# Assessment and Design for Erosion From High Level Waste Slurries on the Waste Treatment Plant - 9409

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## ABSTRACT

The Department of Energy is constructing the Waste Treatment and Immobilization Plant (WTP) at the Hanford site in Washington to treat and immobilize approximately 200 million liters (53 million gallons) of high level radioactive waste. Of the 200 million liters, there are some 42 million liters of sludge that can cause erosion in tanks, piping, and equipment. Of principal concern is erosion in process vessels under pulse jet mixer (PJM) devices that direct high-velocity jets against the vessel walls. As these vessels are not designed to be replaced and are in hard to access or inspect locations, it is essential that the erosion mechanisms and rates are well-understood and accounted for in the design so that the vessels can perform safely and reliably over the 40 year design life of the plant. There is little information in the literature about erosion under PJM mixing conditions, and earlier evaluations involved considerable interpretation and adjustment of existing data to account for the differences. Accordingly, the project undertook an erosion testing program to collect data under prototypic PJM operation and waste characteristic conditions.

This paper describes the process and results of the mixing program, including determining the waste characteristics to be tested, development of the simulant, the testing variables to be examined, the conduct of testing, and the results. Evaluation of the testing results indicate that adequate erosion wear resistance is available in all the WTP vessels

## INTRODUCTION

On the Hanford site, a few miles west of the Columbia River 200 million liters of radioactive and chemical waste from cold war plutonium production are stored in 177 underground tanks. Design and construction of the world’s largest radioactive waste treatment plant is underway to immobilize the waste into glass and place it in stainless steel canisters for safe and permanent disposal. Of the 200 million liters, there are some 42 million liters of sludge that can cause erosion in tanks, piping, and equipment.

The WTP is comprised of three main facilities: the Pretreatment (PT) facility performs separation and concentration of the waste received from the underground tanks. The High Level Waste (HLW) vitrification facility immobilizes the high level fraction of the waste in glass using melters. Similarly, the Low Activity Waste (LAW) facility vitrifies the low-level waste fraction. Both the PT and HLW facilities contain vessels that are mixed by pulse jet mixers (PJMs), 36 vessels in PT and 2 in HLW.

A PJM is a long cylinder with a tapered nozzle, located within the vessel to be mixed, that is pressurized to expel the vessel waste contents into the larger primary vessel to effect mixing. The typical complete cycle of the PJM is to operate in a discharge mode for approximately 40 seconds and refill for approximately 230 seconds. Both the discharge and refill modes contribute to facilitate mixing by establishing currents within the primary vessels. PJMs are typically arrayed around the periphery of the mixed vessel. The size and number of PJMs are a function of the mixed vessel and its contents. At the WTP, the number of PJMs ranges from 4 to 14 per vessel.

Of concern is the mixing action that contributes to erosion of the vessel's walls due to the jet action of the PJM. The PJM jet designs typically have 10 centimeter diameter nozzles that discharge at 8-17 m/s. The discharge point of a PJM is nominally 1.5 times the nozzle diameter in distance from the vessel wall. A 10 centimeter (4 inch) jet would be located approximately 15 centimeters (6 inches) from the vessel wall.

WTP vessels that are mixed with PJMs are made of stainless steel (304L or 316L). As these vessels are not designed to be replaced and are in hard to access or inspect locations, it is essential that the erosion mechanisms and rates are well-understood and accounted for in the design so that the vessels can perform safely and reliably over the 40 year design life of the plant. As there is little information in the literature about erosion under PJM mixing conditions, earlier evaluations involved considerable interpretation and adjustment of existing published experimental data to account for the differences. The project had its erosion prediction methodology reviewed by two experts in the subject, Dr. Margaret Stack and Dr. Hector Clark. They both reported that, while the methodology appeared to be appropriate and should yield reasonable results, they recommended testing be performed to provide greater assurance that the estimates are valid.

Accordingly, the project undertook an erosion testing program to collect erosion rate data under prototypic PJM operation and waste characteristic conditions. The program used recently published Hanford tank farm waste chemical and physical characterization (e.g. particle size distribution) to develop simulant the replicated waste conditions. Testing was accomplished on a 1/4-scale test rig. Testing variables included pulsed vs. continuous flow, velocity, mean particle size, concentration, average particle hardness, and impingement angle. Mass loss data was used to develop calculation exponents for velocity, concentration, and size terms so that erosion rates could be adjusted for different operating and feed conditions. Evaluations were made of predicted erosion rates in each of the vessels and compared to available erosion design allowances in each of the affected vessels. A number of sensitivity analyses were also performed to assess the effect of different operating and waste input variables in order to demonstrate margin in robustness in the design.

Evaluation of the testing data demonstrated that the original predictions were bounding and no adjustment to the design of the vessels was necessary for wear resistance.

## PREVIOUS EROSION WORK TAKEN INTO ACCOUNT

Very limited data was previously available for WTP slurry waste conditions prior to performing the testing described in this paper. Some work had been performed by Enderline and Elmore [6] which investigated a zeolite water slurry in a hydroxide solution as applicable to the US Department of Energy's West Valley Vitrification Plant but the Hanford. In addition, parametric relationships were previously used to compare slurry conditions. The relationships were based on work published by Gupta and Karabelas [7,8] . These relationships were previously applied to mineral-slurry wear data reported by Kabelas and FanAiming to determine erosion allowances for WTP waste slurries [8,9]. From this previous work the exponential relationship of erosion (scar depth) to velocity, particle diameter, and slurry concentration as the main factors affecting erosion were developed. Other work performed by Wang and Stack [10] and Mishra [11] were also reviewed. The results reported by Karbelas and Gupta (under the specific conditions investigated) have produced exponents for the velocity term of the equation in the range of 2-3, for the particle size term from .2 to .3 and for the concentration term at approximately .5. The work performed by BNI as reported in this paper produced exponents on average over the range of conditions of 3 for velocity, 2 for particle size and .8 for concentration.

## WASTE PROPERTIES DETERMINATION

The program used an updated assessment of Hanford tank farm waste chemical and physical characterization (e.g. particle size distribution) published in Reference [1], the so-called 153 Report, as the primary basis for assigning values of the erosion-important constituents of the waste. Important waste characteristics are particle size, density, hardness, and morphology. An additional resource was a detailed evaluation performed by the WTP Project of 518 feed delivery batches contained in the Tank Farm Contractor Operation and Utilization Plan, Rev. 6 [2]. That evaluation is documented in "WTP Waste Feed Analysis and Definition" [3].

Based on the above input, nominal erosive feed characteristics were established as 24 microns mean particle size, an average specific gravity of 2.4, and an average Mohs hardness of 3.6.

The waste particle characteristics are consistent with those used for evaluation of critical slurry flow velocity to ensure that lines within WTP do not plug, and with assessments of the mixing capabilities of the PJMs. These characteristics are included as part of the WTP waste feed acceptance criteria contained in ICD-19-Interface Control Document for Waste Feed [4]. The ability of the tank farm contractor to meet the acceptance criteria was assessed and confirmed in detail in Reference [4].

As a final control, waste characteristic are measured for each feed delivery batch, including the erosive characteristics, such that a running prediction of vessel erosion can be maintained, and if necessary, corrective actions taken.

## SIMULANT DEVELOPMENT

A testing simulant that closely resembled waste feed conditions was prepared by comparison to the weighted mean particle size and hardness. The simulant was comprised of only those significant constituents found in the actual waste, at their nominal sizes.

In addition to the particle properties affecting erosion noted above, waste properties that affect erosion include solids concentration, pH, and liquid viscosity. Consideration was also given to the corrosive potential of the liquid fraction of the slurry against the stainless steel. Corrosion of the stainless steel was measured in all of the testing described below and shown to be negligible when compared to the erosion. The erosion rate predictions for the WTP vessels were shown to not be accentuated by the effect of corrosion.

The base simulant consisted of 15 components, principally various aluminum compounds including boehmite and gibbsite, zeolite, and ferrite. Smaller amounts of other components were included to achieve the hardness and density properties required. While the 153 report indicated that larger particles were agglomerates that broke apart upon mixing or pumping, this feature was not included in the final simulant; the mean particle size was based on primary particle sizes, which is conservative. Other morphology-related aspects were accounted for by using the same components as found in the real waste, in the size range they appear in the waste.

Five simulant compositions were prepared for testing. Simulants were prepared to provide a realistic but bounding set of properties for testing. The simulants were based on weighted mean particle sizes that included 24, 38, and 54 microns. Concentrations included 150, 250, and 350 grams per liter. Particle hardness was averaged for 3.6 and 4.4 on the Mohs scale. The hardness values were calculated averages and were based on vendor supplied information on the primary particle constituents used to make up the slurries.

## TESTING VARIABLES

Testing variables included pulsed vs. continuous flow, velocity, mean particle size, concentration, average particle hardness, and impingement angle. Particle size reduction was noted in shakedown testing and the simulant was replaced, and average particle size restored, every 24 hours to match plant conditions.

The test matrix was designed to gather the minimum information required to adequately predict the erosion over forty years of WTP operation. The matrix varied the jet velocity, concentration, and mean particle size in order to determine the exponential relationship of these parameters as input to the calculational method described below. Hardness was also evaluated as a sensitivity parameter as a secondary investigation. Hardness of the simulant primary particles was not deemed to be a significant contributor to the calculational method so the term was not used as a factor in the method. Another secondary investigation looked at the effect of pulsed versus continuous flow of the PJM jet stream. This investigation considered the concept that an intermittent jet could result in more, less or an equivalent scar depth of the vessel wall. The matrix is provided in Table 1 below.

**Table 1. Erosion Testing Matrix**

| Test | Particle Distribution | Solids Conc. | Average Hardness | Jet Velocity | Jet Angle | Replenish | Flow Pattern |
|---|---|---|---|---|---|---|---|
| Run 1 Jet 1 | 24 micron | 350 g/L | 3.6 mohs | 12 m/s | 90° | yes | continuous |
| Jet 2 | 24 micron | 350 g/L | 3.6 mohs | 12 m/s | 90° | yes | pulsed |
| **Hold** | | | | | | | pulse or not? |
| Run 2 Jet 1 | 54 micron | 350 g/L | 3.6 mohs | 14 m/s | 90° | yes | continuous |
| Jet 2 | 54 micron | 350 g/L | 3.6 mohs | 12 m/s | 90° | yes | continuous |
| Run 3 Jet 1 | 24 micron | 350 g/L | 3.6 mohs | 14 m/s | 90° | yes | continuous |
| Jet 2 | 24 micron | 350 g/L | 3.6 mohs | 12 m/s | 90° | yes | continuous |
| Run 4 Jet 1 | 24 micron | 350 g/L | 3.6 mohs | 14 m/s | 90° | yes | continuous |
| Jet 2 | 24 micron | 350 g/L | 3.6 mohs | 12 m/s | 90° | yes | continuous |
| **Hold** | | highest wear conc.? | | | | | |
| Run 5 Jet 1 | 39 micron | per hold | 3.6 mohs | 14 m/s | 90° | yes | continuous |
| Jet 2 | 39micron | per hold | 3.6 mohs | 12 m/s | 90° | yes | continuous |
| Run 6 Jet 1 | 24 micron | per hold | 3.6 mohs | 17 m/s | 90° | yes | continuous |
| Jet 2 | 24 micron | per hold | 3.6 mohs | 8 m/s | 90° | yes | continuous |
| Run 7 Jet 1 | 24 micron | per hold | 4.4 mohs | 12 m/s | 90° | yes | continuous |
| Jet 2 | 24 micron | per hold | 4.4 mohs | 12 m/s | 90° | yes | continuous |
| Run 8 Jet 1 | 24 micron | per hold | 3.6 mohs | 12 m/s | 65° | yes | continuous |

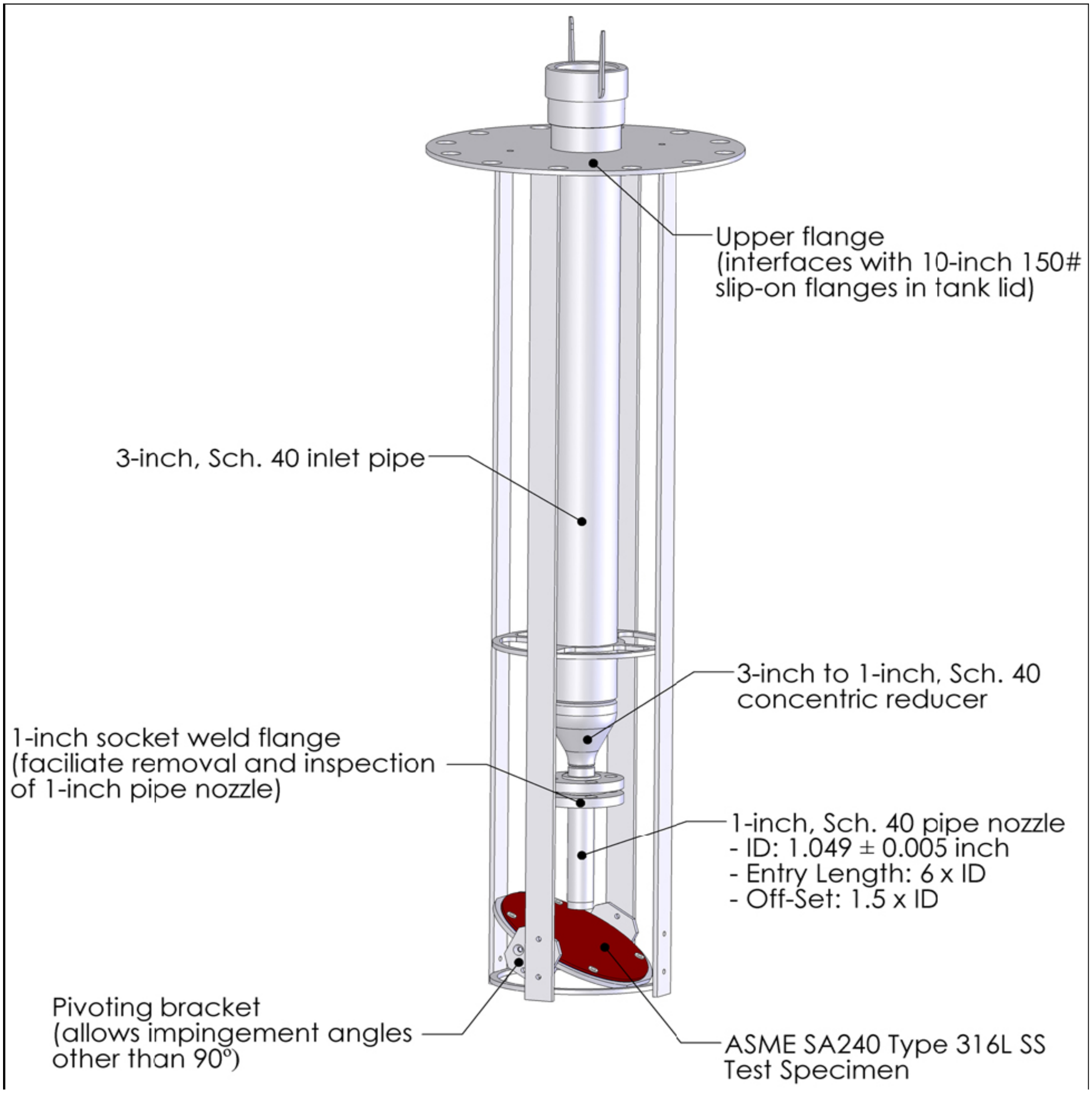
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Jet 2 | 24 micron | per hold | 3.6 mohs | 12 m/s | 90° | yes | continuous |

Run 1 showed that there was little difference between pulsed and continuous erosion rates and the balance of the testing was done with a continuous flow rate. Run 7 jet 2 and Run 8 jet 2 used an Ultimet® test coupon.

## CONDUCT OF TESTING

Testing was conducted by Dominion Engineering at their facilities in Reston, VA. Figure 1 shows the test fixture used for the testing. As noted above, testing was done for 24 hours, at which time the simulant was replaced. Four consecutive 24-hour runs were made to provide a total of 96 hours of continuous wear. Figure 2 shows the overall 1/4-scale test rig.

**Fig. 1. Test fixture for erosion testing**



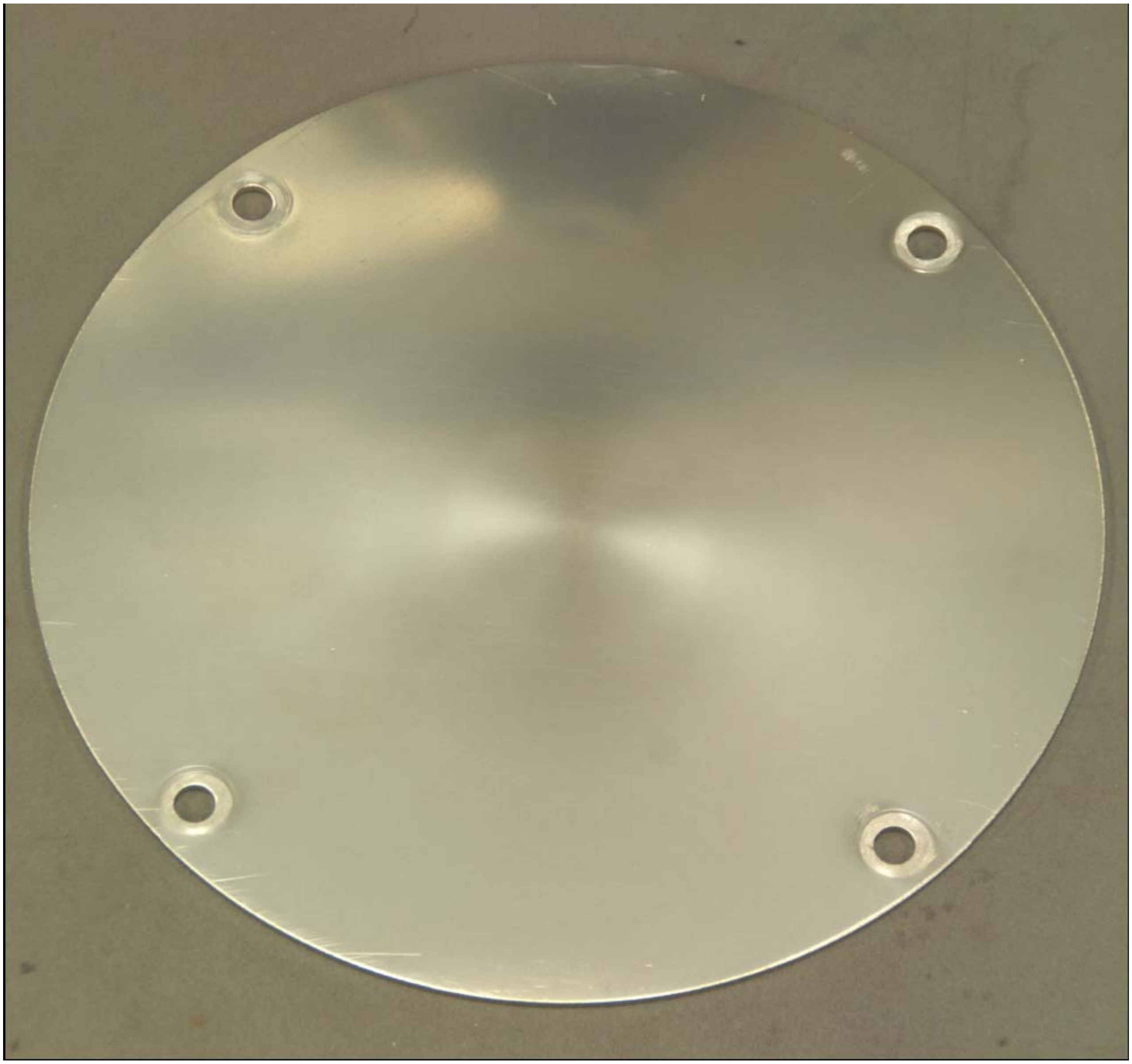

Testing utilized circular, 20 centimeter diameter (8 inch), 316L test coupons that were exposed to geometrically similar conditions as the actual WTP vessels. Two additional tests were conducted using an ULTIMET alloy. ULTIMET was investigated as a potential weld overlay to the stainless steel wear plate of the vessel wall as an added barrier to protect against erosion. Test measurements that are required for use as direct input to WTP design calculations were taken in accordance with ASME NQA-1 standards. Several measurements were taken as commercial grade and were used as information to supplement the understanding of the prediction of erosion behavior in the WTP. The measurements of erosion were taken as mass loss and scar depth. The primary measurement of importance at the WTP is the scar depth.

**Fig. 2. Test Rig with Two Independent Recirculation Loops**


**TEST RESULTS, EVALUATION AND CONCLUSIONS**

Examination of the test coupons revealed a donut shaped depression: the area directly below the centerline of the jet had less erosion than a ring around the center. Micrometer readings were used to measure the scar depth. The incremental scar depth at successive 24-runs was relatively constant. Mass loss data was used to develop exponents for velocity, concentration, and particle size so that erosion rates could be adjusted for different operating and feed conditions. Figure 3 is of a stainless steel test coupon after 96 hours of exposure to jet wear with waste simulant. No visual observance of erosion is detectable other than a polished appearance.

**Fig. 3. Test coupon after 96 hours of erosion**



Testing results are shown in Table 2. Changes in the successive tests are highlighted in purplee.

**Table 2. Data table of test results**

| | Mass loss (grams) | PJM velocity (meters/s) | Slurry concentration (grams/liter) | Coupon | Scar (millimeters) | Mean Particle size (microns) | Angle (Radian) | Hardness (Mohs) |
|---|---|---|---|---|---|---|---|---|
| Test run 1 | 3.4373 | 12 | 350 | SS | 0.0381 | 24 | 1.57 | 3.6 |
| Test run 2 | 5.0141 | 12 | 350 | SS | 0.0508 | 54 | 1.57 | 3.6 |
| | 7.6467 | 14 | 350 | SS | 0.05842 | 54 | 1.57 | 3.6 |
| Test run 3 | 1.2894 | 12 | 250 | SS | 0.02286 | 24 | 1.57 | 3.6 |
| | 2.2124 | 14 | 250 | SS | 0.02286 | 24 | 1.57 | 3.6 |
| Test run 4 | 0.8756 | 12 | 150 | SS | 0.02032 | 24 | 1.57 | 3.6 |
| | 1.4029 | 14 | 150 | SS | 0.02286 | 24 | 1.57 | 3.6 |
| Test run 5 | 2.5691 | 12 | 350 | SS | 0.02286 | 39 | 1.57 | 3.6 |
| | 4.1083 | 14 | 350 | SS | 0.03556 | 39 | 1.57 | 3.6 |
| Test run 6 | 0.2879 | 8 | 350 | SS | 0.01016 | 24 | 1.57 | 3.6 |
| | 6.0005 | 16.5 | 350 | SS | 0.05588 | 24 | 1.57 | 3.6 |
| Test run 7 | 4.3555 | 12 | 350 | SS | 0.04064 | 24 | 1.57 | 4.4 |
| | 4.4727 | 12 | 350 | Ultimet | irregular | 24 | 1.57 | 4.4 |
| Test run 8 | 1.6635 | 12 | 350 | SS | 0.02286 | 24 | 1.13 | 3.6 |
| | 1.3994 | 12 | 350 | Ultimet | irregular | 24 | 1.57 | 3.6 |

The test results were inserted to the equation below to predict the expected erosion rate over 40 years of operation.  The equation is as follows:

$$E_w = E_{wref}\left[\frac{V_a}{V_{ref}}\right]^n\left[\frac{P_a}{P_{ref}}\right]^p\left[(1\text{-}I)\left(\frac{G}{C_{ref}}\right)^q + I\left(\frac{H}{C_{ref}}\right)^q\right](F)(E)(D)(Ia)(Sc)$$

Where:

$E_W$ = Scar depth at end of design life (m)

$E_{wref}$ = Scar depth of reference case (m)

$V_a$ = Velocity of jet actual (m/s)

$V_{ref}$ = Velocity of jet from reference case (m/s)

$P_a$ = Particle weighted mean diameter actual (m)

$P_{ref}$ = Particle weighted mean diameter from reference case (m)

$I$ = Fraction of time for maximum solids loading

$G$ = Normal solids concentration (wt %)

$H$ = Maximum solids concentration (wt %)

$C_{ref}$ = Reference case concentration (wt %)

$F$ = Vessel usage factor (fraction of time)

$E$ = PJM duty factor (fraction of time)

$D$ = Design life (years)

$Ia$ = Factor for impingement angle

$Sc$ = Scale factor (1/4 to full scale)

Test data is used as the reference case for scar depth, velocity, particle weighted mean diameter, and slurry concentration.  The plant operating conditions and actual waste properties are then provided as input to the other parameters in the equation, and a scar depth is estimated for a given period of facility operation (typically for the 40-year design life of WTP) from the calculation.

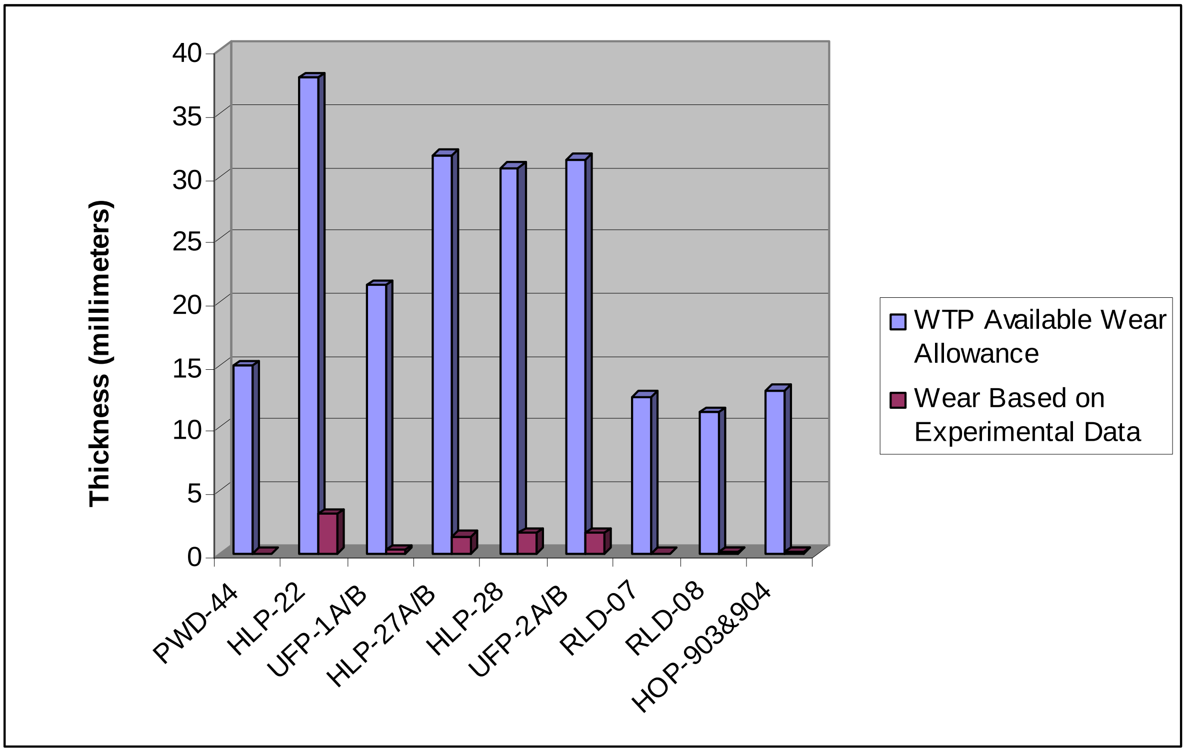
Computational fluid dynamics was used to scale the 1/4 erosion rates to full-scale. Evaluations were made of predicted erosion rates in each of the vessels and compared to available erosion allowances in each of the affected vessels. A number of sensitivity analyses were also performed to assess the effect of different operating and waste input variables in order to demonstrate margin in robustness in the design.

The test results provided exponents for velocity, concentration, and particle size.

Exponents were developed over the range of operating parameters for the pulse jet mixers.  The PJMs range in discharge velocity form 8 to 17 meters per second.  Concentration of the slurry ranges in the WTP from almost no solids content to a maximum of 20wt%.  Particle sizes range from submicron to about 300 micron with the weighted mean being 24 microns.  The work performed by BNI as reported in this paper produced exponents on average, over the range of conditions, of 3 for velocity, 2 for particle size, and .8 for concentration.

Figure 4 shows the results of the evaluation of the test data for the vessels with the most challenging erosion, i.e.., those with the highest concentrations and velocities. As can be seen, there is considerable margin between the available wear allowance and that predicted from the test data.

**Fig. 4. Comparison of predicted 40-year wear to design wear allowances, for key WTP vessels**

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