in the Hanford waste inventory. This shortcoming results in three significant safety issues:

- Dense particles rich in plutonium and uranium are expected to settle preferentially on the bottom of tanks. These settled particles may form a sediment layer with sufficient fissile mass in a geometry such that a criticality accident is credible. Furthermore, if the vessels are not well mixed, samples drawn from the vessels to ensure that such an event does not occur will not be representative.

- The development of a sediment layer on the bottom of tanks may reduce the effectiveness of the pulse jet mixing systems below that assumed in the design. As a result, an initially thin sediment layer could grow sufficiently to retain significant quantities of flammable gas. The existence of a deep sediment layer would not be recognized by plant operators because there is no instrumentation that indicates the quantity of sediment. Gas release events from this sediment layer could exceed the lower flammability limit in the vessel headspace and result in an explosion.

- The presence of a deep sediment layer may also have a detrimental effect on the performance of bubbler systems used to measure the tank level and average density in the vessels. The tank level and average density are inputs to the calculation of the drive time of the pulse jet mixers, which is relied upon to prevent overblows. The cumulative effect of many overblows could result in the material failure of components internal to process vessels located in black cells.

The Department of Energy's Office of River Protection has suggested that these safety issues could be addressed by preventing rapidly settling particles from entering WTP using controls that would limit the particle size and density of the waste stream from the tank farm. This approach would necessitate deployment of new mixing, sampling, and separation systems. The result would be new design basis requirements for particle size and density for WTP that must be consistent with the actual performance of the newly deployed systems.

Therefore, pursuant to 42 U.S.C. § 2286b(d), the Board requests a report within 60 days of receipt of this letter that addresses the safety issues associated with inadequate pulse jet mixing detailed in the enclosed report. This response should describe an approach to (1) establish functional requirements and technical criteria for safe operation of the integrated WTP pulse jet mixing, transport, and sampling systems; (2) establish bounding design basis requirements for particle size and density based on actual feed qualification capabilities; (3) develop design correlations derived from testing of pulse jet mixers at realistic scales that demonstrate actual system performance can meet functional requirements with bounding design basis inputs; and (4) establish a criticality safety strategy that considers the practical performance of the mixing, transport, and sampling systems.

Sincerely,

John E. Mansfield, Ph.D.
Vice Chairman

Enclosure

c: Ms. Shirley J. Olinger
Mr. Mark B. Whitaker, Jr.

DEFENSE NUCLEAR FACILITIES SAFETY BOARD

Staff Issue Report

November 11, 2009

MEMORANDUM FOR: T. J. Dwyer, Technical Director

COPIES: Board Members

FROM: A. Poloski

SUBJECT: Inadequate Mixing, Waste Treatment and Immobilization Plant

This report documents a review by the staff of the Defense Nuclear Facilities Safety Board (Board) of the pulse jet mixing technology for the Waste Treatment and Immobilization Plant (WTP) at the Hanford Site. The Board's staff conducted a video teleconference on June 17, 2009, and an on-site review during the week of September 1, 2009. These discussions addressed design and testing related to the pulse jet mixing technology. Participants included representatives from the Department of Energy's Office of River Protection (DOE-ORP) and Bechtel National, Incorporated (BNI), and staff members A. Poloski, S. Stokes, S. Seprish, D. Campbell, and F. Dozier. This report focuses on several safety issues identified by the Board's staff related to inadequate mixing by the pulse jet mixing systems in WTP.

Background. Pulse jet mixers are the primary means used for mixing process fluids in the process vessels of the Pretreatment Facility at WTP. In addition to several process-related functions, these mixers perform the following safety-related functions: (1) preventing the accumulation of flammable gases generated within the waste and (2) permitting representative sampling to ensure conformance to criticality safety, waste acceptance, and safety basis requirements.

In early 2006, BNI commissioned a third-party review of the WTP design to assess its capability to meet program objectives. This review identified that the design of the pulse jet mixing systems was inadequate and would result in insufficient mixing and/or extended mixing times. The third-party review also found that the design basis for the pulse jet mixing systems did not adequately account for the effects of large particles in the Hanford waste stream and that there had been insufficient testing of the mixing system design.

To address these findings, BNI prepared an extensive issue response plan that included (1) tailored specification of performance requirements for pulse jet mixing in the various process vessels of concern, and (2) several experimental programs to ensure that the design meets the performance requirements. One reason for the difficulty in addressing the third-party review findings is that the mixing and transport systems were designed for average rather than bounding values of particle density in the Hanford waste inventory. As information on the actual performance of the pulse jet mixers in the vessels was experimentally developed, it became apparent that the performance of the mixing systems for waste with average particle density is marginal. Attachment 1 provides further details on the concerns regarding recent test results, which have been identified by the Board's staff. The presence of high density, more rapidly settling particles present in Hanford tank waste results in further degradation of the performance of the mixing systems. Fundamentally, the pulse jet mixers lack the required power to sufficiently suspend and transport a significant fraction of the most rapidly settling particles through the plant. This raises both system performance concerns and safety concerns. The safety concerns are described further below. DOE is considering adding internal components to the vessel design in the hope of redirecting the existing hydrodynamic power to problem areas in the vessel bottoms. This topic is discussed in further detail in Attachment 2.

Currently, BNI's closure plan is limited to a traditional approach involving scaled-down experiments. Closure criteria are based solely on the results of computational fluid dynamics simulation. Predicting full-scale performance accurately using simulations of solids suspension with pulse jet mixers in non-Newtonian fluids is extremely difficult and may not be possible. Gaining confidence in the simulation results will require an extensive verification and validation effort against previous experimental results, which is not planned by BNI. Additional information on verification and validation issues is presented in Attachment 3.

Safety Issues. Inadequate mixing could lead to an inability to suspend solids within WTP process vessels, which could result in the formation of a sediment layer. This sediment layer could accumulate, undetected by plant operators, during the many years planned for the facility's operation. This situation would worsen as sediment deposits in transfer piping were flushed back to the process vessels, as discussed further in Attachment 4. The formation of a sediment layer could prevent the complete transport of particles out of the vessel and could lead to further accumulation as more waste was processed. The formation of a substantial sediment layer could result in three potential safety issues, further discussed below: (1) inadvertent criticality; (2) retention of flammable gases trapped in the sediment layer; and (3) degradation in level-detection performance, which could result in an excessive number of pulse jet mixer overblows that could lead to structural failure of vessel components.

Potential for Inadvertent Criticality. Particles with high concentrations of fissile materials (e.g., uranium or plutonium) are expected to be dense, rapidly settling particles. Test results show that rapidly settling particles can settle preferentially and accumulate as sediment in tanks with underpowered pulse jet mixers. The result is the potential for inadvertent criticality in the WTP Pretreatment Facility. BNI deems criticality incredible in WTP based on assumptions regarding the ratio of plutonium to absorber metals and the ratio of fissile uranium to total uranium. These assumptions will be confirmed through sampling of the process slurry in the feed receipt vessel to a criticality safety requirement that incorporates "5 percent margin allowed for the sample non-representativeness." The criticality safety evaluation report identifies two open technical items in this strategy that are negatively affected by underpowered pulse jet mixers. These items are discussed below.

Gravity Segregation—The majority of plutonium in the Hanford tank farm inventory is believed to have been co-precipitated to the solid phase with other metals that will absorb neutrons. The ratio of the plutonium to co-precipitated metals is believed to always satisfy the criticality safety limits. However, plutonium-rich particles with low levels of neutron absorbers have been observed in micrographs of waste samples from tank SY-102. This tank is considered an anomaly as it contains plutonium-rich waste from Plutonium Finishing Plant (PFP) operations. However, a second tank, TX-118, has been identified as containing similar waste from PFP. The current WTP criticality safety evaluation report states, "Some HTF [Hanford tank farm] waste, such as that in the SY-102 tank, may not be disposed via WTP processing and is therefore outside of the CSER [criticality safety evaluation report] scope." However, DOE-ORP indicated that both SY-102 and TX-118 wastes will be processed in WTP. Sodium diuranate ($Na_2U_2O_7$) and related uranium minerals have been observed in significant quantities throughout the Hanford tank farm. These plutonium- and uranium-bearing solids could accumulate in the bottom of tanks with underpowered pulse jet mixed vessels and exceed the current criticality safety limits.

Nonrepresentative Sampling—If plutonium-bearing solids reside at or near the bottom of tanks with underpowered pulse jet mixers, sampling the vessel contents to an accuracy within the "5 percent margin allowed for the sample non-representativeness" is not feasible. In the scientific literature, MacTaggart and colleagues experimentally tested sampling techniques for a slurry with two primary particle sizes in a mechanically agitated vessel. Significant difficulty was noted in obtaining a representative sample. These difficulties were due to a number of factors, e.g., the variability of sample solids concentration with operating conditions, sample tube geometry, sample tube orientation with respect to the fluid flow, sample velocity, and particle size and concentration. Overall, they found, "It is practically impossible to obtain reliable measurements of local solids concentration by sample withdrawal from a mixed tank." [1]

The difficulty of sampling from slurry tanks was identified by the third-party review as another potential design issue. BNI responded with a testing program for the sampling systems. However, the focus of this testing was on the Low-Activity Waste and High-Level Waste facilities, where conventional mechanical agitation is employed. No testing of the sampling system for pulse jet mixed vessels is planned. DOE-ORP indicated that the only testing of sampling accuracy performed with pulse jet mixed vessels is discussed in a report developed for the previous WTP design authority, British Nuclear Fuels Limited (BNFL). That report presents the results of reverse flow diverter sampler tests from vessels with pulse jet mixer agitation. The test results indicate that the BNFL system was not capable of achieving sampling accuracies within the "5 percent margin allowed for the sample non-representativeness" discussed in the current WTP criticality safety evaluation report. However, the WTP sampler design has changed and currently does not employ reverse flow diverters. The feed to the current sampling system is withdrawn directly from the transport pipeline. Consequently, the project would benefit from an integrated program to test the adequacy of the pulse jet mixers and pipeline transport system with sampling systems.

[1] R. S. MacTaggart, H. A. Nasr-El-Din, and J. H. Masliyah, "Sample withdrawal from a slurry mixing tank," *Chemical Engineering Science*, Volume 48, Issue 5, 1993, pp 921–931.

Flammable Gas Control. The development of a sediment layer from rapidly settling particles could reduce the effectiveness of the pulse jet mixer systems relative to baseline performance expectations. This reduction in mixing effectiveness could accelerate the formation of the sediment layer during normal operations. During off-normal events, DOE-ORP is planning to cease pulse jet mixing in Newtonian vessels. Doing so will allow the formation of sediment layers during a design basis event. Sediment layers can retain significant quantities of flammable gas generated from radiolysis. This gas can be released suddenly through a spontaneous buoyant displacement gas release event or through mobilization of the sediment during restart operations, potentially exceeding the lower flammability limit in the vessel headspace. Considering that there is no instrumentation to determine the depth of an immobile sediment layer, plant operators will be unable to determine whether the sediment layer and retained flammable gas are being adequately managed. DOE-ORP has not considered the formation of sediment layers in vessels with pulse jet mixers as an important aspect of the management of flammable gases in vessel headspaces.

Overblow Control for Pulse Jet Mixers. The presence of a sediment layer could have a detrimental effect on the performance of bubbler systems used to measure the tank level and average density in the vessels. Recent experience with BNI's Pretreatment Engineering Platform has revealed significant errors in level and density measurements using the bubbler-based system. Immersing the system in a sediment layer is likely to increase such errors, because of the potential for bubbler plugging and errors introduced in the calculation of level and density from two layers of fluid with unknown heights and significantly different densities. Suspect height and density data can lead to operator corrections that can increase the potential for overblows.

The tank level and average density are inputs to the calculation of the drive time of the pulse jet mixers, which is relied upon to prevent overblow of the mixers. An excessive number of overblows can result in fatigue failure of internal components. BNI's fatigue analysis limits pulse jet mixer overblows to 1,000 events during the anticipated life cycle of the facility. Given the large number of estimated cumulative pulse jet mixer cycles (between 10^6 and 10^7 cycles in each Pretreatment Facility vessel during the life of the plant), the pulse jet mixer control system will be required to perform at an extremely high degree of reliability. This degree of reliability remains unproven for pulse jet mixer systems.

Considering that insufficient reliability can ultimately lead to failure of structural components in process vessels in the black cells of WTP, the pulse jet mixer control system needs to be tested thoroughly. However, BNI has not conducted nor does it plan to conduct any long-term test to demonstrate the reliability of a fully prototypic mixing system (i.e., testing using prototypic pulse jet mixers, bubbler-based pulse jet mixer controls, and a range of chemically/physically representative WTP simulants).

Feed Qualification. During discussions with the Board's staff, DOE-ORP representatives proposed that the above safety issues could be addressed by preventing rapidly settling particles from entering WTP through the establishment of controls for the feed from the tank farms. These controls would limit the particle size and density of the waste stream, thereby addressing issues concerning the performance of the pulse jet mixers. Implementation of these controls could involve deployment of new mixing, sampling, and separation systems. The result would be new design basis requirements for particle size and density for WTP that must be consistent with the actual performance of the newly deployed systems.

Conclusion. The staff's review identified several safety concerns regarding the inadequate performance of the WTP mixing and transport systems. Specifically, the inability to mix and transport the most rapidly settling particles in the Hanford waste inventory results in three significant safety concerns: (1) the potential for a credible inadvertent criticality scenario; (2) retention of flammable gases trapped in the sediment layer in an amount beyond that assumed in the safety basis; and (3) degradation in level-detection performance, which could result in an excessive number of pulse jet mixer overblows that could lead to the structural failure of vessel components. A strategy for achieving a safe process design should include the following elements: (1) functional requirements and technical criteria for safe operation of the integrated WTP pulse jet mixing, transport, and sampling systems; (2) bounding design basis requirements for particle size and density based on actual feed qualification capabilities; (3) a plan to develop design correlations, based on prototypic testing, demonstrating that actual system performance can meet functional requirements with bounding design basis inputs; and (4) a plan for establishing a criticality safety strategy that considers the practical performance of the mixing, transport, and sampling systems.

Attachment 1

Experimental Testing of Pulse Jet Mixing Technology

Based on the first phase of testing conducted to assess the mixing system design, Pacific Northwest National Laboratory presented correlations for cloud height (the height to which solids will be lifted by the mixer action) and critical suspension velocity (the minimum velocity needed to ensure that all solids are suspended off the vessel bottom, though not fully mixed). The correlations showed that several of the current WTP designs were incapable of suspending a significant fraction of Hanford tank waste off the vessel bottom. Additionally, the particles that are suspended off the bottom of the vessel are not uniformly distributed throughout each vessel, but are distributed based on settling velocity: slowly settling particles are farthest from the bottom, while rapidly settling particles are nearest to the bottom.

Concerns Identified by the Board's Staff. Preliminary results from the second phase of testing indicate that critical suspension velocities are higher than expected compared with the values predicted based on the first phase of testing. This result suggests that greater mixing energy may be required to suspend solids than was previously believed. This question requires resolution, possibly necessitating additional testing to fully assess the effectiveness of the mixing systems in suspending solids.

Testing has been conducted with noncohesive, granular simulants (e.g., sand and glass beads), which are adequate for developing a basic understanding of mixing performance. However, the testing conducted to date has not included cohesive simulants representative of WTP wastes. Simulants with bounding cohesive properties are likely to be more difficult to suspend and need to be investigated. Testing with cohesive simulants may also result in the development of new design correlations. DOE-ORP has cancelled an extensive phase of testing with cohesive simulants.

Attachment 2

Design Improvements for Pulse Jet Mixed Vessels

DOE-ORP has initiated a modest effort to expedite testing of potential design improvements using new concepts (e.g., using components designed to enhance mixing efficiency and modified vessel layouts). The design options for improving the performance of pulse jet mixing systems are limited by the overall facility design requirement of having no maintenance required in the process cells where the vessels of concern are located.

The intent of the design improvement effort is to rapidly test new concepts and provide ideas for further testing. Some of the new concepts derived from expedited testing that have shown promise include flow diversion devices, such as pyramidal hydraulic diverters and draft tubes. These new components, if successfully demonstrated, will be critical to system effectiveness and will be required to perform their function over the life of the facility

Concerns Identified by the Board's Staff. This approach has distinct limitations. For example, the expedited testing program did not implement the WTP project quality requirements (e.g., ANSI/ASME NQA-1, *Quality Assurance Requirements for Nuclear Facility Applications*) that are necessary to provide data suitable for use directly in plant design. DOE-ORP appears to recognize that a fully qualified follow-on testing program is required, but great care is needed to ensure that favorable results from the expedited testing program do not overly influence the follow-on testing; for example, results from the expedited testing must be independently validated before implementation in the WTP design. Given the anticipated erosive quality of WTP sludge, a robust erosion analysis is required to ensure that the additional components will perform properly over the anticipated life of the facility.

Attachment 3

Computational Fluid Dynamic Modeling of Pulse Jet Mixed Vessels

The focus of the third phase of the testing program to assess the mixing system design is on the mobilization of the sediment layer along the tank bottom rather than suspension of solids. This testing measures the zone of influence (the region directly beneath the pulse jet mixer nozzles that is cleared of stationary sediment). BNI intends to calibrate an existing computational fluid dynamic model to match the experimental results for the experimentally measured zone of influence. The model will then be used to predict the degree of sediment mobilization in the full-scale vessels. If the amount of mobilization predicted by the model is sufficient, the design of the pulse jet mixed vessels will be considered adequate.

Concerns Identified by the Board's Staff. Validation of the model using the experimental results for critical suspension velocity and cloud height is not planned. Consequently, the staff has low confidence in the model predictions relative to scaled experimental results. Vessels with mixing system designs currently considered adequate, based on a computational fluid dynamic model that has not yet been validated, need to be reassessed using available experimental correlation predictions.

Attachment 4

Integration of Mixing and Transport Systems in Pulse Jet Mixed Vessels

Mobilization of a sediment layer does not ensure that the particles will exit the vessel. If mobilized particles in the sediment layer cannot be entrained in the pump suction piping, the particles may begin to accumulate in vessels with underpowered pulse jet mixers during the life of the facility. Even if the particles are entrained in the pump suction piping, the transport velocity may be low enough to allow the formation of sediment deposits in the piping systems. The sediment is removed from the pipeline at the end of a transfer operation by means of flushing with high-velocity water.

Concerns Identified by the Board's Staff. A significant portion of the piping system is flushed back to the source vessel. This potentially results in no net removal of solids from the source vessels. Additionally, the correlation used to predict a Newtonian viscosity for slurries based on solids concentrations near the tank bottom has been shown to be inaccurate and biased low. The result could be pipe designs for the pump suction that do not provide sufficient net positive suction head available (NPSHA). In extreme situations, inadequate NPSHA can result in severe pump cavitation, limited pumping capability, and frequent pump replacement. Based on these pumping system issues, experimental testing of an integrated mixing and transport system (i.e., pulse jet mixing with centrifugal pump transport) should be considered.