DEFENSE NUCLEAR FACILITIES SAFETY BOARD

Washington, DC 20004-2901

January 20, 2012

Mr. David Huizenga
Acting Assistant Secretary for Environmental Management
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585-0113

Dear Mr. Huizenga:

During the past nine months, the staff of the Defense Nuclear Facilities Safety Board (Board) has been evaluating wear allowances specified by Bechtel National, Incorporated (BNI) for the design of piping, process vessels, and pulse jet mixers (PJMs) for the Waste Treatment and Immobilization Plant (WTP). As the result of our effort, the Board is concerned that the project team has not shown that the design wear allowances for vessels, piping, and PJM nozzles are adequate to ensure that components located in the black cells will reliably function for the 40-year design life of the facility.

WTP's system piping and vessels perform the safety-significant function of confining radioactive material. PJMs support other safety functions, including waste mixing and hydrogen control. Much of the piping and many of the vessels are contained in black cells. The design of the black cells prevents observation and tracking of wear (erosion and corrosion) on components and does not provide ready (or easy) access for the repair or replacement of failed components. Consequently, project requirements state that the design of components must include wear allowances that support maintenance-free operation of the piping and vessels in the black cells for the 40-year design life of the facility. Inadequate wear allowances for piping, vessels, and PJM nozzles could result in component failures. Component failure due to wear jeopardizes the above safety functions and could stop waste processing for indefinite periods resulting in significant extensions in the time required to accomplish the facility mission. The existing design margins offer little or no flexibility for future operations or the opportunity to extend the life of the plant, if required.

The Board's staff identified the following specific issues:

- The design wear rates were derived mainly from information found in the literature. That information comes from experimental studies performed using slurries and conditions that are not representative of WTP processes. Consequently, the WTP project team used a set of assumptions to extrapolate or scale the relationships derived from the studies so they could be applied to the piping and vessels in WTP. Many of the assumptions have not been adequately validated.

- The WTP project team has stated that its wear models are conservative but has not analytically substantiated the claimed conservatism. They have neither quantified the conservatism nor applied any safety factors to account for uncertainty in the design inputs. Additionally, the wear allowances provided in the design of some vessels and PJMs are nonconservative.

- The WTP project team performed experimental testing to close the External Flowsheet Review Team's Issue M2, *Mixing Vessel Erosion*, and validate the wear model. However, the scope of that testing was limited and the results were flawed. Specifically the data collected lack a discernable trend and display significant scatter and physically unrealistic results. The safety basis design curve does not bound data collected by the wear testing. Consequently, the experimental testing does not validate the relationships and assumptions used to establish the design wear rates.

- The WTP project team has not established controls for key assumptions and operating parameters, or demonstrated any other means to protect the safety basis assumptions. The controls are required in order to establish a credible and reliable means of estimating in-service wear for components located in black cells. The project's Safety Requirements Document requires wear monitoring and wear monitoring is necessary to protect the Safety Basis.

The enclosed report provides additional detail in support of the above findings.

The Board is aware that DOE is developing a course of action to address wear design issues at the WTP. The information contained in the attached report is provided for your use in the development of that plan. The Board will continue to follow the results of those efforts. Therefore pursuant to 42 U.S.C. § 2286b(d), the Board requests a report and a briefing within 45 days of receipt of this letter identifying the approach to be used to resolve the above issues and provide confidence that WTP will operate safely and reliably for its 40-year mission life.

Sincerely,

Jessie Roberson

for Peter S. Winokur, Ph.D.
Chairman

Enclosure

c: Mr. Scott L. Samuelson
Mr. Dale E. Knutson
Mrs. Mari-Jo Campagnone

DEFENSE NUCLEAR FACILITIES SAFETY BOARD

Staff Issue Report

October 12, 2011

MEMORANDUM FOR: T. J. Dwyer, Technical Director

COPIES: Board Members

FROM: P. Fox, J. MacSleyne, and R. Rosen

SUBJECT: Erosion/Corrosion Wear Allowances, Waste Treatment and Immobilization Plant

This report documents a review by the staff of the Defense Nuclear Facilities Safety Board (Board) of wear (erosion and corrosion) allowances used for the design of piping, vessels, and pulse jet mixer (PJM) nozzles at the Waste Treatment and Immobilization Plant (WTP).

Background. WTP's system piping and vessels perform the safety-significant function of confining radioactive material. PJMs support other safety functions, including waste mixing and hydrogen control. Much of the piping and many of the vessels are contained in black cells. The design of the black cells prevents observation and tracking of wear (erosion and corrosion) on components and does not provide ready (or easy) access for the repair or replacement of failed components. Consequently, project requirements state that the design of components must include wear allowances that support maintenance-free operation of the piping and vessels in the black cells for the 40-year design life of the facility. Inadequate wear allowances for piping, vessels, and PJM nozzles could result in component failures. Component failure due to wear jeopardizes the above safety functions and could stop waste processing for indefinite periods resulting in significant extensions in the time required to accomplish the facility mission. The existing design margins offer little or no flexibility for future operations or the opportunity to extend the life of the plant, if required.

Review Findings. The staff determined that the design approach used by the WTP project team for determining wear allowances has weaknesses. Specifically:

- The design wear rates were derived mainly from information found in the literature. That information comes from experimental studies performed using slurries and conditions that are not representative of WTP processes. Consequently, the WTP project team uses a set of assumptions to extrapolate or scale the relationships derived from the studies so they could be applied to the piping and vessels in WTP. Many of the assumptions have not been adequately validated.

- The WTP project team has stated that its wear models are conservative but has not analytically substantiated the claimed conservatism. They have neither quantified the conservatism nor applied any safety factors to account for uncertainty in the design inputs. Additionally, the wear allowances provided in the design of some vessels and PJMs are nonconservative.

- The WTP project team performed experimental testing to close the External Flowsheet Review Team's Issue M2, *Mixing Vessel Erosion*, and validate the wear model. However, the scope of that testing was limited and the results were flawed. Specifically the data collected lack a discernable trend and display significant scatter and physically unrealistic results. The safety basis design curve does not bound data collected by the wear testing. Consequently, the experimental testing does not validate the relationships and assumptions used to establish the design wear rates.

- The WTP project team has not established controls for key assumptions and operating parameters, or demonstrated any other means to protect the safety basis assumptions. The controls are required in order to establish a credible and reliable means of estimating in-service wear for components located in black cells. The project's Safety Requirements Document requires wear monitoring and wear monitoring is necessary to protect the Safety Basis.

Basis for Design Wear Rates. The project team estimated wear rates for piping and vessels using a relationship that is a function of slurry velocity, mean particle size, and solids concentration. The relationship contains several parameters (exponents and weighting factors) that vary depending on the material used to fabricate the components and on slurry and environmental conditions. To apply the relationship to a specific system, a user must determine the values for the parameters. The project team applied an approach that involved identifying, extrapolating, and scaling data from reference slurries found in the literature to define the parameters instead of obtaining experimental data using actual tank waste or a conservative simulant. This approach has several weaknesses, described below.

Source Information Does Not Match WTP Conditions—The project team applied data from sources that do not match WTP conditions. Application of the data required the project team to extrapolate and scale the data. The staff believes that without adequate validation it is questionable to extrapolate and scale data from multiple studies where many of the experimental parameters are different, the process knowledge is poor, and variables lack independence. Consequently, this approach may have resulted in faulty or nonconservative design relationships. For example, the project team used experimental studies[1,2] performed with carbon steel wear samples and flow velocities above 4 meters per second (m/s) to establish a wear rate for low-velocity flow (less than 4 m/s in the type 316L stainless steel pipes used in WTP). To apply the

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[1] Zhou, S., M. M. Stack, and R. C. Newman, "Electrochemical studies of anodic dissolution of mild steel in a carbonate-bicarbonate buffer under erosion-corrosion conditions," *Corrosion Science* 38, 7 (1996).
[2] Zhou, S., M. M. Stack, and R. C. Newman, "Characterization of synergistic effects between erosion and corrosion in an aqueous environment using electrochemical techniques," *Corrosion* 52, 12 (1996).

results to WTP conditions, the project team extrapolated the data to obtain estimated wear rates for lower velocities and applied a scaling factor to adjust for material type to establish the parameter values for design wear relationships. The extrapolations and scaling are required to account for differences between WTP conditions and the conditions used to obtain the data in the literature. Such extensive use of extrapolations and scaling is questionable, particularly when data that better represents WTP conditions are available.

The staff reviewed another study[3] by the same research group that obtains wear rates using stainless steel samples and flow at velocities of 4 m/s and below. These conditions are more similar to WTP conditions. Comparison of the project team's results with the wear rates determined in the alternative study using materials and velocities similar to those of WTP shows that the project team's approach yields less conservative values for wear.

Assumptions Not Validated—The project team used assumptions to justify the extrapolations, scaling, and adjustments. In most cases, the project team based a given assumption on information from a single study in the literature. The project team has stated that documentation in the literature obviates any need to validate the assumptions.

The calculation[4] and associated changes,[5,6,7,8] used to establish estimated wear rates reference 36 assumptions. Ten of these will be validated. Of the remaining 26 assumptions, most are derived from experimental work documented in the literature. The staff's review of the source documents revealed that many fail to provide adequate information to support a sufficient level of certainty regarding the applicability of their methods and data to WTP or the repeatability of the relationships derived from the studies. Consequently, the basis for many assumptions is not adequate to justify their use in a calculation used to support safety design.

For example, in its calculation the project team assumes that changes in temperature will have a negligible effect on erosion. This assumption is based on information from the literature[9] that concluded that the temperature effect on pure erosion is small. The project team, therefore, determined that temperature effects can be neglected without validation. However, the paper also notes that the same temperature increase evaluated in the paper will increase corrosion rates in stainless steel by an order of magnitude. The increased corrosion has a synergistic effect that increases overall wear by a factor greater than what would be expected due to erosion or corrosion alone. The synergistic effect becomes more pronounced at higher velocities. This

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[3] Wang, H. W., and M. M. Stack, "The erosive wear of mild and stainless steels under controlled corrosion in alkaline slurries containing alumina particles," *Journal of Material Science, 35,* (2000).

[4] Vail, S. W., "Wear Allowance for WTP Waste Slurry Systems," 24590-WTP-M0C-50-00004 (2009).

[5] Vail, S. W., "Calculation ofWear Rates for Glass Formers at Velocities and Usage Factors," 24590-WTP-M0E-50-00011 (2009)

[6] Vail, S. W., "Calculation of Wear Rates for Piping Containing Waste Streams of Weighted Mean Particle Diameter of 24 Microns," 24590-WTP-M0E-50-00012 (2010)

[7] Vail, S. W., "Correct Velocity Exponent in Table 10.8E and Figure 10.8-A," 24590-WTP-M0E-50-00013 (2010)

[8] Vail, S. W., Wear Due to Segregation of Particles Reported in EFRT M3 PJM Vessel Mixing Assessments," 24590-WTP-MOE-50-00014, (2011)

[9] FanAiming, LongJinming, and TaoZiyun, "An investigation of the corrosive wear of stainless steels in aqueous slurries," *Wear 193* (1996).

concern becomes even more important since some stainless steel vessels, PJM nozzles, and piping will be operating near the critical temperatures for onset of pitting and cracking corrosion. The combination of effects could result in higher than expected wear rates. Consequently, prudence would dictate that additional studies or testing are needed to determine if the temperature effect can be neglected.

As a second example, the project team applies two assumptions to determine the wear rates resulting from a slurry comprised of rounded silica sand based on wear rate data of an angular alumina slurry. Based on these assumptions the vessel and PJM wear rate is reduced by a factor of approximately 3 when compared to wear rates without the assumptions. However, the experimental study referenced as the basis for these assumptions[10] was conducted with slurries composed of particulates that were significantly larger (more than 60 times) than the mean particle size used by the project team to calculate wear rates. Further, the scope of testing in the study is not documented and appears to be based on a single 4-hour wear test. While the staff agrees that the referenced study may be used to support a qualitative comparison between the expected wear due to rounded silica and angular alumina, the staff does not agree that there is sufficient evidence to support a quantitative comparison particularly in light of the differences in particle size between the referenced study and the conditions to which it is applied. However, the project team will not validate these assumptions since they are "based on relevant studies that are used to provide conservative wear rates."

Additionally, the staff determined that substantial variation exists in the parameters that affect erosion rates. For example, the staff found[11,12] that experimental values observed for the exponent used to describe the effect of fluid velocity on erosion rate ranged from 2 to 4.1. When used to extrapolate the wear relationship, either value could be more conservative depending on the direction of the extrapolation. Because of wide variation and uncertainty of effect, the assumptions used to establish a basis for design wear rates require validation that specifically considers the characteristics of the Hanford tank waste and operating conditions at WTP.

Conservatism of the Wear Models—The project team believes that its wear models are conservative, but cannot quantify the conservatism.

The project team based the design for vessels with PJMs on wear caused by a slurry containing rounded silica sand particles with a mean diameter of 24 micrometers (μm). Although the 24 μm size may not bound possible WTP waste inputs, the project team stated that this approach would be conservative since silica sand is much harder than most WTP waste. However, the team had no data for 24 μm rounded silica sand. Instead, data from the literature that used a slurry of alumina particles with a mean diameter of 150 μm was used. Since the alumina particles were both larger and harder than 24 μm rounded silica sand, the project team used nine unvalidated assumptions, including the two previously discussed assumptions that are used to account for differences between angular particles and rounded silca particles, to establish a scaling factor to extrapolate the wear for 150 μm alumina to an expected wear value for 24 μm

[10] Backmark, U., "Wear testing in water slurries," *Wear 162-164*, (1993).
[11] FanAiming, LongJinming, and TaoZiyun, op. cit.
[12] Vail, S. W., "Followup items from the 4/12-14/2011 Erosion/Corrosion DNFSB Review," CCN 237773 (2011).

rounded silica sand. The extrapolated value is approximately 12 times less than the wear rate for the alumina slurry reported in the literature.[13] There is no basis for direct comparison of 150 μm alumina to 24 μm rounded silica sand to confirm the validity of the approach.

The staff agrees that alumina slurry with 150 μm mean diameter particles will cause more wear than silica sand slurry with 24 μm mean diameter rounded particles. However, mixing various conservative assumptions (silica sand is harder than most WTP waste) with nonconservative assumptions (the 24 μm mean particle size may not bound WTP waste) and unvalidated assumptions (factor of 12 scaling of data for alumina particles) with limited technical justification for the starting value (a single 30-minute test with alumina particles) makes it difficult to determine whether the end result provides a conservative basis for design.

Consequently, the project team's assertion of conservatism cannot be defended. A more consistent approach is needed to provide greater confidence that wear allowances are adequate.

Validation of Wear Models. With the exception of the one-quarter scale testing accomplished as part of closure of EFRT Issue M2, the project team has not generated experimental data to validate the design wear models. However, the scope of the Issue M2 testing was inadequate to validate design wear models, and the testing did not validate related scaling assumptions. Specifically, the Issue M2 testing:

- Collected limited data regarding average wear rates for vessel bottoms. During eight test runs, a total of 16 tests were performed, during which the following were studied: three different slurry particle size distributions, three different velocities, three different solids concentrations, two different nozzle angles, two different flow types, and two types of wear coupons. The number of tests was insufficient considering the number of variables tested.

- Collected limited data regarding localized wear rates for vessel bottoms. However, the method and location of the data measurements do not support the determination of maximum localized wear rates.

- Collected "information only" measurements for wear on the PJM nozzle exit. However, the geometry of the test nozzles does not match the system geometry, further reducing confidence in the nozzle wear results.

Additional concerns with the EFRT Issue M2 testing are summarized below:

Measured Wear Is Higher Than Design Wear Rate—Figure 1 shows a subset of the data collected during the testing to close EFRT Issue M2. The plot shows the measured erosion rate (E) based on depth measurements as a function of velocity (V). Each datum on the plot represents the wear rate derived from depth measurements made at one of thirteen predetermined locations on each wear specimen. Each wear specimen was exposed to 96 hours of submerged

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[13] Wang and Stack, op. cit.

jet flow that was intended to represent PJM flow against vessel bottoms at a one-quarter scale. Tests were performed using different jet velocities, angles, and flow modes, as well as simulants with different solid concentration and particle size. For simplicity, the plotted data are limited to tests with a solids concentration of 29.2 weight percent and tests conducted with continuous slurry flow perpendicular to the stainless steel wear coupons. The figure also plots the WTP design basis wear rate for a solids concentration of 29.2 weight percent (black curve). The data from the three different test simulants are shown as black triangles, blue squares, and red circles, which correspond to the 24 μm, 39 μm, and 54 μm test simulant, respectively.

A substantial number of the localized wear data measurements for velocities of interest (8–12 m/s) for WTP PJM nozzles and vessel bottoms, including those obtained using the nonbounding but representative 24 μm simulant, lie above the curve that defines the design basis wear rates for WTP vessels and piping. Some of the measured data are 30 percent above the design basis wear rate. Consequently, the relationship used to define design wear rates for the vessels and PJMs does not provide sufficient conservatism.

Test Duration and Measurement Methods Cause Substantial Uncertainty—The short-duration used for the above testing (96 hours) did not cause enough wear to permit accurate measurement of localized wear. In many cases, the resulting wear was close to or less than the accuracy of the instrument used to measure the wear. The result was unreliable measurements and, as shown in Figure 1, large data scatter. The staff analyzed the data and found that the mean difference between independent measurements performed by two different analysts was 0.23 mils with a standard deviation of 0.18 mils (which corresponds to a mean difference and standard deviation of 21.1 and 16.4 in mils per year [mpy], respectively). This error is substantial considering that, as shown in Figure 1, the expected wear for 8 m/s flow is 40 mpy.

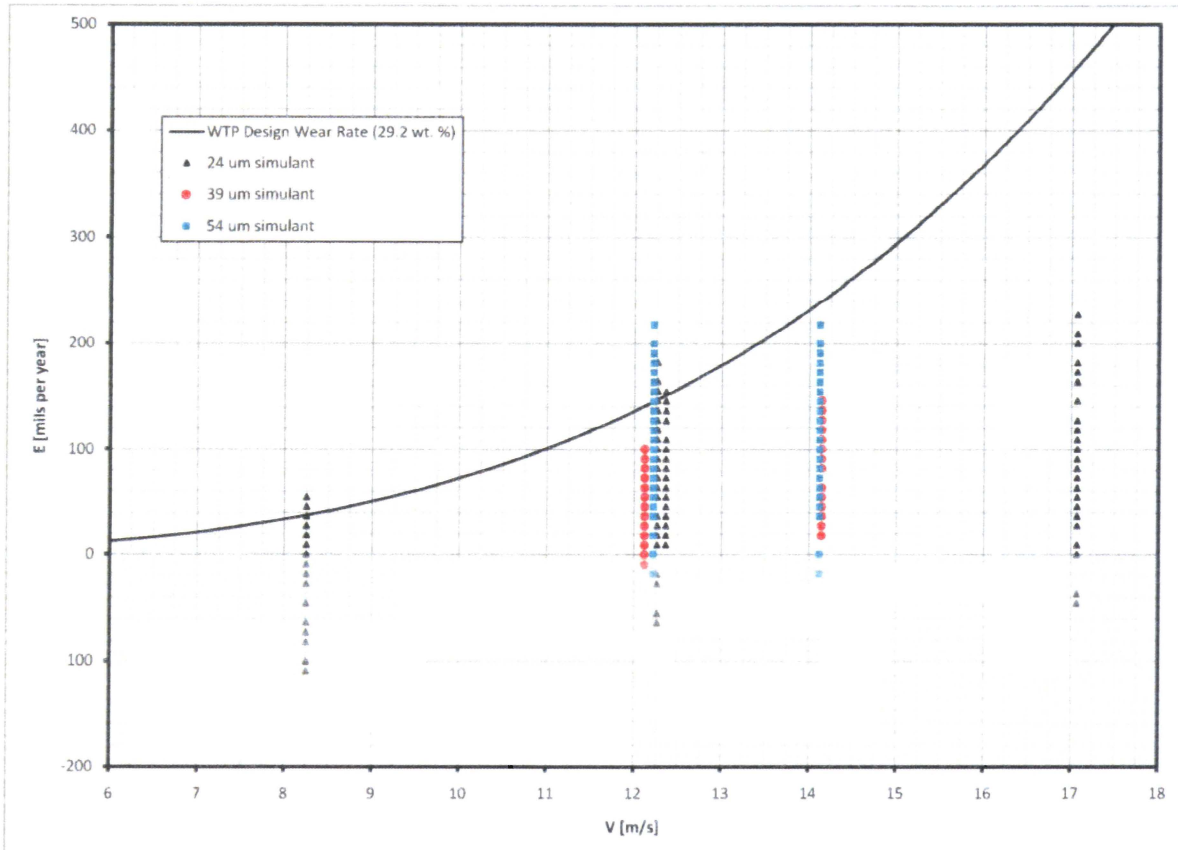

Figure 1. Comparison of experimentally determined wear rate data based on depth measurements with the WTP design basis wear rate for vessels with pulse jet mixers.

As a further indication of uncertainty, data collected at a flow rate of 8 m/s displayed a scatter over a range of -115 mpy to +55 mpy. Data collected at 12 m/s scatter over a range of -65 mpy to +220 mpy. There is no discernable pattern or trend in the data. The experimental data that suggests a negative wear rate (gray region in Figure 1) are physically unrealistic (i.e., indicate that the wear coupons were increasing in thickness during testing).

Measurement Locations Do Not Support Validation of Localized Wear Rates—The project team understood that wear resulting from PJM flow will not be uniform and determined that localized wear will be the predominant failure mode resulting from erosion. Consequently, their original test plan stated that the wear rate would be determined by measuring erosion depth. However, the test plan did not provide a method for ensuring that the depth measurements coincided with areas of maximum wear. Rather, the test plan identified predetermined locations for the measurements.

The use of predetermined locations to obtain data for maximum localized wear is flawed because wear patterns on wear surfaces will vary unpredictably in size and shape depending on flow characteristics and variations, as well as the material and physical configuration system. The unpredictable variations coupled with predetermined measurement locations make it unlikely that any of the depth measurements obtained during the tests correlate with maximum wear locations. Consequently, the wear rates determined during the tests may not be representative of actual maximum wear rates. The failure to match measurement locations with maximum wear locations yields nonconservative wear results that cannot be used legitimately as the basis for validating design wear rates.

The project team considers the testing used to close EFRT Issue M2 to provide an adequate validation of the design wear models. This determination is based primarily on their evaluation of average wear rates determined from weight changes in the wear specimens even though localized wear will be the cause of most erosion failures. The project team also believes that it can extend this evaluation to other wear models including the model for vessels that contain glass formers, the model for piping that contains glass formers, and the model for piping without glass formers. However, based on the limited scope of testing, uncertainty in the data, and prediction of wear exceeding the relevant design allowance, the staff does not agree with this assessment. Further work is required to support validation of WTP design wear models.

Wear Design of Some Vessels and PJMs Is Nonconservative. The project team selected the plate thickness for PJM and vessel fabrication by ensuring that the selected plate would be thicker than the minimum required thickness. The minimum required thickness is the sum of the material thickness required for strength, the material thickness required for wear allowance, and the material thickness allowances for fabrication thinning and plate underthickness. In some cases, the design uses wear plates to provide additional thickness in areas with localized high wear and uses Stellite® to improve the wear performance of some PJM nozzles. The project team calculated the 40-year design life wear allowances for vessels with PJMs and PJM nozzles using a design wear rate equation and a number of assumptions regarding various operating parameters, such as PJM duty factors, cycle times, and drive velocities.

Uncertainty exists in these calculations since the project team does not plan to validate the assumptions before startup or ensure by inspection that estimated wear is not exceeded in service.

Evaluation of Existing Material Margins—The staff studied the design to determine whether it includes adequate material margin to accommodate uncertainty in waste composition and operating parameters, or allow for operational flexibility. "Operational flexibility" is the ability to increase mixing durations, waste concentrations, PJM velocities, or mission life without redesign, repair, or modification of the affected components. Such flexibility would allow for processing modifications to resolve unexpected problems that might emerge after completion of the facility. For example, although the project team addressed variations in concentration within the WTP vessels, the project team still needs to review recent studies regarding waste stratification and that indicate that the fraction of large particles present in the Hanford tank waste may be greater than previously identified. Subsequent modifications to the current wear rate calculations may be required to account for particle size stratification within the vessels that could result in wear greater than that currently estimated in and under the PJM nozzles.

The staff found that the current design for piping and vessels meets the specified design wear allowance criteria, but with little margin for uncertainty. However, PJM nozzles in two vessels have no material margin when the wear relationships and assumptions defined by the project team are applied. Allowances for other vessels are small, providing little margin for unplanned wear.

Evaluation of Variation in Input Parameters—The staff performed a sensitivity study to evaluate the relationship between the erosion allowance and variations in waste properties and operational parameters. This study revealed that relatively small variations in a single parameter could eliminate available material margin for both PJM nozzles and vessels. Even smaller variations in multiple parameters would have the same effect.

Based on the above evaluations and the weaknesses discussed in the previous section, the staff considers that the wear design of some vessels and PJMs is questionable. Additionally, design with no or minimal material margin is inappropriate for PJM nozzles and vessels located in the black cells. It would be advisable for the project team to identify and apply a safety factor when calculating the required thickness allowance for wear to account for uncertainties in operational parameters and in the wear relationship.

Tracking of Estimated Wear and Identification of Controls. The project team has not determined how to protect the design basis assumptions in the safety basis documents so that they remain valid.

Establishing an effective surveillance program that links to the safety basis will be difficult given the limitations imposed by the black cell design. The project team stated that it expects to measure wear on hot-cell jumpers and extrapolate the results of those measurements to estimate wear on black cell piping. The project team stated that it intends to monitor the abrasivity of waste going into the plant in order to estimate and track wear on vessels and PJMs. The staff pointed out that this will be difficult since there is no direct correlation between abrasivity and impingement wear. The lack of experimental wear data for Hanford waste adds further uncertainty to the comparison. Consequently, additional laboratory testing may be required to establish valid relationships between abrasivity and wear rates to support this effort.

Additionally, the project team has not addressed limits on operational parameters or waste characteristics that affect wear. Uncontrolled changes during either design or operation can lead to wear that exceeds available material margin. Failure to define limits could result in unexpected and premature failure of the piping, vessels, or PJMs.

The project team needs to establish a reliable means of estimating accumulated wear and controlling design or process conditions to protect the wear design of WTP components.

Conclusions. Based on the above information, the staff determined that the design basis used by the project team to define wear relationships cannot be defended and that assumptions are unprotected. Therefore, the current wear design for some vessels, PJMs, and piping may be inadequate to ensure that systems located in the black cells will perform their functions for the expected 40-year mission life of the facility. Additional work is required to resolve the above issues.

The staff notes that based on follow up discussions with DOE staff members at both the Office of River Protection and at DOE headquarters, that DOE is working to address issues similar to the ones discussed above that were developed from independent sources. However, the current pace of the contractor's efforts to close the issues does not support timely resolution of the above questions. The staff notes that some of these vessels are scheduled for installation in the Pretreatment Facility in August of 2012 and that modifications become progressively more difficult and costly after the vessels are closed and installed.