DEFENSE NUCLEAR FACILITIES SAFETY BOARD

Washington, DC 20004-2901

January 20, 2016

Dr. Monica Regalbuto
Assistant Secretary for Environmental Management
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585-1000

Dear Dr. Regalbuto:

The enclosed Defense Nuclear Facilities Safety Board Technical Report is provided for your information and use. It discusses opportunities for improving the Department of Energy's (DOE) path forward to resolve the issues associated with the formation of sliding beds of solids and pipeline plugging at the Waste Treatment and Immobilization Plant. The Technical Report provides a number of actions that warrant consideration to address the hazards associated with process piping and pump failures.

Sincerely,

Joyce L. Connery

Joyce L. Connery
Chairman

Enclosure

c: Mr. Joe Olencz

DNFSB/TECH-40

PLUGGING AND WEAR OF PROCESS PIPING AT THE WASTE TREATMENT AND IMMOBILIZATION PLANT

Defense Nuclear Facilities Safety Board

Technical Report

January 2016

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PLUGGING AND WEAR OF PROCESS PIPING AT THE WASTE TREATMENT AND IMMOBILIZATION PLANT

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EXECUTIVE SUMMARY

This report identifies opportunities to improve the slurry transport system design at the Waste Treatment and Immobilization Plant (WTP). As currently designed, the slurry transport system for non-Newtonian slurries is susceptible to formation of a bed of sliding solids. The presence of sliding beds in the slurry transport system could lead to loss of primary confinement through spills and spray releases and/or catastrophic failure of transfer pumps. Also, energetic pump failures may result in damage to adjacent structures, systems, and components (SSCs).

After receiving the Department of Energy's (DOE) April 28, 2014, letter, members of the Defense Nuclear Facilities Safety Board's (Board) staff have been following DOE's efforts in resolving the issues associated with formation of sliding beds and pipeline plugging. The Board's staff agrees with DOE's findings that reconstitution of the safety basis, establishment of defensible erosion allowances to account for formation of sliding beds, and development of a defensible waste acceptance criteria (WAC) are valuable and integral parts of resolving these issues. However, the project's recent change to a criterion in Interface Control Document 19, which serves as the WAC for waste feed to WTP, indicates the intent to allow for formation of sliding beds of solids in slurry transport systems. This increases the potential for pipeline plugging. Further, a proposed target transport velocity of 6 feet per second for the non-Newtonian transfer line design strategy lacks the technical basis to establish it is adequate to avoid solids settling and, thus, to avoid pipeline plugging.

Consistent with the hierarchy of controls principles outlined in DOE directives, the Board's staff identified opportunities to improve DOE's path forward for resolution of the issues associated with formation of sliding beds and pipeline plugging. While some of these opportunities are similar to current DOE efforts, the underlying design and safety strategies differ. These opportunities are as follows:

1. Based on physical and rheological properties of the process slurries, establish design criteria and methodology to perform non-Newtonian slurry transfers within the WTP facilities in either a turbulent or homogeneous laminar flow regime throughout the plant whenever feasible.

2. For the parts of the WTP slurry transport system where it is not feasible to perform slurry transfers in either a turbulent or homogeneous laminar flow regime, establish design and safety requirements to adequately control the hazards associated with sliding beds and pipeline plugging.

    a. Based on the physical and rheological properties of process slurries, develop a design methodology to ensure that a settled bed of solids is always mobilized during transfers.

    b. Identify or develop means to detect and mitigate the onset of pipeline plugging in the WTP slurry transport system, and demonstrate their effectiveness.

c. Perform hazard and accident analyses to establish safety controls needed to prevent or mitigate process piping failures and pump explosions due to pipeline plugging and valve misalignments, including impacts to SSCs located near the centrifugal pumps at WTP facilities.

d. Determine the amount of erosion wear and erosion geometries expected for the WTP slurry transport system due to a bed of sliding solids. Using advanced stress analysis techniques, evaluate the effects of sliding bed erosion on the structural performance of the WTP slurry transport system. Based on this information, establish WTP allowances for non-uniform wear in non-Newtonian transport piping.

3. Demonstrate the ability to obtain representative samples of the solids and liquids in the WTP slurry transport system to ensure that slurry transfers meet the requirements imposed to prevent formation of sliding beds and pipeline plugging.

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1. INTRODUCTION

The radioactive slurries to be processed at the Waste Treatment and Immobilization Plant (WTP) at the Hanford Site vary widely in their rheological properties, from Newtonian to Herschel-Bulkley fluids, a type of non-Newtonian fluid with a semisolid structure. When designing a slurry pipeline, engineers typically establish a requirement for the minimum transport velocity, often called “critical velocity.” Critical velocity is defined as the minimum velocity demarcating turbulent flows from flows in which the solids contained in the stream form a stationary or sliding bed at the bottom of the pipe (i.e., the pipe invert) [1]. This crucial design parameter is needed to prevent the accumulation of a layer of solid particles in the process piping. The presence of sliding beds in the slurry transport system could lead to loss of primary confinement through spills and spray releases and/or catastrophic failure of transfer pumps.

Accumulated solids can obstruct process piping, leading to increased head losses and fluctuating flow conditions, and may plug the process piping completely [2]. Prolonged operation of a centrifugal pump with a plugged process line could cause the pump to explode [3]. In some cases, it can result in a boiling liquid, expanding vapor explosion (BLEVE) [4]. Historical cases of several centrifugal pump explosions show that failure of the cover plate fasteners is a common mode of pump failure [5], [6], [7], [8], [9], [10]. Even without brittle failure and fragmentation of the pump casing, the fasteners, cover plate, and pump itself may become highly energetic projectiles. Therefore, a pump explosion could result in the loss of primary confinement and damage to adjacent structures, systems, and components (SSCs). Although stainless steel pumps used for the WTP systems are less likely to fail catastrophically than similar carbon steel pumps, there is no firm technical basis to exclude the possibility of pump components becoming highly energetic projectiles as a result of pump failure. Centrifugal pump explosions are a recurring problem in the mining industry, where pumping slurries is a common activity. To address this safety issue, the Mine Safety and Health Administration issued Program Information Bulletin P11-32, detailing safety controls that should be used to prevent pump explosion accidents initiated by a pipeline plugging hazard [5]. Additionally, accumulated solids can form a sliding bed of particles in horizontal piping, potentially leading to increased wear from erosion and premature failure of the piping.

To reduce these hazards in the WTP slurry transport system, the project team would need to take one of the following three approaches: (1) impose a design requirement to perform slurry transfers above the critical velocity, i.e., in a turbulent flow regime—this would reduce the likelihood of the formation of sliding beds, pipeline plugging, and associated process piping and pump failures; (2) impose a design requirement to perform slurry transfers in a homogeneous laminar flow regime, which would also reduce the likelihood of these hazards—in this flow regime, closely packed solids limit solids segregation and settling [12]; or (3) if neither flow regime is feasible, then the hazards associated with sliding beds and pipeline plugging would need to be adequately controlled.

2. BACKGROUND

On October 25–26, 2011, members of the Defense Nuclear Facilities Safety Board's (Board) staff conducted an onsite review of the design of the slurry transport system in the Pretreatment (PT) Facility with representatives of the Department of Energy Office of River Protection (DOE-ORP) and the WTP contractor, Bechtel National, Incorporated (BNI). Based on the results of the onsite review, the Board's staff concluded that the design of the WTP slurry transport system had a substantial number of specific safety issues. To determine what actions DOE-ORP and BNI took toward resolving these safety issues following the initial review, the Board's staff held a follow-up teleconference on May 8, 2012. As a result of this effort, the Board communicated concerns about deficiencies in the safety analysis and the design of the WTP slurry transport system in a letter to the DOE Office of Environmental Management (DOE-EM) on August 8, 2012 [13]. In particular, the Board expressed concerns that the WTP safety analysis did not address the hazard of centrifugal pump explosions and the effect of erosion from a bed of sliding solids on pipeline wear and pipe strength.

On April 28, 2014, DOE-EM provided a response to the August 8, 2012, Board letter describing the path forward for resolution of issues associated with the formation of sliding beds and pipeline plugging in the WTP slurry transport system [14]. In this response, DOE-EM described a resolution strategy for these issues consisting of four elements: reconstituting the safety basis, reassessing the design strategy for non-Newtonian transfer lines, establishing a defensible basis to account for erosion by sliding beds, and establishing defensible Waste Acceptance Criteria (WAC).

The Board's staff reviewed the DOE-EM response and held preceding and follow-up discussions with WTP project personnel on April 23, 2014, and October 16, 2014, on progress in resolving concerns with the slurry transport system at the PT and High-Level Waste (HLW) Facilities. The Board's staff determined that DOE's path forward for resolution of these issues would benefit from several improvements discussed in detail in the sections below.

3. UNRESOLVED ISSUES

The Board’s unresolved issues are associated with the slurry transport system design and safety strategies, and the ability to obtain representative slurry samples to meet the WTP WAC. Specific issues and opportunities for improvement in resolving these issues are detailed below.

3.1. DESIGN STRATEGY

The Board’s August 8, 2012, letter communicated a concern that the WTP design strategy for non-Newtonian slurries did not preclude a bed of sliding solids from forming in the process piping during a transfer. At the time of the Board’s August 8, 2012, letter, the WTP design strategy relied on several design guides written by BNI to minimize the likelihood of pipeline plugging. BNI used these design guides to determine the critical velocity, pressure drop, and flush requirements for each process line. The design guides stated that flow in process lines that transfer Newtonian slurries should be turbulent and exceed an empirical prediction of critical velocity. These requirements prevented formation of a bed of sliding solids on the pipe invert. For process lines that transfer non-Newtonian slurries, the design guides relied on pressure drop and line slope requirements, and did not impose critical velocity or turbulent flow requirements. Therefore, the design strategy did not preclude formation of sliding beds of solids in non-Newtonian process lines.

In its April 28, 2014, response to the Board’s letter, DOE-EM agreed with the Board that the WTP design strategy for non-Newtonian slurries did not preclude a bed of sliding solids from forming in the process piping. To address pipeline plugging concerns, the WTP project team plans to incorporate a “target” transport velocity of six feet per second for non-Newtonian piping systems to avoid solids settling and thereby avoid pipeline plugging. However, in the April 28, 2014, DOE-EM response, the WTP project team also acknowledged that a transport velocity of six feet per second may not always be achievable for all non-Newtonian systems. In those cases, the project team plans to impose a requirement for flushing the pipes with water after a waste transfer.

The Board’s staff determined that the proposed target transport velocity of six feet per second does not have an adequate technical basis. As described in DOE’s response, the selected value for the transport velocity is based on a series of tests performed at the Pacific Northwest National Laboratory (PNNL) [15], [16], [17]. In these tests, the experimental flow loop design included a feedback control system that varied the pump speed to keep the average flow velocity/flow rate constant. This control system ensures that if particles settle on the pipe invert, reducing the unobstructed cross sectional area of the pipe, the local velocity would increase, leading to re-suspension of these particles. Hence, by ensuring that the flow rate was maintained, the likelihood of solids settling was minimized. However, the current WTP design does not include feedback control systems to maintain a constant average flow velocity. Also, the waste simulant used in the PNNL tests did not cover the full range of particle size, density, and rheological properties for non-Newtonian slurries expected at WTP. Therefore, a transport velocity of six feet per second may not be adequate to avoid pipeline plugging in non-Newtonian piping systems.

Furthermore, in September 2014, the WTP project team changed the critical velocity definition in Interface Control Document 19, which serves as the WAC for waste feed to WTP [18]. Previously, the project team defined critical velocity as the minimum flow velocity that demarcates "fully suspended" flows from flows in which solids contained in the stream form a stationary or sliding bed of solids at the pipe invert. This definition is consistent with critical velocity definitions used in academia and industry. The project team's current definition of critical velocity addresses only stationary beds. This change indicates the project team's intent to allow for formation of sliding beds of solids in the WTP slurry transport system, thus increasing the potential for pipeline plugging and erosion.

A stationary or sliding bed is a characteristic of a stratified laminar flow regime in a horizontal pipe, where a concentration of solids varies throughout the pipe cross section. An asymmetric concentration of solids leads to an asymmetric velocity profile (refer to Figure 1). For non-Newtonian slurries to flow, the applied stress must be greater than the slurry yield stress. The stress also determines the size of the sheared annulus and unsheared plug. The slurry viscosity is lowest at the pipe wall and rises to an infinite value at the pipe center, where the local shear stress is equal to the slurry yield stress. Therefore, flow in the pipe center region cannot occur and the slurry is transported as a rigid plug at the maximum velocity in the pipe [19]. Particles in the unsheared plug remain suspended, whereas in the sheared annulus, settling of particles may occur. As flow develops, the slurry viscosity decreases in the shear annulus leading to settling of particles. As particles settle toward the pipe invert, the velocity profile changes from uniform to non-uniform, shifting the location of the maximum velocity upward. In turn, the effective sheared annulus also moves upward. Solids that were in the unsheared plug are now in the sheared annulus where they are exposed to local shear and begin to settle and form a bed [12]. This is different from a homogeneous laminar flow regime, where the concentration of solids is constant throughout the pipe cross section (refer to Figure 2).[1]

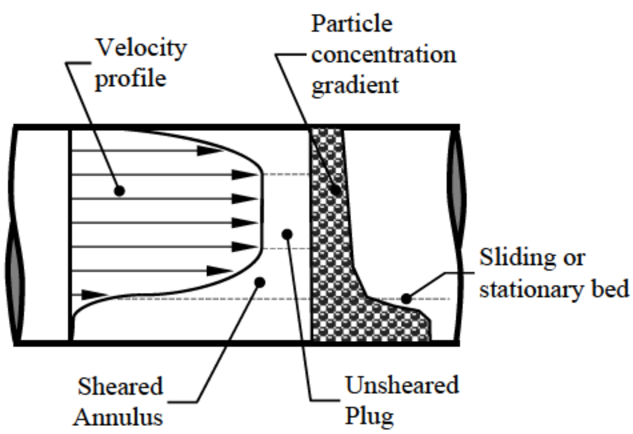

Figure 1. Stratified laminar flow

[1] Figures 1 and 2 were developed by the Board's staff.

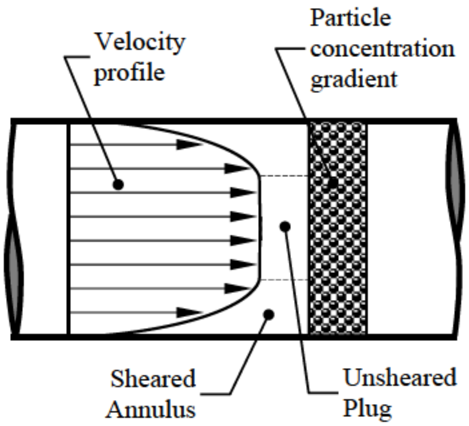

Figure 2. Homogeneous laminar flow

In stratified laminar flows, the solids settle on the pipe invert to their gravitationally driven solids concentration, i.e., the freely settled solids concentration. The higher the solids concentration and the closer it is to the freely settled solids concentration, the greater the slurry viscosity becomes as the particle interaction increases. If the solids concentration is high and close to the freely settled solids concentration, non-Newtonian slurries can be transferred in a homogeneous laminar flow regime. This is because closely-packed solids limit solids segregation. If the solids concentration is less than the freely settled solids concentration, segregation occurs and the solids form a settled bed on the pipe invert. Once solids form a settled bed, there is no mechanism within the laminar flow regime to re-suspend these solids. The solids remain stationary until either there is a pressure gradient large enough to make the bed slide or the flow regime becomes turbulent. For the flow regime to become turbulent, the transport velocity must be increased or the solids concentration must be decreased to reduce the viscosity, thereby reducing the critical velocity [12].

The Board's staff concluded that the updated WTP design strategy for non-Newtonian slurries does not preclude a bed of sliding solids from forming in the process piping. As a result, this design strategy does not minimize the likelihood of pipeline plugging. To reduce the pipeline plugging hazard, the WTP project team would need to impose a design requirement to perform slurry transfers in a turbulent flow regime. To achieve this requirement, the project team would need to increase the transport velocity for non-Newtonian slurry transfers or to modify properties of the waste to reduce the critical velocity. Alternatively, the WTP project team may choose to perform slurry transfers in a homogeneous laminar flow regime. To achieve this, the project team would need to impose a requirement on the solids concentration for non-Newtonian slurries to be at or above the freely-settled solids concentration and identify a minimum pressure gradient sufficient for this flow regime.

If the WTP project team finds that the requirements to perform slurry transfers in either a turbulent or homogeneous laminar flow regime are not feasible, then the project team would need to impose pressure gradient requirements sufficient to move a settled bed of solids. In this case, the WTP project team would also need to adequately control the hazards associated with sliding beds and pipeline plugging.

To mitigate solids settling and thereby to avoid plugging of non-Newtonian process piping, the WTP project team plans to perform routine post-transfer flushing. Post-transfer flushing may be used to mitigate settling of solid particles when non-Newtonian slurries transport cannot be achieved in turbulent or homogeneous laminar flow regimes. However, in this case, several requirements must be imposed on the design of the slurry transport system. These requirements include the ability to monitor a rise in pump discharge pressure over time to identify the onset of settling, ensure adequate flushing capacity so that the solids can be flushed in a turbulent flow regime, and provide for sufficient pump power to generate additional head and flow requirements for flushing [12].

3.2. SAFETY STRATEGY, PUMP EXPLOSIONS

In its August 8, 2012, letter, the Board communicated a concern that the safety analysis for the PT Facility [20] did not address the hazard of centrifugal pump explosions. Specifically, the WTP project team did not perform accident analyses for energetic releases due to pump explosions and fragmentation that would lead to a loss of primary confinement. This accident can occur when a centrifugal pump is operated for a prolonged period while isolated. Under certain operating conditions the flow in the slurry pipeline may reduce to low or zero flowrates. Slurry particles may then settle out and block the slurry intake and discharge branches [3]. For example, the loss of flow initiated by pipeline plugging in the slurry intake branch (due to either chemical plugging or settling of solid particles) or valve misalignment may lead to a secondary blockage in the slurry discharge branch. Pump isolation causes the contained solution to heat up and vaporize, resulting in pump over-pressurization. This accident is more energetic than the spills and spray releases associated with pipeline breaches considered in the safety analysis and poses additional hazards from fragmentation to adjacent SSCs.

During the Board's staff's onsite review in October 2011, WTP project personnel agreed with the team's observations that the safety analysis did not address the hazard of centrifugal pump explosions. The project personnel committed to complete a project issue evaluation report and address this potential hazard in the planned updates to the hazard analysis for the PT Facility. During the May 8, 2012, follow-up discussion, the Board's staff determined that the WTP contractor had extended this evaluation to all WTP facilities [21].

In its April 28, 2014, response, DOE-EM agreed with the Board that the safety analysis did not address the hazards of centrifugal pump explosion and fragmentation that would lead to a loss of primary confinement. DOE committed to reconstitute the safety basis and perform a hazard analysis that will encompass potential causes and consequences of pipeline plugging and pump failure under normal, off-normal, and accident conditions. However, because the WTP pumps are constructed of highly ductile materials, DOE does not agree that a pump failure would create energetic fragments [22].

In August 2013, the American Institute of Chemical Engineers issued a Process Safety Beacon on centrifugal pump explosions [4]. The beacon described that when a centrifugal pump operates while isolated, the pump energy is converted to heat. The heated fluid expands and generates hydrostatic pressures that could cause the pump seal to fail or the pump casing to rupture. This type of failure can cause significant damage due to built-up energy. The beacon also warns that if the fluid temperature exceeds the boiling point before the pump fails, superheated fluid is released, which rapidly boils and expands. This generates an energetic explosion called a BLEVE. The severity and damage from the BLEVE is similar to a steam boiler explosion. The Board's staff reviewed historical cases of several centrifugal pump explosions and determined that failure of the cover plate fasteners is a common mode of failure [5], [6], [7], [8], [9], [10]. Even without brittle failure and fragmentation of the pump casing, the fasteners, cover plate, and pump itself may become highly energetic projectiles. DOE has not provided a firm technical basis to exclude the possibility of the pump housing and internal and external pump components becoming highly energetic projectiles in the event of catastrophic failure of the pump housing. These projectiles may pose additional hazards to SSCs located near the centrifugal pumps at WTP.

Further, on April 23, 2014, the Board's staff held a discussion with WTP project personnel to assess the progress that DOE and BNI made in resolving the Board's concerns associated with pipeline plugging. During this discussion, the WTP project personnel stated that the hydrogen explosion events in the HLW Facility bound a postulated pump explosion accident in the HLW process vessels and that a similar approach may be used to address this hazard in the PT Facility. The Board's staff note that the initiators for a pump explosion (e.g., pipeline plugging or valve misalignment) will likely require different nuclear safety controls than those intended for a hydrogen explosion event. The WTP project personnel also stated that because the centrifugal pumps are located inside the process vessels in direct contact with the waste and without intervening isolation valves, these pumps will not heat up and vaporize contained solutions and, therefore, will not experience over-pressurization. The Board's staff notes that the WTP project team did not support these assertions with technically adequate information or hazard and accident evaluations.

3.3. SAFETY STRATEGY, EROSION FROM SLIDING BEDS

In its August 8, 2012, letter, the Board communicated a concern that the safety analysis for the PT Facility did not address the effect of erosion from a bed of sliding solids on pipeline wear, including the resulting reduction in pipe strength. The WTP wear allowances for piping containing non-Newtonian slurries were incomplete because the WTP project team did not evaluate the extent of erosion due to a sliding bed of solids.

In its April 28, 2014, response, DOE-EM acknowledged that sliding beds could be present for short time intervals, i.e., during initial startup of pumps, near the end of a waste transfer, or when the target transport velocity cannot be achieved due to competing design requirements. DOE-EM committed to perform a "literature search based evaluation" to determine whether sliding-bed erosion is more aggressive than turbulent erosion in small-diameter pipelines. If the evaluation determines that sliding-bed erosion is more aggressive, the WTP contractor will perform testing to determine the amount of erosion expected. In response to DOE-ORP request, Savannah River National Laboratory (SRNL) personnel performed an assessment of PT Facility process pipelines and transfer lines to the HLW Facility [23]. The SRNL personnel concluded that "there is insufficient data available to determine if sliding beds will cause more erosion compared to turbulent flow and the mechanism of sliding bed erosion is different than that experienced in turbulent flow."

As discussed above, the updated WTP design strategy for non-Newtonian slurries does not preclude a bed of sliding solids from forming in the process piping. The presence of a sliding bed of particles in non-Newtonian process lines will lead to increased erosion rates of the pipe invert and result in uneven pipe wear, with reduced pipe wall thickness at the invert location [24], [25], [26]. This asymmetric wear pattern is different from the uniform pipe wear expected for turbulent erosion. The pipe wall thinning caused by sliding bed erosion reduces the strength of the pipe more than uniform wear. This is because erosion of the pipe invert can create high stress concentrations at that location. Operating at maximum allowable pressure established for an eroded pipe per methodologies outlined in ASME B31.3 [27] may result in stresses that exceed the allowable stress if the wear is asymmetric. Stress analysis using an advanced technique, such as finite element modeling or other nonlinear techniques, would provide important information on the effects of pipe erosion on the structural performance of the slurry transport system. To perform such an analysis, the WTP project team would need to establish the amount of erosion and erosion geometries expected for the WTP slurry transport system due to sliding solids beds.

3.4. SAMPLING TO MEET WASTE ACCEPTANCE CRITERIA

In its August 8, 2012, letter, the Board communicated concerns associated with the rheological and physical properties of the radioactive slurries to be processed in the WTP slurry transport system. Specifically, the Board emphasized the importance of using bounding waste properties for developing values for the critical velocity and pipeline flush requirements. The WTP design did not provide a capability to obtain representative waste samples to ensure that WTP waste feed conforms to the WAC [28]. Also, WTP process lines thought to contain Newtonian slurries could instead contain non-Newtonian slurries during a pump transfer because of elevated concentrations of particles near the bottom of underpowered pulse-jet-mixed vessels [29].

In its April 28, 2014, response, DOE-EM agreed with the Board's concerns and committed to develop means for providing the capability to characterize waste to ensure it conforms to the WAC. Also, DOE committed to develop safety control strategies for preventing or mitigating the abnormal condition of non-Newtonian slurry being present in a line intended for transferring Newtonian slurries [14].

Currently, the WTP project team is working on resolving mixing and sampling issues and developing a safety controls strategy for the PT Facility [30]. The WTP project team plans on using the Isolok sampler to characterize the waste feed and for process sampling at WTP. Based on the most recent test results from the Remote Sampler Demonstration testing, the Isolok sampler, as currently designed, produces samples that contain significantly more solids than the reference samples for particles larger than 75 μm. Therefore, the Isolok sampler has a positive bias for larger particles and is not capable of obtaining a representative sample [31]. The ability to obtain representative samples is a prerequisite for meeting safety-related aspects of the WAC [32]. Representative slurry samples also are needed for controlling waste properties throughout WTP processes. Samples are necessary to ensure that the WTP slurry transfers meet requirements (e.g., critical velocity, flow regime) imposed to reduce the likelihood of formation of sliding beds, pipeline plugging, and associated process piping and pump failures.

4. CONCLUSIONS

Based on the review of DOE-EM's April 28, 2014, response and follow-up discussions with WTP project personnel, the Board's staff determined that the path forward for resolving the issues associated with the formation of sliding beds and pipeline plugging in the WTP slurry transport system would benefit from several improvements.

The updated WTP design strategy for non-Newtonian slurries does not preclude a bed of sliding solids from forming in the process piping. As a result, this design strategy does not minimize the likelihood of pipeline plugging. To reduce the pipeline plugging hazard, the WTP project team would need to impose a design requirement to perform slurry transfers in a turbulent flow regime. To achieve this requirement, the project team would need to increase the transport velocity for non-Newtonian slurries transfers or modify rheological properties of the waste. Alternatively, the WTP project team may choose to perform slurry transfers in a homogeneous laminar flow regime. To achieve this, the project team would need to impose a requirement on the solids concentration for non-Newtonian slurries to be at or above the freely-settled solids concentration and identify a minimum pressure gradient sufficient for this flow regime.

If the WTP project team finds that the requirements to perform slurry transfers in either a turbulent or homogeneous laminar flow regime are not feasible, the project team would need to impose pressure gradient requirements sufficient to move a settled bed of solids. In this case, the WTP project team would also need to adequately control the hazards associated with sliding beds and pipeline plugging.

Further, the WTP project team needs to address the possibility that internal and external pump components can become highly energetic projectiles in the event of an energetic failure of the pump housing. These projectiles may pose additional hazards to SSCs located near the centrifugal pumps at WTP.

The Board's staff consider that stress analysis using finite element modeling or other nonlinear techniques would provide important information on the effects of pipe erosion on the structural performance of the slurry transport system. To perform this type of analysis, the WTP project team would need to establish the amount of erosion wear and erosion geometries expected for the WTP slurry transport system due to a bed of sliding solids.

Representative samples are needed for controlling waste properties throughout WTP processes. Samples are necessary to ensure that the WTP slurry transfers meet requirements (e.g., critical velocity, flow regime) imposed to reduce the likelihood of formation of sliding beds, pipeline plugging, and associated process piping and pump failures.

5. SUGGESTED IMPROVEMENTS

Consistent with the hierarchy of controls principles outlined in DOE directives, the Board's staff consider that the following actions may improve DOE's path forward for resolving the issues associated with the formation of sliding beds and pipeline plugging in the WTP slurry transport system:

1. Based on physical and rheological properties of the process slurries, establish a design criteria and methodology to perform non-Newtonian slurry transfers within the WTP facilities in either a turbulent or homogeneous laminar flow regime throughout the plant whenever feasible.

2. For the parts of the WTP slurry transport system where it is not feasible to perform slurry transfers in either a turbulent or homogeneous laminar flow regime, establish design and safety requirements to adequately control the hazards associated with sliding beds and pipeline plugging.

   a. Based on the physical and rheological properties of process slurries, develop a design methodology to ensure that a settled bed of solids is always mobilized during transfers.

   b. Identify or develop means to detect and mitigate the onset of pipeline plugging in the WTP slurry transport system and demonstrate their effectiveness.

   c. Perform hazard and accident analyses to establish safety controls needed to prevent or mitigate process piping failures and pump explosions due to pipeline plugging and valve misalignments, including impacts to SSCs located near the centrifugal pumps at WTP facilities.

   d. Determine the amount of erosion wear and erosion geometries expected for the WTP slurry transport system due to a bed of sliding solids. Using advanced stress analysis techniques, evaluate the effects of sliding bed erosion on the structural performance of the WTP slurry transport system. Based on this information, establish WTP allowances for non-uniform wear in non-Newtonian transport piping.

3. Demonstrate the ability to obtain representative samples of the solids and liquids in the WTP slurry transport system to ensure that slurry transfers meet the requirements imposed to prevent formation of sliding beds and pipeline plugging.

Several of these improvements require reassessing the design of process piping for non-Newtonian slurry transfers, while others require reconstituting the safety bases for the PT and HLW Facilities. The WTP project already plans to reconstitute the safety bases for the PT and HLW Facilities, and to redesign portions of the PT Facility for processing non-Newtonian slurries to accommodate a Single High Solid Vessel design. Also, the WTP project is currently conducting testing to resolve pulse jet mixing and sampling issues, as well as issues associated with erosion and corrosion design basis.

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