Department of Energy
Washington, DC 20585

JAN 2 9 2018

The Honorable Sean Sullivan
Chairman
Defense Nuclear Facilities Safety Board
625 Indiana Avenue NW, Suite 700
Washington, DC 20004

Dear Chairman Sullivan:

On April 5, 2011, the Defense Nuclear Facilities Safety Board (DNFSB) sent a letter to the Department of Energy (DOE) Assistant Secretary for Environmental Management regarding treatment of uncertainty from the use of the Waste Treatment and Immobilization Plant (WTP) methodology for estimating dose consequences due to spray leaks from pressurized piping. In the letter, the Board expressed concern with three major sources of uncertainty: 1) orifice configuration - the use of a single rectangular slit to represent all potential leak size geometries; 2) droplet size distribution - the assumed probability distribution of potential droplet sizes; and 3) agglomerate structure - whether the assumed dried agglomerates transform into a monolith without void space versus a sub-micron behavior that could form loosely packed agglomerates.

The first and second concerns regarding orifice configuration and droplet size distribution were addressed by testing and the development of a spray leak conservative correlation. The third concern regarding agglomerate structure was addressed by DOE expert review and evaluation, which was discussed in the report accompanying the Department's June 3, 2011, response letter. Additional details and associated technical bases addressing the Board's concerns and actions taken by DOE to resolve them, are provided in the enclosed Resolution Record.

If you have any questions, please contact Mr. William F. Hamel, Assistant Manager, Federal Project Director, WTP, Office of River Protection, at (509) 376-6727.

Sincerely,

James M. Owendoff
Principal Deputy Assistant Secretary for
Environmental Management

Enclosure

Resolution of Defense Nuclear Facilities Safety Board Issue: Waste Treatment and Immobilization Plant Methodology for Assessing Spray Leak Dose Consequences

Statement of Issue

In April 2011 the Defense Nuclear Facility Safety Board (DNFSB) identified the following concerns related to the methodology for assessing dose consequences from pressurized spray leaks involving radioactive liquids (Reference 1):

> The Board is concerned with the WTP project's treatment of uncertainty in the spray leak methodology. Major sources of uncertainty include:
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> Orifice Configuration – The WTP methodology uses a single rectangular slit to represent all potential leak site geometries. Leak site geometry is a major contributor to the total quantity of radioactive material released and the distribution of droplet sizes. Both of these parameters have a direct effect on the postulated unmitigated consequences to the public receptor. An analysis by the Board's staff shows that using different possible leak site geometries (i.e. several small orifices encompassing no more total crack area than assumed in the WTP analysis) results in higher unmitigated dose consequences to the public receptor. The small orifices may be more representative of an actual crack that causes a spray leak.
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> Droplet Size Distribution – The WTP methodology assumes that the distribution of droplet sizes in a spray release is accurately described by a Rosin-Rammler probability distribution (with assumed values for the mean and variance of the distribution). The type of droplet distribution and its variance have significant impact on the postulated unmitigated dose consequences to the public receptor. The Rosin-Rammler distribution, a cumulative Weibull distribution, was originally proposed as a natural distribution of particle diameters from crushing and grinding coal, although it has been used in industry for spray drop size distribution. An analysis by the Board's staff shows that other equally viable distributions of droplet sizes, such as lognormal distribution, will result in higher unmitigated dose consequences to the public receptor because they have more small droplets.
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> Agglomerate Structure – WTP process slurry contains a significant population of submicron-sized particles that could form loosely packed agglomerates; however, the WTP methodology assumes that the dried agglomerates transform from multiple discrete particles into a solid monolith with no void space. Analyses considering more probable sub-micron behavior of formation of agglomerates instead of a monolithic particle upon drying yield higher unmitigated dose consequences to the public receptor.

In the DNFSB *27th Annual Report to Congress* (Reference 2), this concern was summarized as follows:

> *Inadequacies in the Spray Leak Methodology*—In an April 5, 2011, letter to DOE, the Board identified safety issues related to DOE's model for estimating radiological consequences to the public from spray leak accidents in the PT and HLW Facilities. WTP recently incorporated test results from the Pacific Northwest National Laboratory spray leak testing program into its accident analyses.

Summary

The DNFSB raised three concerns regarding the treatment of uncertainty in the Waste Treatment and Immobilization Plant (WTP) spray leak methodology (as quoted above in the Statement of Issue section and in Reference 1). The U.S. Department of Energy (DOE) responded to these concerns in Reference 3 and agreed that the spray leak release estimates had uncertainties associated with orifice configuration and droplet size distribution. The resolution of these two issues would be decided upon by completion of spray leak testing. The third issue on agglomerate structure was addressed in the 2011 DOE response letter (Reference 3) that included a review of the process stream properties as summarized below:

> To clarify, the WTP model assumes the specified (average) solid fraction in each spray droplet. The solid particle sizes are not identified, but implicitly involve combinations of the original solid particle size distribution that yield the assumed fraction of solids in the droplet. Typically, there would be multiple smaller particles that may or may not be in direct contact within the droplet. As evaporation occurs, the solid particles would approach each other within the droplet held together by surface tension of the exterior liquid surface. As such, there are two cases of interest:
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> - For the solutions with significant Na, the evaporation process stops when a 19 M NaOH solution remains. The thick, residual sodium hydroxide solution is assumed to hold the remaining particles together in a coherent droplet. No void space is postulated in calculating the droplet size, since drying is not approached in these cases. For WTP, the significant Na cases are not the bounding cases.
> - For solutions without significant Na, it is assumed that essentially all of the liquid can evaporate provided the initial droplet size is 100 μm or less. Evaporation occurs as the droplet is falling toward the cell floor. The remaining solid particles are assumed to stay together absent any evident mechanism to separate them.

As a clarification to the previous DOE response provided in Reference 3, WTP does not postulate a complete dry-out of particle agglomerates from slurry streams containing dilute sodium hydroxide resulting from a hypothetical spray leak event. Because sodium hydroxide is hygroscopic, it will dry to a condition where the vapor pressure of the solution equals that of moisture in air. The small amounts of this very viscous gel will migrate to inter-particle spaces, and provide cohesive forces binding the solid particle agglomerates. In addition, any porosity (and resulting reduction in apparent density), and deviation from spherical shape are modeled by using a shape factor of 1.5. This value of shape factor is adopted from International Commission on Radiological Protection (ICRP) Publication 68 (Reference 4, Section 2.2, Table 1 on page 6). The ICRP 68 adopts this value from ICRP 66 (Reference 5), and uses it with 1 and 5 micron particles to develop dose conversion factors for radionuclides.

DNFSB staff provided the DOE Office of River Protection (ORP) a closeout briefing of their review of the WTP spray leak correlation/methodology on June 14, 2017. DNFSB staff continued to focus their concern on potential low sodium molarity slurries (e.g., waste stream UFP07 a washed and leached solids containing stream from the Pretreatment (PT) Facility ultrafiltration system), which could evaporate to the point where formation and separation of loosely packed sub-micron particle agglomerates could potentially yield a higher dose consequence to the public receptor. ORP has evaluated the process flowsheet waste composition projections of the low sodium molarity waste stream (i.e., UFP07) as presented in Bechtel National, Inc. calculation 24590-WTP-M4C-V11T-00021(Reference 6) and observe at the low concentrations projected there are approximately 2.8 kg/m^3 of dissolved chemical constituents (dissolved salts) predicted in the process stream at an estimated pH of 13. A great majority of the dissolved constituents are hygroscopic hydroxides. The ionic nature of the waste stream composition in UFP07 supports the basis that sufficient salts would be present to ensure strong intermolecular forces would bind small size solid particle agglomerates (e.g., 10 microns or less) from breaking apart in the event these particles are released and evaporated from a spray leak event. Furthermore, Bechtel National, Inc. is evaluating process design changes for the PT Facility flowsheet to remove the steps for oxidative leaching, nitric acid recovery, and lowering of the caustic leaching temperature. These process changes will result in higher concentrations of hydroxide and other soluble salts in the interstitial liquid phase of the washed and leached sludge (e.g., UPF07). Therefore, a postulated breakup of loosely packed evaporated sub-micron solid particle agglomerates is not considered credible. ORP considers that the risk of a breakup of sub-micron solid particle agglomerates is mitigated by process control and should not be considered a realistic phenomenon for evaluation in nuclear safety analysis.

DOE Commitment to Address Uncertainties in the WTP Spray Leak Methodology

ORP agreed with the DNFSB concern that the methodology for assessing dose consequences from pressurized spray leaks involving radioactive liquids on the WTP Project prior to 2011 was not conservative based on the treatment of uncertainties used in the methodology.

The WTP spray leak methodology used in assessing dose consequences from pressurized spray leaks depended on an empirical correlation to determine the amount of liquid flow that atomizes into respirable droplet sizes. This correlation determined an average droplet diameter and used a probability distribution function to predict the spray droplet distribution. The spray leak methodology had inherent uncertainties in the model with respect to WTP conditions because the correlation was derived from experiments using pure liquids and engineered nozzles. An expert panel of reviewers (Reference 7) noted that using this empirical correlation for breach configuration modeling of through-wall cracks with waste containing low sodium suspended configuration modeling of through-wall cracks with waste containing low sodium suspended solids in modeling aerosol generation would likely introduce significant uncertainty in estimating dose consequence. Hence, it was decided testing would be conducted to resolve these uncertainties

The Pacific Northwest National Laboratory (PNNL) was contracted to complete an experimental spray leak test program designed to provide experimental data from prototypic spray leaks to better predict release fractions supporting unmitigated consequence analysis. Some of these test parameters included aerosol generation rates, release fractions, droplet size distribution, and dependency of generation rate on leak site geometry.

Actions Taken Since 2011

Consistent with Reference 3, a formal DOE-approved test plan for spray leak testing and analysis to be performed was approved by ORP (References 8 and 9). Spray leak testing was conducted by PNNL during the 2012 to 2013 time frame. Testing was performed to mimic WTP process conditions (e.g., simulants of suspended solids, washed/leached slurry, dissolved salts); assessment of orifice (breach slot) orientation and orifice aspect ratio (change in slot length or width); multiple nearby orifices; aerosol contribution from splash, splatter, and free fall of an atomized spray released from an orifice (breach); and evaporative effects on measurements. Below is a discussion of the two DNFSB concerns within the context of the test experiments and results/conclusions.

Discussion of Orifice (Breach) Configuration

A spray leak is postulated to occur from a breach in the primary confinement boundary of a pipe or vessel. The breach may be caused by corrosion, erosion, jumper misalignment, weld crack, seal leak at pump or valve stem, impact, or other initiators. Due to the large differences in the design, operating conditions, and the failure mechanisms, the size and morphology (i.e., detailed geometrical and finish characteristics) of the breach is indeterminate with the currently available knowledge. However, the postulated breach can be divided into two broad groups:

- Those resulting from sudden change (i.e., impact, seismic event, and jumper misalignment)
- Those resulting from gradual deterioration (i.e., corrosion and erosion).

The breach from erosion or corrosion may start as one or more nearby holes, and, if left unattended for an extensive time period, these holes may increase in number and size, and may merge to form a breach with irregular edges, varying width, multiple connected branches, rough tortuous flow path, etc. DNFSB's concern was that several small orifices encompassing no more total crack area than assumed in the breach slot configuration used in the WTP model may be more representative of an actual crack and may result in higher unmitigated consequences to the public receptor.

Consistent with the DOE-approved test plan, a series of spray release tests were directed at acquiring data to address this concern. The PNNL tests and conclusions regarding breach configuration are described below.

PNNL Testing Results and Conclusions

To evaluate the two situations (i.e., several small nearby holes versus one larger orifice of equal area), PNNL conducted tests with several nearby holes and compared the results with those for an equivalent area larger hole. These tests are described in Section 7.1.2 in Reference 10 and in Section 8.2.2 in Reference 11. The test results showed no statistically significant difference, although there was a slight reduction in generation rates for smaller droplets for the several nearby holes configuration as compared with a large hole with equivalent area. This small reduction is postulated to be due to either the wash-down (interaction) effect of aerosol plumes from the nearby jets (i.e., due to agglomeration), and/or due to reduced air entrainment into the spray plume for nearby jets.

To gain further information and confidence, the release rates from slots were measured with the slot orientated along the pipe axis, along the pipe circumference, and also in the dead-end condition. In the dead-end condition, the only flow is through the breach. These tests are described in Section 7.1.1 in Reference 10 and Section 8.2 in Reference 11. Based on these data, the PNNL reports (References 10 and 11) concluded slot orientation and flow around the slot have no appreciable effect on the release fractions or cumulative generation rates.

The spray testing was also done by varying slot length and slot width. These tests are described in Section 7.1.4 in Reference 10 and Section 8.2.4 in Reference 11. Overall, the PNNL reports considered the amount of data to be insufficient to support any correlation of release fractions with slot width, length, or aspect ratio (Reference 11, Section 8.2.5). The PNNL reports also observed further testing was not needed because the orifice area adequately captured the effect of orifice geometry (Reference 11, Section 8.2.5).

The PNNL correlation for aerosol generation rates from additional test results (Reference 12, Equation 10.4), shows a weak dependence of cumulative release fraction on orifice size, and the experimental data discussed above show that aerosol generation rates from several nearby small holes are not much different from the aerosol generation rates from a larger hole of equal cross sectional area. These results support modeling of the postulated breach for spray leak source term as a single orifice.

At the DNFSB staff closeout briefing on June 14, 2017, a continued concern was presented that the generation rate from multiple orifices would exceed the generation rate from a single orifice by a factor of $N^{0.207}$, where N is the number of orifices. ORP has evaluated this concern and considers that this risk is mitigated by assessing the likelihood of multiple orifice spray leaks in the PT Facility when applying the PNNL conservative correlation. For piping and vessels located in black cells and hard-to-reach areas, 24590-WTP-SRD-ESH-01-002, *Waste Treatment and Immobilization Plant Safety Requirements Document*, Volume II, Rev. 9 Appendix M, "Ad Hoc Implementing Standard for Closed Cell (Black Cell) and Hard-to-Reach Areas" (Reference 13), specifies a number of features to be included in the design of vessels and piping systems in closed cells "to achieve a comparable reliability with systems that are expected to last over the 40 year design life without failure." One of the features includes volumetric inspection. The requirement is that "full volumetric inspection of the welds in the primary confinement boundary of vessels and the girth welds in process piping is performed to ensure that weld defect are discovered and repaired." This weld inspection requirement is above and beyond what is required by the American Society of Mechanical Engineers national consensus code for process piping (i.e., ASME B31.3, *Process Piping* [Reference 14]) used by WTP in the code of record. ORP relies on this design requirement to ensure the integrity of black cell and hard-to-reach area vessel and piping welds over the PT Facility design life. Thus, ORP believes that a risk of nearby (or remotely located) multiple orifice spray leaks in a piping route occurring simultaneously as a postulated event in black cell and hard-to-reach areas for dose consequence analysis is extremely unlikely, and analysis using the postulated breach slot for a particular pipe size in the PNNL conservative correlation is appropriate for assessing risk in estimating unmitigated dose consequences.

Postulated spray leaks occurring in the PT Facility hot cell should be evaluated using a single breach slot because the likely initiation for a spray leak in the hot cell is a misalignment of a jumper connection. Jumper connections are considered replaceable and can be changed out to support different operating configurations. ORP also considers the breach slot to be reasonably conservative even for a multiple orifice spray leak in the hot cell. There is no reasonable assumption for predicting how many multiple orifice leaks could simultaneously occur as a technical basis for using a factor of $N^{0.207}$ in estimating spray leak generation rate for a bounding event. Therefore, ORP believes using the PNNL conservative correlation provides a reasonably conservative approach for use in single/multiple orifice and large breach slots using the total breach/orifice area for spray leak analysis in the hot cell.

The orifice area used in the PNNL conservative correlation is modeled as a rectangular slit where length is determined by the following criteria:

- One pipe diameter with a nominal diameter less than 3 inches
- Three inches for a pipe with a nominal diameter from 3 inches to 6 inches
- One-half of the pipe diameter for a pipe with a nominal diameter greater than 6 inches.

WTP will continue to use the U.S. Nuclear Regulatory Commission (NRC) method for evaluating through-wall leakage cracks for moderate-energy fluid system piping (Reference 15) using a rectangular breach slot in the WTP spray leak methodology. The NRC criteria is fully used for nominal pipe diameters greater than 6 inches. For smaller pipe sizes (less than 6 inches), the orifice area uses the NRC criteria for breach width only, and relies on similar analysis assumptions used by the Hanford Tank Operations Contractor for breach length.

Discussion of Droplet Size Distribution

The droplet size distribution in a spray is needed to determine the number (or rate) of respirable droplets (i.e., less than 10 microns aerodynamic equivalent particle size) that reach the receptor of concern. Consequently, for the same total release rate, the spray containing finer droplets leads to larger unmitigated consequences to the public and workers. The droplet size distribution can be described by one of many probability distribution functions, such as the Rosin-Rammler and log-normal probability density functions. Both distributions, in general, use two parameters (related to mean and spread) to describe the population distribution. Consequently, fitting either distribution or other distributions specifically developed or modified for spray droplet size representation, to any experimental data is approximate, and a frequent focus of discussions in research papers.

To clarify, the particle size distribution adopted in the previous WTP methodology (Reference 16) used two parameters: (1) the Sauter mean diameter based on extrapolations of the Dombrowski and John correlation; and (2) a droplet size distribution based on fuel oil spray data in the Rosin-Rammler probability distribution. The use of a smaller fitting constant (spread of droplet size) as compared with best fit in the Rosin-Rammler provided a larger proportion of smaller diameter droplets in comparison to the fuel oil spray data. This was judged by WTP to be more conservative yielding a higher respirable fraction. The Rosin-Rammler distribution was adopted by WTP drawing upon the Hanford tank farm spray leak methodology. The basis for using the Rosin-Rammler probability distribution over a log-normal distribution is cited in Reference 3. Reference 3 cites a Hanford contractor evaluation showing that for the same mean and variance in the range of predicted Sauter mean diameters, the Rosin-Rammler probability density function had significantly greater proportion of particles predicted at the smaller sizes and was considered conservative as compared with a fit to log-normal distribution.

As with any analytical model, there is an uncertainty in its application, especially if the model is based on unrelated test media and had a limited range of experimental data. To reduce these uncertainties that ORP had acknowledged in its previous spray leak methodology, ORP directed a spray leak test program to obtain data associated with orifice (breach) configurations formed from through-wall cracks and droplet size distribution using various WTP simulant slurry and solution (e.g., sodium nitrate and anti-foam agent solutions) sprays representing expected waste conditions at WTP. The test program was subsequently expanded to include water droplet size distribution data. The basis for acquiring this data would bound the simulant slurry and solution droplet generation rates and droplet size distribution for any given set of conditions (e.g., pressure, breach size).

<u>PNNL Testing Results and Conclusions</u>

Based on the completed PNNL test results (References 10 through 12, 17, and 18), a conservative correlation was developed to bound all upper 95 percent confidence droplet generation rate data for droplets less than 100 micron for all test simulants.

Note: Droplets larger than 100 micron are not a concern in safety analysis as they settle out and do not reach the receptors of concern (Reference 20).

The conservative PNNL correlation uses in-chamber measurements for the smaller droplet sizes and in-jet measurements for larger droplets. The droplet size distribution is incorporated into the PNNL correlation, as is the orifice flow-rate equation. Thus, the PNNL correlation reduces to a single equation for conservatively estimating the respirable aerosol generation rate incorporating breach slot (orifice) configuration in terms of area, release pressure (psig), droplet diameter (micron) including the contribution to spill/splash of jet spray, and entrainment from liquid pool.

The revised WTP spray leak methodology (Reference 20) incorporates the conservative PNNL correlation for generation rates for different droplet sizes. In the revised methodology the empirical correlation and probability distribution function used to estimate droplet size distribution from the previous methodology (Reference 16) are replaced by a single (PNNL) correlation. As determined by PNNL test results, the previous methodology (Reference 16) was conservative for smaller breaches and lower pressures but non-conservative for larger breaches and higher pressures. Overall, the revised methodology is conservative for the WTP conditions of range of pressures, fluid characteristics, and tested breach sizes.

ORP concurred with the revised spray leak methodology and directed the PNNL correlation be incorporated into the WTP spray leak methodology (Reference 21). ORP will evaluate the conservatism of the PNNL correlation for any parameters outside of what was previously tested. Therefore, future engineering design changes differing from testing parameters used (e.g., spray leak pressure) will need to be thoroughly evaluated for consideration of additional margin to ensure conservatism in the aerosol generation rate used in unmitigated dose consequence analysis. At present, the PT Facility ultrafiltration recirculation line pressure is identified as a pipe route potentially exceeding the correlation's test parameters. The revised WTP spray leak methodology was issued in 2015 (Reference 20). The PNNL correlation is now being used to determine unmitigated consequences for liquid spray leaks.

Conclusions

Orifice Configuration – The DNFSB staff's concern regarding orifice configuration has been addressed through spray leak testing and is considered resolved. The concern that different leak site geometries (i.e., several small orifices encompassing no more total crack area than the one single orifice assumed in the WTP analysis) results in higher unmitigated dose consequences to the public receptor is not supported by the test results.

Droplet Size Distribution – The DNFSB staff's concern regarding non-conservative choice of droplet size distribution was resolved through testing and is considered resolved. The PNNL correlation is based on water sprays, which provide significantly more conservative results when compared to high solids and non-Newtonian slurries.

Agglomerate Structure – The concern regarding agglomerate structure was resolved based on expert review. This review (refer to Reference 3) and evaluation of PT Facility process operating conditions support the WTP position on particle agglomeration for the low-sodium waste streams (i.e., agglomerates in the aerosol will not de-agglomerate causing increased dose consequences).

Summary

The PNNL revised correlation for spray leak generation rate, derived from extensive spray leak testing (presented in References 10 through 12, 17, and 18), addressed and resolved uncertainties regarding orifice configuration and droplet size distribution as described in the DNFSB letter to DOE in April 2011 (Reference 1). The concern related to agglomerate structure was addressed separately in DOE's response letter to the DNFSB in June 2011 (Reference 3) along with additional discussion in this document.

DOE considers that the concerns of uncertainty for the spray leak methodology described by the DNFSB in 2011 are resolved. The revised spray leak methodology incorporating the spray leak testing by PNNL has been accepted by the WTP contractor and concurred on by ORP for use in estimating unmitigated consequences for liquid spray releases in WTP. ORP will also evaluate the conservatism of the PNNL correlation for any parameters outside of the previously conducted test program as required.

Concurrence

Victor L. Callahan — 8-7-17

Victor L. Callahan, Senior Technical Advisor, Waste Treatment and Immobilization Plant, Office of River Protection — Date

Langdon K Holton — 8-7-17

Langdon K Holton, Senior Technical Authority, Waste Treatment and Immobilization Plant, Office of River Protection — Date

Approval

8/9/17

Robert G. Hastings, Assistant Manager, Technical and Regulatory Support, Office of River Protection — Date

8/14/17

William F Hamel, Federal Project Director, Waste Treatment and Immobilization Plant, Office of River Protection — Date

Ken W. Smith — 9/8/17

Kevin W. Smith, Manager, Office of River Protection — Date

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