Jessie H. Roberson, Vice Chairman
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DEFENSE NUCLEAR FACILITIES SAFETY BOARD

Washington, DC 20004-2901

March 25, 2015

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

Dear Mr. Whitney:

Over the last several years, the Waste Treatment and Immobilization Plant (WTP) contractor has executed a test program and analysis effort to establish an aerosol entrainment coefficient (AEC) value for confinement ventilation system designs. The Board advises that the recommended AEC values from this program may not bound expected conditions at the WTP. The AEC values are key design parameters for sizing high-efficiency particulate air (HEPA) filters. The current safety basis for the Pretreatment and High-Level Waste Facilities rely on the HEPA filters as a safety control for several design basis accidents. Use of incorrect AEC values may produce undersized HEPA filter designs that would not perform their safety function to provide filtration of radioactive material. Further details on the technical concerns are discussed in the enclosed report.

At this time, the WTP project is working on resolution of safety issues associated with the confinement ventilation systems at WTP facilities, including the radial HEPA filters testing. The Board will continue to review and monitor these activities and will advise as necessary to ensure the adequate protection of the public health and safety.

Sincerely,

Jessie H. Roberson
Vice Chairman

Enclosure

c: Dr. Monica Regalbuto
Mr. Joe Olencz

DEFENSE NUCLEAR FACILITIES SAFETY BOARD

Staff Issue Report

November 18, 2014

MEMORANDUM FOR: S. A. Stokes, Technical Director

COPIES: Board Members

FROM: R. Kazban and P. Meyer

SUBJECT: Aerosol Entrainment Coefficient Based on Testing and Data Analyses for the Waste Treatment and Immobilization Plant

Summary. Members of the Defense Nuclear Facilities Safety Board's (Board) staff reviewed the aerosol entrainment testing and a recommended aerosol entrainment coefficient (AEC) value for use in the design of high-efficiency particulate air (HEPA) filters at the Waste Treatment and Immobilization Plant (WTP). The AEC values are key design parameters for sizing HEPA filters. Use of incorrect AEC values may produce undersized HEPA filter designs that do not ensure adequate protection of the public and the workers. On October 10–11, 2012, the Board's staff held a video-teleconference with representatives from the Department of Energy (DOE) Office of River Protection (ORP); the WTP contractor, Bechtel National, Incorporated (BNI); and BNI subcontractors, Fauske and Associates, Incorporated (FAI), and Parsons Corporation (Parsons). The subject of the discussion was the small-scale aerosol entrainment test report issued by Parsons. Subsequently, the staff team evaluated Parsons' medium-scale aerosol entrainment test report and a report by FAI that analyzed the test results and recommended an AEC value for the WTP project. The Board's staff team identified several concerns with the testing and analysis, and on March 26, 2013, transmitted an agenda to ORP on the FAI recommendations. However, on September 9, 2013, DOE informed the Board's staff team that a discussion on the AEC would be delayed for at least another year. In August 2014, ORP invited the Board's staff team to clarify the concerns identified in the agenda transmitted in 2013. On August 27, 2014, the Board's staff team held a teleconference with ORP, BNI, Pacific Northwest National Laboratory, and FAI personnel. The Board's staff team is concerned that the aerosol test program used simulants that lacked a sufficient range of physical and chemical properties, and contained unverified assumptions about the aerosol composition. Further, the analysis that established the recommended AEC value is not technically defensible. Therefore, the recommended AEC may not bound expected conditions at WTP.

Background. As currently designed, mixing systems in non-Newtonian process vessels at the WTP Pretreatment Facility (PTF) utilize air spargers to supplement mixing by pulse-jet mixers. Air spargers are safety class controls credited in the WTP safety basis for preventing hydrogen explosions in non-Newtonian vessels by releasing and diluting hydrogen generated within high-level waste (HLW) slurries. The action of the sparger bubbles rising and bursting on the surface of the waste generates radioactive aerosols, which may be carried over into the vessel ventilation system. The PTF vessel ventilation system is comprised of the pretreatment vessel vent process (PVP) and process vessel vent exhaust (PVV) systems. Air sparging in non-Newtonian vessels is the primary long-term source of aerosols that challenges these ventilation systems following a seismic design basis accident (DBA). The current PTF Preliminary Documented Safety Analysis (PDSA) credits the vessel ventilation systems for confinement and filtration of radioactive aerosols before the air is released to the atmosphere.

The design of the HLW Facility process vessels includes mechanical agitators and air spargers for agitating the waste. The current HLW Facility PDSA credits spargers as a safety class control for hydrogen explosions. Following a seismic DBA or failure of mechanical agitators, spargers are relied on to periodically agitate the waste to gradually release generated hydrogen into the vessel headspace so it can be removed in the vessel vent system. During the development of the HLW Safety Design Strategy (SDS) the WTP project decided to pursue alternative control strategies because spargers were identified as a contributor to technical challenges. These challenges are associated with generation of an aerosol loading that challenges HEPA filter systems and operability issues due to sparger plugging and vessel foaming [1]. As a result, the control strategy for hydrogen explosions in HLW process vessels is not defined in the SDS; rather, it is accounted for as a project risk.

The AEC is the proportionality "constant" that relates the aerosol generation rate to the air sparging rate. The AEC value is a dimensionless number that is sometimes reported as a volume-based number, i.e., volume of aerosol per volume of air, and is sometimes reported as a mass-based number such as mass of aerosol per mass of air. For consistency, all AEC values in this report are mass-based numbers. The value of the AEC has a significant impact on predictions of HEPA filter loading rates. BNI will use the AEC to determine specifications for both the HEPA filtration loading capacity and replacement frequency during post-DBA conditions due to aerosols produced by air sparging systems.

Prior to 2009, the project used an AEC value of 2.0×10^{-4} [2]. In 2009, the project adopted a more conservative value of 2.0×10^{-3} from DOE Handbook 3010, *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities* [3], which was derived from test data for boiling liquids. This AEC value increased the predicted amount of aerosols generated from spargers by a factor of 10. In a separate effort, BNI reclassified the PVP and PVV systems from passive to active confinement post-seismic DBA systems. ORP approved the change in November 2009 as part of an addendum to the PTF PDSA. The revised safety functions of the PVP and PVV systems are identified in the PDSA addendum as maintaining confinement and filtration of vessel exhaust gasses during normal, off-normal, and accident conditions, as well as providing a vent pathway for hydrogen mitigation.

In 2010, BNI identified that the new AEC value would result in predicted HEPA filter loading in excess of the capacity of the PVP and PVV systems (i.e., the loading rate would exceed the rate at which the filters could be replaced after a seismic DBA). If the loading on the HEPA filters exceeds their design basis, they will fail to perform their safety function. It is important that the value of the AEC be conservative and technically defensible for the facility to meet the DOE Order 420.1B, *Facility Safety*, requirements that "Safety SSCs [systems, structures and components] and safety software must be designed, commensurate with the importance of the safety functions performed, to perform their safety functions when called upon …" and that "Hazard Category 1, 2, and 3 nuclear facilities with uncontained radioactive materials … must have the means to confine the uncontained radioactive materials to minimize their potential release in facility effluents during normal operations and during and following accidents" [4].

To resolve this issue, the project initiated several test programs to support the design of the PVP and PVV systems. This included the AEC test program, which was intended to determine the expected aerosol loading from spargers into the PVP and PVV systems. After the aerosol entrainment testing was completed, a report by FAI recommended an AEC value of 4.0×10^{-5}, lower than both BNI's previous value and the DOE-HDBK-3010 value.

Aerosol Testing. Between December 2011 and July 2012, Parsons conducted small-scale and medium-scale AEC testing. The sparger in the small-scale tests was a non-prototypic array of small orifices intended to generate evenly distributed 1/8-inch bubbles across the surface of the liquid [5]. The sparger in the medium-scale tests was a single sparge tube centered in the test vessel, similar in design to the sparge tubes in WTP process vessels [6]. The intent of the small-scale testing was to determine the amount of aerosols generated with different simulants and test conditions, while the intent of the medium-scale testing was to verify that the values for the small-scale testing bound the actual sparger operation [7].

During testing, air was introduced into the test vessel through the spargers, bubbled through the simulant, and drawn out via an exhaust fan located near the top of the apparatus. Non-prototypic mixers located at the bottom of both test vessels were intended to keep the simulant well-mixed and homogeneous during testing. To measure the AEC, part of the air in the headspace was passed through a filter system, which collected the aerosols. The weight of the collected aerosols on the filter was then used to calculate the AEC. The test results from small-scale and medium-scale testing were interpreted in a report by FAI [8].

A summary of the Board's staff team's assessment of the Parsons small-scale and medium-scale tests is presented below.

Range of Simulant Properties—The ranges of physical and rheological properties of the small-scale testing simulants are listed in Table 1. These bound the properties of the medium-scale testing simulants. For comparison, the expected ranges of physical and rheological properties of the non-Newtonian waste in WTP process vessels are also listed in Table 1. The properties of the small-scale and medium-scale test simulants did not span the range of properties (i.e., particle size distribution, viscosity, Bingham yield stress) expected in the WTP waste. The Board's staff team questioned this testing approach during the October 2012 video-teleconference. The project's outside experts from FAI stated that AEC values plateau to low, constant values when enough contaminants (e.g., salts, undissolved solids) are present and, therefore, parametric testing to span the full range of WTP properties is not necessary. The basis for this assertion was later captured in a graph generated by the author of the FAI report (as shown in Figure 1). The staff team examined the graph, but could not conclude that the AEC values plateau to a low, constant value with increasing concentration of solids. For example, the graph shows that for a given concentration of solids, the AEC values can vary more than one order of magnitude. The staff team concludes that the provided graph does not support the previous assertion. As a result, the staff team was not able to conclude that the testing conservatively predicts the aerosol challenge to the WTP ventilation systems.

Table 1: Parsons Small-Scale Simulant Properties and Expected WTP Waste Properties

Property (unit)	Parsons AEC Testing Simulant [5]	WTP Non-Newtonian Vessels [9][b]
Insoluble solid particle size distribution, d_{50} (µm)	23.5[a]	0.3-42
Liquid specific gravity	1.0-1.4	1.1-1.4
Slurry viscosity (cP)	0.6-17	6-30
Slurry yield stress (Pa)	20-65	6-30

[a] 23.5 µm value is from [10].
[b] These values are based on information available at the time that reference [9] was written. Further characterization of tank waste and/or testing may change the expected range of these values.

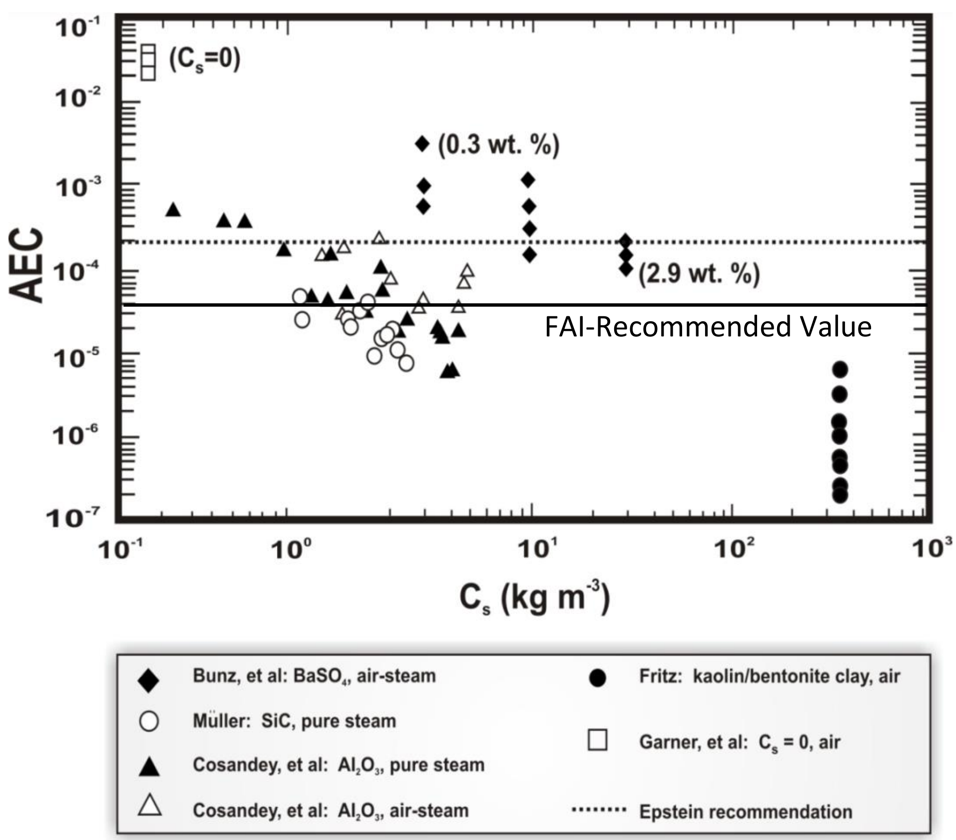

Figure 1: Entrainment coefficient above bubbling or boiling water pools containing non-soluble solid particulate material. The x-axis is concentration of solids in the simulant. The solid line is the FAI-recommended AEC value [8].

Composition of Solids in Aerosols—The test simulant contained large particles, e.g., 50 volume percent of the simulant solids had a diameter (d_{50}) greater than 23.5 µm. Parsons stated that solid particles with diameters over 20 µm are not expected to be suspended in aerosols and, therefore, to impact the AEC value [10]. However, to convert raw test data to an AEC value, Parsons' calculations assumed that the composition of aerosols on the filter media was identical to the composition of the bulk slurry in the test vessel. Given Parsons' methodology and reasoning, simulants with a larger d_{50} will produce smaller AEC values. But non-Newtonian waste at WTP may have d_{50} values as low as 0.3 µm (see Table 1). The Board's staff team is concerned that Parsons' choice of simulant, together with the assumption of equal aerosol and test slurry compositions, result in non-conservative AEC values.

Sparger Plugging—Several of the small- and medium-scale tests with a high-density simulant resulted in plugging of the spargers, which Parsons confirmed by visual inspection. FAI identified the tests that featured sparger plugging and other equipment failure in their analysis. FAI advised Parsons and BNI that the plugging phenomenon caused air to jet (rather than bubble) from the spargers, which resulted in AECs higher than expected during normal sparger operation at WTP [5]. Because several of the small-scale tests experienced sparger plugging, the Board's staff team is concerned that these tests demonstrate the possibility of frequent sparger plugging at WTP that will result in elevated AEC values and greater than anticipated HEPA filter loading rates.

Recommended AEC. BNI contracted FAI to review the aerosol entrainment test results and provide a recommendation on an appropriate upper bound AEC value for use in predicting aerosol generation rates in WTP process vessels. A summary of the major conclusions of the FAI report [8] follows:

- The maximum AEC values from the small-scale test were higher than the maximum AEC values measured during the medium-scale tests. FAI attributed this difference to two artifacts of the small-scale tests. For the first artifact, FAI argued that the vertical convection rates in the headspace of the small-scale tests were larger than those in the medium-scale test vessel, as well as those expected under prototypic plant conditions. Consequently, FAI concluded that the measured AEC values were artificially elevated in the small-scale tests. For the second artifact, FAI argued that gas jetting from the small orifices in the small-scale test sparger system resulted in the formation of very small bubbles, which, upon bursting at the waste surface, produced additional aerosols, thereby increasing the measured AEC values.

- The largest values of AEC measured in the small-scale tests exceeded 1.0×10^{-3}, and the medium-scale test values exceeded 5.0×10^{-5}. Using arguments regarding enhanced aerosol production and entrainment in the small-scale tests, FAI based the recommended AEC value for WTP on the medium-scale test data. FAI examined the medium-scale test data and concluded plugging of the sparge tubes and gas jetting was also present in some tests and contributed to elevated values of AEC. FAI recommended two bounding values for the AEC:

  AEC = 1.0×10^{-4} (for severely partially plugged spargers with gas jetting)

  AEC = 4.0×10^{-5} (for clean or partially plugged spargers)

Figure 2 shows these two recommended values of AEC in relation to all the small- and medium-scale test data [8].

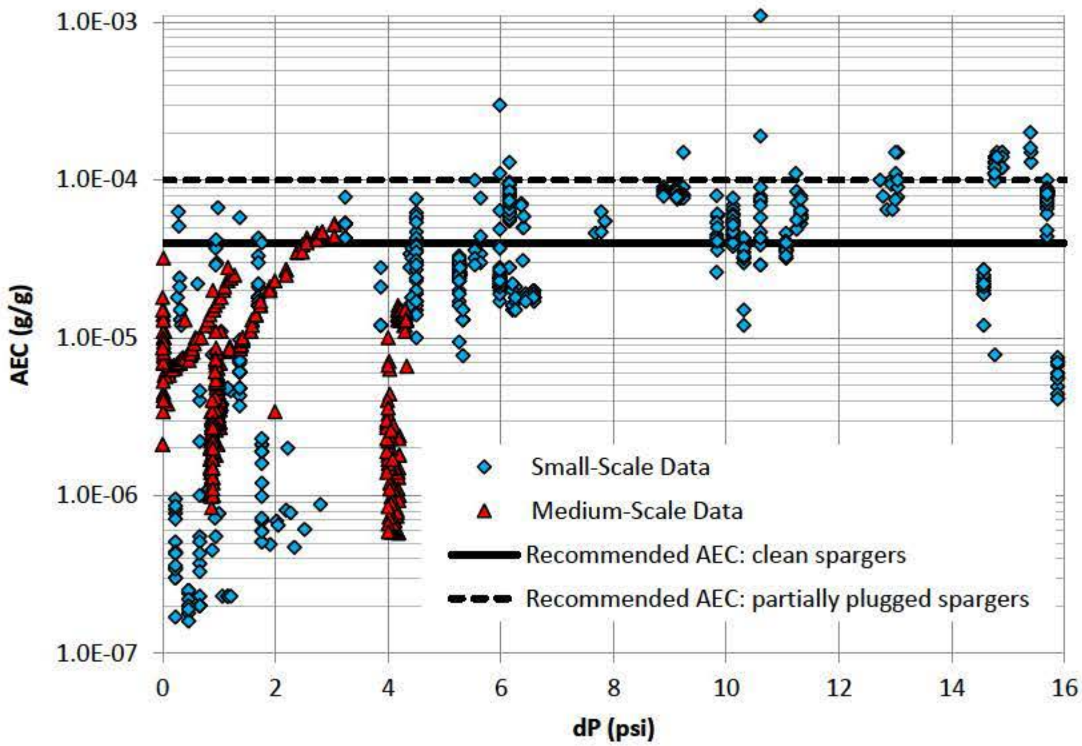

Figure 2. Recommended AEC values in relation to all small- and medium-scale test data analyzed as a function of sparger pressure difference (dP).

To support the recommendations, FAI developed several models and calculations. These included a model for enhanced aerosol transport due to natural convection, a model for the plugging process in a prototypical sparger pipe, and a model of sparge gas jetting from plugged nozzles, as well as a fairly complex model for enhanced aerosol generation due to gas jetting.

A summary of the Board's staff team's assessment of the models and calculations [8] is presented below.

Model for Enhanced Entrainment Due to Natural Convection—The FAI report stated that a contributing factor to high AEC values measured in the small-scale test tank was natural convection caused by temperature gradients in the headspace. This natural convection increased the upward gas flow rate in the small-scale headspace and, heavier droplets were entrained. The report concluded that the upward velocity due to natural convection was significant compared to the upward velocity due to the forced sparge flow alone. The report also concluded that because the medium-scale test tank was heat-traced, natural convection was not expected and, therefore, was not analyzed in the report. The report also stated that natural convection in WTP vessels should not significantly influence aerosol entrainment.

The Board's staff team examined the FAI report's model and equations for natural convection in the small-scale tank. The model assumes natural convection in the small-scale tank is driven by a temperature difference between the cooler wall of the vessel and the warmer headspace atmosphere, which results in a downward flow along the wall of the vessel. FAI's proposed flow pattern within the small-scale tank is given in Figure 3 below. The boundary layer shown in the figure is the zone of downward flowing cold air adjacent to the tank wall. The natural convection model solves for both the boundary layer thickness and downward flow rate at the wall. The downward flow at the tank wall was converted to an upward velocity in the headspace through an area relationship that neglects the area contained within the boundary layer. The magnitude of the upward velocity due to natural convection was compared with the magnitude of the sparge-induced upward velocity and found to exceed it by about a factor of three. The report concludes that natural convection artificially increased the droplet vertical transport, resulting in artificially high values of AEC.

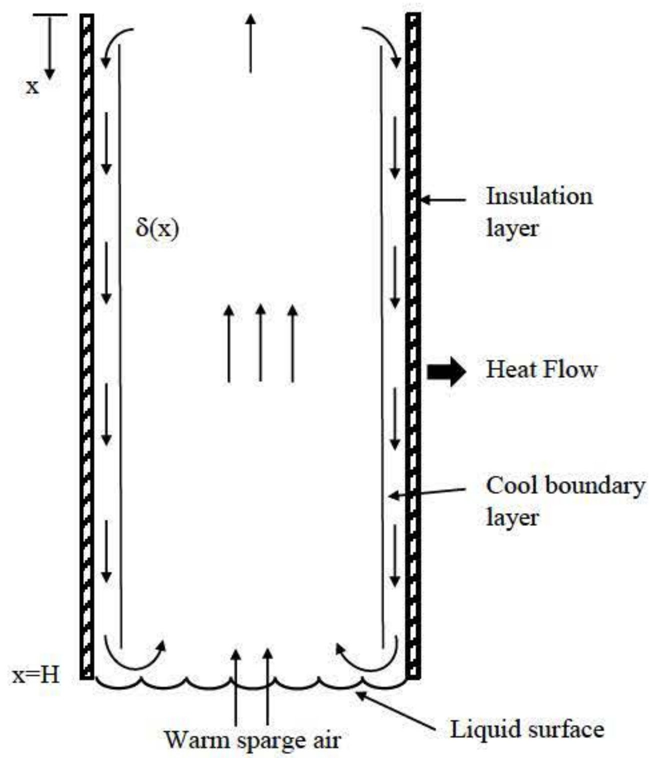

Figure 3. Conceptual model for natural convection in headspace

The analysis presented in the report implicitly assumes that the boundary layer is very thin compared to the diameter of the tank. Specifically, the report estimates the boundary layer thickness along the wall of the tank using an equation for a vertical plate, an approach that is generally valid when the boundary layer thickness is much less than the tank diameter. The Board's staff team calculated the boundary layer thickness in the small-scale test tank using the equations given in the report and found that the boundary layer grows rapidly to exceed the tank radius. Because the key modeling assumption of a thin boundary layer is not supported by the model results, the conclusion in the FAI report that enhanced entrainment is due to natural convection in the small-scale test tank is not supported by the analysis.

The report also repeats the calculation for PTF process vessel UFP-02 to demonstrate that enhanced entrainment due to natural convection is not expected to be significant in plant vessels. However, the staff team found that the calculation does predict significant enhanced convection in the vessel. The conclusion that enhanced entrainment due to natural convection is not significant in plant vessels is not technically justified by the analysis presented. The Board's staff team found that the technical basis of enhanced entrainment due to natural convection during small-scale testing is not defensible. The staff team concludes a more realistic analysis of natural convection utilizing a computational thermal-fluid model would be required to determine the role of natural convection in both test vessels and plant vessels.

Model for Sparger Jetting Due to Nozzle Plugging—The FAI report presents an analysis that attempts to demonstrate that gas jetting due to sparger plugging occurred in the small-scale tests. Gas jetting occurs when the air velocity at the orifice is sufficiently large such that an air-only momentum jet is formed. At lower velocities, discrete bubbles form at the orifice. The report hypothesizes that during gas jetting, large droplets at the edge of the gas jet break up due to gas dynamic forces overcoming liquid surface tension forces, resulting in droplets capable of being suspended within very small gas bubbles. These very small (millimeter size) bubbles, upon bursting at the waste surface, will produce additional aerosols, thereby increasing the AEC values. The basis for the gas jetting model is a semi-empirical expression for the critical sparger orifice velocity for the formation of a gas jet [11]. For the small-scale tests, FAI calculated the critical gas velocity for jetting in an unplugged sparger orifice of 0.7 mm diameter to be 168 m/s and the corresponding pressure drop to be 6.1 psi. The report concluded that when pressure drops greater than about 6.1 psi were observed during testing, sparger jetting was likely. Further, the report claimed that the test data collected at 8 ft elevation showed a "jump" in measured AEC values at a pressure drop of about 5.6 psi. The report concluded that the correspondence between the calculated pressure drop for sparger jetting and the pressure drop above which AEC values increased was strong evidence of severe sparger plugging, resulting in elevated values for AEC.

The Board's staff team independently analyzed whether the data "jump" at 5.6 psi claimed in the report was meaningful and not an artifact of data noise or some other phenomena. The staff team attempted to validate the report's conclusion by evaluating the data collected at all elevations and found that, while there was some discernable increase in AEC for pressure drops in the range of 5–6 psi, it was a statistically insignificant local feature of the data, and no general trend can be established.

The staff team also found that the pressure drop criterion for sparge jetting presented in the report was conceptually flawed and inconsistent with the model presented in the report. For example, when a plug begins to form, the effective diameter of the sparger orifice is reduced, resulting in an increase in both critical velocity and pressure drop. Using the model equations presented in the FAI report, together with the test data, the staff team calculated the average sparge nozzle velocity and the predicted critical velocity for jetting for all of the small-scale tests. Figure 4 below shows the ratio of these two velocities plotted versus measured pressure drop. The staff team determined that the average nozzle velocity was less than the critical velocity for jetting for all test points. This means that, according to the jetting model presented in the report, when numerically evaluated, the critical pressure drop for jetting was always found to be higher than the measured pressure drop. Therefore, according to the report's criteria, no jetting was present in any of the tests. Further, the staff team repeated the evaluation for the results of the medium-scale test data and found that, based on the report's model, sparger jetting was present in all but one test series. This is inconsistent with the report's claim that only two of the medium-scale test cases exhibited sparger plugging.

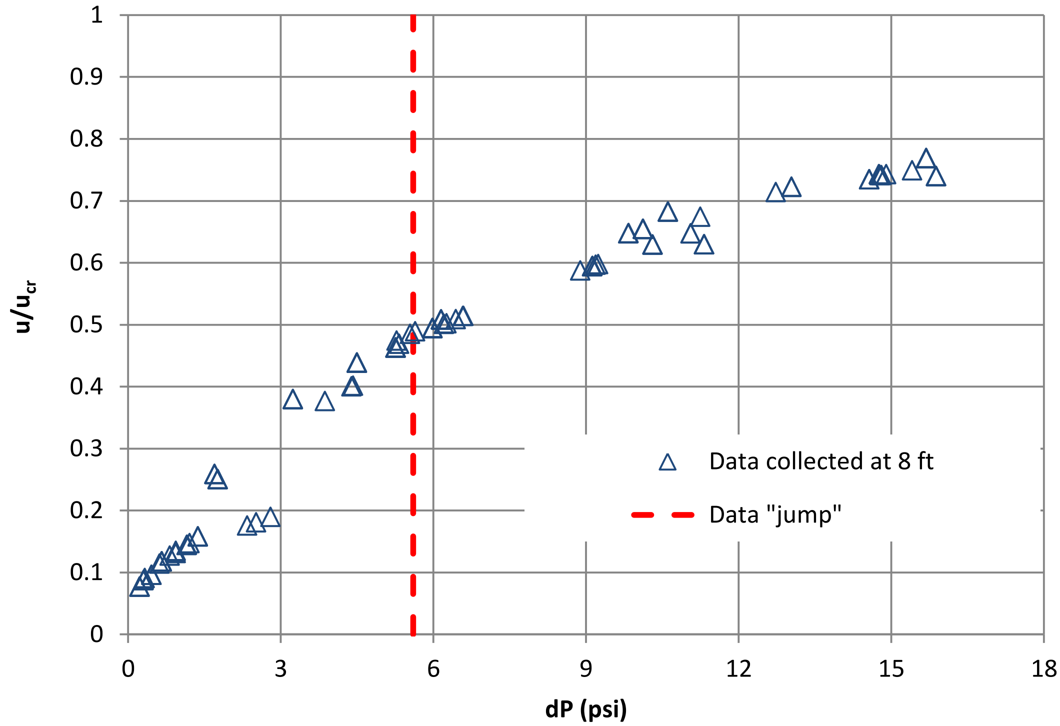

Figure 4. Sparger nozzle velocity relative to the critical velocity for jetting for the small-scale test data based on jetting model [8]. Also shown is the pressure drop corresponding to the "jump" in AEC data claimed in the FAI report.

Based on these findings, the Board's staff team concluded that the proposed jetting model does not adequately reflect the data collected. Consequently, this model does not provide an adequate technical justification for asserting that small-scale testing experienced enhanced AECs due to gas jetting. Moreover, the model does not provide an adequate technical justification that the medium-scale data only experienced enhanced AECs due to jetting in two specific cases.

Model of Enhanced Aerosol Generation Due to Gas Jetting—The FAI report included a model for prediction of the enhanced aerosol entrainment coefficient, *E*, due to gas jetting in the medium-scale tests. The model incorporated relationships describing the gas jet structure and break-up process, as well as the distribution of liquid droplets (aerosols) inside submerged bubbles. The model relied on various empirical and semi-empirical correlations, and various mathematical analyses and assumptions. The report found that the computed value of *E* for Test 103 was larger than the measured value of AEC at low sparge flow rate, and when added to that value, was consistent with measured values of AEC at higher flow rates where plugging was deemed important. For Test 107, the computed value of *E* was about twice the measured value. The report concluded that the model predictions "appear to be in rough agreement with the data, suggesting that gas jetting and aerosol production at the sparger orifice were probably responsible for the high AEC values" [8]. The report also acknowledged the model is quite sensitive to bubble size and droplet size distribution within the bubbles.

Given the complexity of the mathematical model and number of inputs, the Board's staff team examined the sensitivity of the model result to model input uncertainty in order to determine if model agreement with the data was statistically meaningful. In lieu of a complete Monte-Carlo uncertainty analysis, the staff team numerically computed sensitivity coefficients for 10 of the model inputs. From these, the staff team defined a total model sensitivity ratio, which is the ratio of model output given uncertain inputs to the model output with the reported inputs. The staff team determined a conservative lower and upper bound for this ratio as a function of model input uncertainty (assuming all inputs had the same uncertainty). The staff team noted that to achieve a model result that is accurate to about one order of magnitude, the average input parameter uncertainty needs to be about 3–4 percent. Based on the staff team's judgment, a challenging, but reasonable, input parameter uncertainty of about 20 percent will result in a model uncertainty of about six orders of magnitude. Based on the sensitivity analysis of the model, the staff team concludes FAI has not shown that correspondence of the model result with test observations is anything more than coincidental.

Conclusions. The Board's staff team found that the aerosol test programs used simulants that lacked a sufficient range of physical and chemical properties and contained unverified assumptions about the aerosol composition. Due to data showing pressure increases and flow decreases over time while sparging, the staff team agrees that there is evidence of sparger plugging in both the small- and medium-scale tests, and that plugging may have affected measured AEC values. However, given the instances of unsupported assumptions and conclusions, and a high degree of uncertainty in the report's analysis, the staff team concludes there is an inadequate technical basis for the recommended AEC values. Additionally, because the small-scale tests were intended to parametrically examine various waste properties, elimination of these data results in a very limited data set from which the recommended AEC values were obtained. Consequently, the staff team concludes both the quality and quantity of data are insufficient to determine conservative values of AEC for use in the WTP design.

The staff team concludes that, if the project uses the recommended AEC value for the ventilation systems design, it will not meet the safety requirements in DOE Order 420.1B that "Safety SSCs and safety software must be designed, commensurate with the importance of the safety functions performed, to perform their safety functions when called upon …" and that "Hazard Category 1, 2, and 3 nuclear facilities with uncontained radioactive materials … must have the means to confine the uncontained radioactive materials to minimize their potential release in facility effluents during normal operations and during and following accidents" [4].

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