<u>RAI 2-1.</u> Explain why the guidance of ASTM C869 was not followed to determine the significant properties of the Low-Density Cellular Concrete (LDCC).

In chapter 2, "Materials," subsection 2.2.1, the applicant describes the different standards used to manufacture the LDCC. The applicant, in the same subsection, establishes the properties of LDCC by assuming values of density and compressive strength. The LDCC was prepared in accordance with ACI 523.1R using a foaming agent per ASTM C869.

The guidance of ASTM C869 states that "this is accomplished by using the foaming agent in making a standard cellular concrete test batch (see Method C796) from which test specimens are cast. Then, significant properties of the concrete are determined by tests and compared with the requirements of Section 3."

This information is required to support staff conclusions about the properties used in the non-linear analyses performed to satisfy the requirement of Title 10 of the Code of Federal Regulations (10 CFR), Section 71.71 and 10 CFR 71.73

RAI 2-1 Response:

ASTM C796 and ASTM C869 provide standard test methods and specifications for foaming agents used in the making of pre-formed foam for LDCC. ASTM C869 certified foam from the foam manufacturer is used in the LDCC formulation and the foam is tested by an independent ASTM recognized laboratory using ASTM C796 test protocols. The ASTM C869 foaming agent is required via an Orano Decommissioning Services (ODS) grout specification. Regarding the foaming agent, the guidance in ASTM C869 was used in comparing the significant properties of the LDCC to that identified in the standard. This is confirmed in the ODS grout specification wherein it states that when the foaming agent is used it follows *"applicable guidance in ASTM C869 when tested using guidance from ASTM C796."*

It is important to note that the ASTM C869 specification scope states that it is used "*to provide the means for evaluating the performance of a specific foaming agent*". Significant properties of the LDCC are determined by tests (ASTM C796) and may be compared with properties identified in Table 1 of ASTM C869. ASTM C796 states this in Section 5, that the significance of the standard may be for "*comparison or compliance with the requirements of Specification C869*". Therefore, a discussion of the two significant properties, wet-cast density and compressive strength follows.

The wet-cast density (i.e., density prior to aeration) in ASTM C869 is listed as 40 ± 3 pcf, which is bounded by the LDCC density in the SAR of 30-60 pcf. A higher density was used in the LS-DYNA® drop impact analyses in order to establish the correct overall weight in the model for the RPV (See SAR Appendix Section 2.12.2.4.1, *Model Geometry and Weight Check*).

Recently, grout testing was conducted by ODS to downselect the optimum density for filling the RPV. As a result of this testing, a LDCC density of 53 pcf was chosen in order to maximize the flowability of the grout while maintaining a conservative margin of adherence with respect to CR3MP weight and void content constraints. As part of this final LDCC formulation selection process, it was determined that the usage of admixtures, besides the foam concentrate itself will not be necessary. In addition, it has been decided by ODS that the usage of HDCC will also be unnecessary.

The minimum compressive strength of ASTM C869 is 200 psi. Whereas, for the non-linear free-drop analyses, a minimum assumed compressive strength of 100 psi is used in the SAR. Therefore, a more conservative assumption was taken. During the recent short-listing selection process for the grout mentioned above, performance indicators such as the minimum compressive strength were studied. As a result of the measurements taken, the actual 28-day compressive strength value obtained for the 53-pcf LDCC was 210 psi. This 210-psi value is greater than double the minimum compressive strength of 100 psi in the SAR and greater than the ASTM C869 minimum compressive strength of 200 psi.

The selection of these significant properties of both density and compressive strength are conservative options when applied to the free drop impact analyses for the CR3MP. As a result of changes to the grout formulation by ODS, the usage of HDCC has been eliminated and usage of admixtures except for the foam concentrate in the LDCC have been removed. Relevant sections of the SAR have been updated to reflect the removal of the HDCC and removal of the LDCC admixtures.

[changes to SAR]

As a result of removing the HDCC, numerous wording updates to various sections of the SAR have been made (See SAR Change List enclosure included with the SAR letter).

<u>RAI 2-2.</u> Explain, in SAR subsection 2.5.2, how the contact surface loads, between the skid and the CR3MP, and between the tiedown frame and CR3MP, are addressed in the structural analysis for normal conditions of transport (NCT).

In chapter 7, "Package Operations," the applicant states that the CR3MP package is secured in place on the barge and during transport by the heavy haul trailer by a configuration using a skid at the bottom and a tiedown frame at the top. The frame contacts the CR3MP package at the top and the skid with its lateral restraints at the bottom.

This information is required to support staff conclusions on the structural integrity of CR3MP steel shell in meeting the requirements of 10 CFR 71.71 (c)(1),(2),(3) and (4).

RAI 2-2 Response:

SAR Section 2.5.2 has been revised to provide further description regarding the tiedown hardware and also to discuss how this hardware will have an inconsequential effect upon contact forces placed on the CR3MP under the conditions of 10 CFR 71.71(c)(1), (c)(2), (c)(3), and (c)(4) during both conveyance modes, barge and road transport.

[changes to SAR]

In response to this RAI, SAR Section 2.5.2 has been revised. Some unrelated clarifications to the load securement narrative from the customer have been incorporated into Sections 2.5.2, 7.1.1, 7.1.3 and 7.2.1 as well.

<u>RAI 2-3</u> Provide an assessment of other drop orientations to explain how it was determined that the governing drop orientations bound all other drop orientations.

In section 2.6.7, "Free Drop," the applicant states that only three governing drop orientations were considered for the free drop analysis under NCT conditions. However, the applicant did not assess other drop orientations, nor did it explain how it was determined that the governing drop orientations bound all other drop orientations.

This information is required to support staff conclusions on the structural integrity of CR3MP steel shell in meeting the requirements of 10 CFR 71.71.

RAI 2-3 Response:

SAR Section 2.6.7, *Free Drop* and its subsections have been revised to assess the NCT free drop orientations and to further clarify the governing drop orientations and how they bound other possible drop orientations. A summary of these revisions is included in this response and in new SAR Table 2.6-1, showing the results of the various drop case orientations. CR3MP drop orientation results are compared, and various assessments are provided for each of the drop orientations.

Based on experience, a package having a diameter-to-height ratio near to 1 (diameter and height nearly the same), as is the case for the CR3MP, will not have a significant slapdown response. Therefore, the worst-case orientation will be the one where the drop energy is concentrated on the least material volume (i.e., the CG over corner drop). This would be the drop case with the highest structural deformation potential.

However, it is noted that a follow-through tip-over condition from the CG over corner drop may have more energy than a pure NCT top-down end drop. This continuation condition is studied because the CG vertical height drop for this case is greater than that of the simple 1-ft NCT End Drop. Therefore, for completeness, a simulation of the follow-through tip-over analysis onto the top cover is run for comparison and considered along with the other cases. Such a follow-through drop case onto the cover occurs as the overall CR3MP diameter is slightly greater than the total height. This drop condition is documented in new SAR Section 2.6.7.5, *NCT CG over Corner Drop Tip-Over*, where the CR3MP end state condition after the corner drop becomes the initial state for the tip-over simulation. As the results show during the tip-over event, the additional energy available produced a relatively high acceleration. Although the corner drop had higher deformation and higher resultant Effective Plastic Strain (EPS) build-up, the tip-over case includes the accumulated strain limit damage from the corner drop case, hence it provides the bounding margins.

Regarding a bottom-down end drop, the CR3MP is symmetrical by design, hence this drop case is not included. In addition, the top-down case already includes any effect of contents shifting within the CR3MP 3-in. upper headspace. The side drop case is included for completeness. In all cases, when subjected to a 1-ft free drop onto an unyielding surface, the containment boundary of the CR3MP remains intact.

[changes to SAR]

In response to this RAI, the LS-DYNA® drop impact models in SAR Appendix Section 2.12.2, *Free Drop Evaluation*, have been updated. In addition, statements in SAR Section 2.6.7 have been updated and SAR Table 2.6-1, *Assessment of Free Drop Orientations* has been added. Also, because of other RAI responses, a new Section 2.6.7.1, *Material Properties and Acceptance Criteria Used in Free Drop Analysis* has been added. This has resulted in expanded and renumbered SAR Sections 2.6.7.2, 2.6.7.3, 2.6.7.4. Due to the addition of the tip-over follow-through drop case, a new SAR Section 2.6.7.5, *NCT CG over Corner Drop Tip-Over* has been added.

<u>RAI 2-4</u> Provide a plot of the material behavior simulation with those of the ASTM material test curves for A516 steel using the same time steps used in the analysis. Demonstrate how effectively the selected approach simulates the stress-strain behavior of the ASTM A516 Grade 70 steel through the entire range of the simulated drop.

In section 2.6.7, "Free Drop," the applicant describes the methodology adopted to simulate the stress-strain behavior of the modeled material using a piecewise linear stress-strain curve. However, the applicant has not demonstrated how effectively this approach simulates the stress-strain behavior of the ASTM A516 Grade 70 steel through the entire range of the simulated drop. Also, the applicant did not provide a plot of the material behavior simulation with those of the ASTM material test curves for A516 steel using the same time steps used in the analysis.

This information is required to support staff conclusions on the ability of the material model to simulate the material non-linearity during a drop condition required by 10 CFR 71.71 and 71.73.

RAI 2-4 Response:

Tensile tests were initially performed on specimens as part of the certified material test reports (CMTRs). These tests provided basic material properties for both the 3-in. thick and 6.5-in. thick ASTM A516, Grade 70 plate raw material used for CR3MP fabrication. These tests verified the material strength properties, including the yield and tensile strength and elongation. This testing also provided stress-strain data in the elastic region, and as a result allowed for determination of the elastic modulus (See SAR Appendix Figure 2.12.2-7). A second set of tensile tests was performed on the same original material heats used in CR3MP fabrication, using two samples of both the 3-in. thick and 6.5-in. thick plate. The two samples of each plate thickness represented the material lots which had the lowest tensile strength recorded for the initial tests conducted. This second set of follow-up tests were used to characterize the stress-strain curves in the plastic region out to fracture (See SAR Appendix Figure 2.12.2-8). Both the first and second tests were conducted in conformance with the ASTM A370 standard, using ASTM A370, Figure 3 dimensions for a standard 0.50-in. diameter by 2-in. long gauge length test specimen. The engineering stress-strain curves for all four samples are depicted in SAR Appendix Figure 2.12.2-13. Based on this physical testing, the input deck for the LS-DYNA® material was developed with resultant stress-strain curve data used in LS-DYNA® shown in SAR Appendix Table 2.12.2-4. Based on this data, the material true stress-strain curve and the actual input deck true stress-strain curve are shown in in SAR Appendix Figure 2.12.2-9.

To demonstrate how effectively the selected approach simulates the physical tests of the steel, the physical tests were used to benchmark the stress-strain curve used in the LS-DYNA® material model. To benchmark the LS-DYNA® input stress-strain curve used in the material model; a tensile test simulation was performed on a simulated sample specimen. The test simulation specimen was modeled with the same geometry as used in the ASTM A370 physical testing. The goal of the analysis was to verify the material behavior through the entire range of expected tensile stress-strain states that occur during the impact. The model is a ¼-symmetry model with one end fixed and the other end pulled at a constant velocity until failure. The simulation time steps are automatically adjusted and optimized by the LS-DYNA® software code. The test simulation is setup to use an initial timestep of 1 microsecond. The test terminates when the sample necks and finally fractures while under constant tension. Both the start and end states of the test are shown in SAR Appendix Figure 2.12.2-10 and Figure 2.12.2-11, respectively.

While the yield point is at a slightly higher stress at onset, the simulation curve converges with and follows the test data curves. Necking and failure of the LS-DYNA® curve occurs at a lower stress and strain than the test data, which provides conservatively bounding results. The new stress-strain curve is used in all drop test simulation cases. Based on the simulation and material model, the simulated material stress-strain data effectively assesses the model's non-linearity during the drop cases.

[Changes to SAR]

SAR Appendix Section 2.12.2.4.2.4, *Packaging Steel*, has been added in response to this RAI.

<u>RAI 2-5.</u> Provide details on the material properties of the grout used in the analysis. Provide a comparison of the results from the material model used in the simulation to the actual grout properties from testing data.

The finite element model (FEM) includes the contents of the cask which is the grouted mass of the RPV mid-section and pieces of the RPV internals. However, the applicant did not present information as to how this mass of the model participates in the drop. Also, the applicant did not explain how the internal mass participates in the drop analysis and its role in energy dissipation on impact, if any; and did not provide details on the material properties of the grout used in the analysis.

This information is required to support staff conclusions on the ability of the material model to simulate the material non-linearity during a drop condition required by 10 CFR 71.71 and 71.73.

RAI 2-5 Response:

As shown in SAR Figure 1.1-1, *CR3MP Cross-Section*, there are two homogenous regions of LDCC (i.e., grout) in the CR3MP. The first LDCC region is within the RPV walled-off middle segment and is the large central volumetric region encompassing and surrounding the embedded RVI materials. The second annular region is a narrower, thinner (3-in. thick) area which is located between the exterior RPV shell wall and interior CR3MP shell wall. Both regions will have the LDCC filler material.

The LDCC has a wet cast density range between 30 and 60 pcf. However, a target LDCC wet cast density of 53 pcf has been down-selected by the customer from tests performed. The material properties of the LDCC are not vital as this filler material is not an Important-To-Safety component. Nonetheless, based on the design requirements, the LDCC compressive strength used in the model is conservatively set to 100 psi and a conservative elastic modulus of 89,000 psi is used. 89,000 psi is the minimum elastic modulus reported in Table 3.1 of ACI 523.1R [1]. Typically, foam concretes have poor tensile strength and will fail at a fraction of the strain shown in the compressive stress-strain plot (e.g., 10 to 15%) (Page 18 of [4]). Based on previous testing of similar foam concrete [2], a Poisson's ratio in the range of (0.20-0.30) is considered applicable to the LDCC. Therefore, conservatively, a minimum Poisson ratio of 0.20 is applied.

Regarding the central LDCC region, in the LS-DYNA® model, the mass of the RVI is accounted for by evenly distributing its mass in this region. This is accomplished by increasing the LDCC as-modeled density above the actual wet cast density for the LDCC alone, in order to closely match the combined weight of RVI and LDCC. Because the central LDCC region includes the extra RVI mass, the LDCC/RVI region is modeled as an LS-DYNA® MAT_ELASTIC material (Material Type 1). This LS-DYNA® modeling technique treats the material as an isotropic hypoelastic material, in essence providing for a more rigid effect to the region during the drop impact. This conservatively lends itself to more energy being experienced by the CR3MP containment boundary shell, rather than being absorbed and dissipated by the central LDCC region.

On the other hand, the annular LDCC region has no RVI, and is a thin, discrete layer between the RPV shell wall and CR3MP shell wall. Since the annular LDCC region behaves differently than the central LDCC region, an hypoelastic model is not appropriate. There are multiple options for modeling the annular LDCC that may be selected depending on the purpose of the simulation. However, Material Type 16 (*MAT_PSEUDO_TENSOR) is a typical LS-DYNA® model that has been used for concrete structures subject to impulsive loadings. LS-DYNA® Mode II of material type 16 is implemented to provide a simple 'generic' concrete model (See LS-DYNA® Manual Vol II [6]).

To demonstrate the Material Type 16 behavior, a compression benchmark simulation with a test specimen of LDCC was created. The specimen was modeled to be 3 inches in diameter and 6 inches long. The sample was compressed along its axis at a rate of 0.05 in/sec for 8 seconds. The unconfined compressive stress-strain diagram for this simulation is shown in SAR Appendix Section 2.12.2.4.2.2, *LDCC* (Figure 2.12.2-6). The stress-strain curve resembles a bilinear elastic-plastic model with an approximate elastic and tangent modulus of 52.6 ksi and 40.2 psi, respectively. In terms of material strength behavior in the plastic region, this Figure 2.12.2-6 stress-strain diagram shows a high elastic modulus, peaking out at the yield point and then compressing at the yield stress over large strain values, via a combination of internal compressive and shear mechanisms.

Regarding the LS-DYNA® model's mass contribution, the CR3MP shell, bottom and top covers represents 24% of the total mass, while the RPV shell represents 26.5% of the total mass. Another 1.1% of the total mass is contributed by the annular LDCC. The remainder of the total mass contribution consists of the central LDCC region with the RVI payload.

In terms of LDCC's role in energy dissipation on impact, it is expected to generally perform well in terms of crushable impact energy dissipation. Low density foam concretes such as LDCC can be used as shock dissipators, having documented large energy absorption and deformation capabilities [5]. For example, energy absorption has been studied on similar 37.5 pcf and 62 pcf foamed concrete with similar water to cement (w/c) ratios of 0.6 [3]. In the study, the 62 pcf, 0.6 w/c ratio performed the best, but a 0.5 w/c ratio foam concrete may conservatively absorb around 7 MJ/m^3 (1.46×10^5 $ft\text{-}lb/ft^3$) of energy per unit volume (Figure 6 of [3]). As noted in the study, since there is additional space (e.g., porosity) in the lower density mixes to accommodate impacts, they would dissipate higher energy than higher density formulas.

However, in the LS-DYNA® model, because of its large mass and low strength, a large fraction of the energy is transferred through the central region LDCC (see Figure 2.12.2-96 as a typical drop case example). Ultimately though, the energy is restored to the model due to the elastic characteristic of the as-modeled LDCC. Therefore, at the end of the simulations, deformation of the other packaging components (i.e., RPV and CR3MP packaging steel) accounts for approximately 80-90% of the energy dissipated (depending on drop case) with approximately only 10-20% of the remaining energy absorbed by the central RVI and LDCC regions.

As a result, the LS-DYNA® central region LDCC material model does not take credit for an enhanced energy absorption capability that it otherwise would in actual drop scenarios. Thus, any energy dissipation afforded by the LDCC would be considered only qualitatively and be an added level of uncredited margin to the model energies experienced by the CR3MP. The LDCC, modeled as a simplified hypoelastic material, is not allowed to substantially deform, and instead transfers energy into the steel. As mentioned above, doing so ignores the energy dissipation potential afforded by the LDCC. In summary, the model for the central LDCC/RVI region is modeled in a conservative way. The LDCC/RVI region has both kinetic and potential energy which is performing external work to the CR3MP containment boundary steel components with very little internal work being performed within. In a real impact, the LDCC/RVI central region will have a substantial amount of internal work within (e.g., pieces deforming and breaking and LDCC crushing), which would remove kinetic energy that currently in the model is impinging upon the containment boundary.

RAI Response References

[1] ACI 523.1R – 2006, "Guide for Cast-in-Place Low-Density Cellular Concrete," American Concrete Institute, August 2006.

[2] Binod Tiwari et al, "Mechanical Properties of Lightweight Cellular Concrete for Geotechnical Applications," Journal of Materials in Civil Engineering, Vol. 29, Issue 7, July 2017.

[3] Jones et al, "Energy absorption of foamed concrete from low-velocity impacts," Magazine of Concrete Research, Volume 65, Issue 4, December 2012.

[4] Binod Tiwari et al, "Review of State of the Practice Use of Lightweight Cellular Concrete (LCC) Materials in Geotechnical Applications," California Nevada Cement Association, July 2020.

[5] G.C. Hoff, "New Applications for Low-Density Concretes," U.S. Army Engineer Waterways Experiment Station, Miscellaneous Paper C-70-8, Vicksburg, MS, May 1970.

[6] Livermore Software Technology Corporation, "LS-DYNA Keyword User's Manual, Volume II, Material Models," Version R7.0, February 2013.

[changes to SAR]

In response to this RAI, LDCC material model details are added to SAR Appendix Section 2.12.2.4.2.2, *LDCC*.

RAI 2-6. **Explain why the simplifications made are reflective of the non-linear behavior of the material during the different drop scenarios considered in the NCT and HAC analyses, providing a basis for the simplified strain-based analysis approach. (2) Describe why a biaxial tension state of stress may be assumed beforehand to determine an acceptance criterion for all elements in the containment vessel.**

The applicant, in section 2.6.7, has used a strain-based analysis that is based on the one described in ASME BPVC, Section VIII, Division 2, Article 5.3.3, for protection against local failure using a local strain limit (ASME 2017c). The implementation of this methodology in the SAR is performed using a simplified approach, wherein a worst-case (bounding) loading condition is assumed to apply to all elements within the containment vessel. As a result, a plastic strain limit (i.e., "limiting triaxial strain") is derived beforehand, instead of the derivation of a plastic strain limit at the conclusion of the analysis using resultant stresses "for each point in the component" (ASME 2017c, Article 5.3.3.1, Step 2).

The applicant did not explain why such a simplification would be reflective of the non-linear behavior of the material during the different drop scenarios considered in the NCT and HAC analysis, providing a basis for the simplified strain-based analysis approach. In particular, the SAR should describe why a biaxial tension ("balanced uniaxial tension") state of stress may be assumed beforehand to determine an acceptance criterion for all elements in the containment vessel. Additionally, the SAR should verify that the state of stress in the FE model at each element in the containment vessel meets the stated assumption.

This information is required by the staff to evaluate compliance with 10 CFR 71.71 and 71.73 drop tests.

RAI 2-6 Response:

In SAR Appendix Section 2.12.2, *Free Drop Evaluation*, the usage of a simplified approach to the LS-DYNA® strain-based structural analysis wherein a worst-case bounding loading condition is applied to all elements has been revised. In addition, the assumption of biaxial tension beforehand as an acceptance criterion for all elements has been amended. Instead, the containment boundary acceptance criteria, including the allowable plastic strain limits have been ascertained after running the simulation model, during post-processing.

Therefore, the new acceptance criterion examines the stress state (via triaxiality criterion) at limiting points in the containment via the limiting triaxial strain and assesses the combined effect using the damage accumulation procedure of Subarticle 5.3.3.2 [1].

All drop cases involve collisions between the steel CR3MP and an essentially unyielding horizontal drop pad, resulting in plastic deformation. The CR3MP shell, top and bottom covers, and closure welds are all evaluated based on their plastic behavior during the drop impact. Note that the weld region is not explicitly modeled as it relies on the same material properties as the shell and top and bottom covers.

As was mentioned in RAI 2-7, the packaging steel erosion criterion had been defined so that erosion would occur when the EPS in the element exceeded a limiting strain value. However, during for example corner drop simulations, this was then represented as a catastrophic, and unrealistic failure of all elements in the highly deformed corner region of the CR3MP structure. Hence, a very large region of material along with its capacity for absorbing impact energy disappeared from the model.

Since ductile fracture strongly depends on the stress state, this effect has been accounted for in a revised simulation, generating more precise model predictions. As a result, a more descriptive methodology to provide for a material limiting triaxial strain at each critical location in the containment boundary was determined after the LS-DYNA® drop analyses were run. EPS failure was defined as dependent on the triaxial stress relationship and an evaluation of the extent of the deformation in the simulations. This relationship is based on Subarticle 5.3.3.1 of [1], with the triaxial limiting strain calculated using Equation 5.6 of [1], as follows:

$$\varepsilon_L = \varepsilon_{Lu} \cdot \exp\left[-\left(\frac{\alpha_{sl}}{1+m_2}\right)\left(\left\{\frac{\sigma_1+\sigma_2+\sigma_3}{3\sigma_e}\right\}-\frac{1}{3}\right)\right]$$

Therefore, as detailed in SAR Appendix Section 2.12.2, *Free Drop Evaluation*, for the ASME A516, Grade 70 material used in the containment boundary, the limiting triaxial strain (ε_L) can be reduced to:

$$\varepsilon_L = 0.92 \cdot \exp\left[-1.705\left(\mu-\frac{1}{3}\right)\right]$$

Where the triaxiality factor (μ) is simply the ratio of the hydrostatic stress to the equivalent (Von Mises), as follows:

$$\mu = \frac{\sigma_1+\sigma_2+\sigma_3}{3\sigma_e}$$

This procedure using Section 5.3.3.1 of [1] is applied, with one refinement to characterize any fracture assessment. One of the methods for modeling strain failure allowances includes incorporating accumulated damage scenarios. This is consistent with the procedure in Section 5.3.3.2 of the ASME BPVC Code, Section VIII, Division 2 [1] for determining local strain limit failure criterion. By including the loading sequence, an accumulated strain limit damage calculation may be ascertained.

The material model that is implemented within LS-DYNA® works as a combination of an elasto-plastic model and a failure model called General Incremental Stress-State dependent damage Model (GISSMO) [2]. LS-DYNA® allows for such a definition of failure and damage using GISSMO through the keyword *MAT_ADD_EROSION, where different failure models and fracture criteria are coupled with the selected plasticity model in an ad-hoc fashion.

Therefore, a definition of allowable failure strain based on the state of stress is defined by both the triaxiality factor and the accumulated damage. Hence, the LS-DYNA® model is evaluated based on these formulations and resultant limits. As described in the LS-DYNA manual [2], damage is incrementally accumulated using the following relation:

$$\Delta D = \frac{DMGEXP \times D^{\left(1-\frac{1}{DMGEXP}\right)}}{\varepsilon_L} \Delta\varepsilon_p$$

Where D is the damage 1E-20 < D < 1.0, $\Delta\varepsilon_p$ is the change in EPS between each load increment, and ε_L is the failure strain as a function of the triaxiality factor. Damage only accumulates when the plastic strain is changing. Elements will not fail due to the state of stress (measured through the triaxiality factor) without a measured change in the plastic strain. The erosion model in LS-DYNA® is conservatively configured to implement damage accumulation with a damage exponent of 1 (DMGEXP=1). With damage exponent set to 1, the damage accumulation for each (k^{th}) load increment reduces to Equation 5.9 in [1]:

$$\Delta D = \frac{(1)}{\varepsilon_L} D^{\left(1-\frac{1}{1}\right)} \Delta\varepsilon_p = \frac{\Delta\varepsilon_{p,k}}{\varepsilon_{L,k}}$$

The damage exponent set to 1 is conservative since many metals damage exponent (i.e., DMGEXP) ranges from 1.3 to 3 (Section 2.2 of [3]). In this range, the change in the damage is reduced by a factor consisting of the current damage state raised to a power less than unity, resulting in the accumulation of only a fraction of the damage as it is currently set using DMGEXP = 1. Therefore, any modeled damage accumulates in a more conservative manner with any element failure occurring more rapidly. When the plastic strain limit accumulated damage exceeds unity (Equation 5.11 of [1]), then the element erodes.

Including the Equation 5.10 [1] strain limit damage from forming ($D_{\varepsilon form}$ = 0.029) (See SAR Appendix Section 2.12.2.2.1, *Acceptance Criteria*), then the accumulated strain limit damage is calculated using Equation 5.11 [1], as follows:

$$D_\varepsilon = D_{\varepsilon form} + \Sigma\, \Delta D_{\varepsilon,k} \leq 1.0 \qquad \text{Equation 5.11 [1]}$$

Each element in the model is acceptable if the value is less than unity ($D_\varepsilon < 1$). Then, rearranging Equation 5.11, the margin of safety with respect to accumulated strain limit damage can be written as follows:

$$MS = \frac{D_\varepsilon}{D_{\varepsilon form} + \Sigma\, \Delta D_{\varepsilon,k}} - 1 = \frac{1}{.029 + \Sigma\, \Delta D_{\varepsilon,k}} - 1 > 0$$

If the margin of safety with respect to accumulated strain limit damage is above 0, no portion of the containment boundary fractures, thus no elements are shown as eroded in the LS-DYNA® model.

As a result of the revised acceptance criterion for the drop analyses, the plastic strain limit is derived after the non-linear analyses are completed. Resultant stresses are used for each point in the component via the triaxiality limit, as is stated in the ASME BPVC Subarticle 5.3.3.1 (Step 2 of [1]). The triaxial strain limit is determined at the controlling locations and compared to the local strains experienced by the CR3MP structure for each drop case. This evaluation is further refined by assessing the accumulated damage experienced by the CR3MP and comparing with the strain limit damage procedure defined in Subarticle 5.3.3.2 of [1]. The margin of safety with respect to accumulated strain limit damage is then determined for the controlling locations in the containment boundary (See SAR Appendix Section 2.12.2.2.1, *Acceptance Criteria* for details).

RAI Response References

[1] American Society of Mechanical Engineers (ASME), "Boiler and Pressure Vessel Code, Section VIII, Rules for Construction of Pressure Vessels, Division 2, Alternate Rules," 2017 Edition.
[2] Livermore Software Technology Corporation, "LS-DYNA® Keyword User's Manual/Volume II/Material Models," Version R7.0, February 2013.
[3] Xue, Liang, "Damage accumulation and fracture initiation in uncracked ductile solids subject to triaxial loading," International Journal of Solids and Structures, 44 (2007) 5163-5181.

[changes to SAR]

In response to this RAI, SAR Appendix Section 2.12.2, *Free Drop Evaluation*, has been revised. In addition, the summary statements and sub-sections in SAR Section 2.6.7 and SAR Section 2.7.1 have been updated in response to this RAI.

<u>RAI 2-7.</u> Justify why the erosion feature was applied only to the welds and not extended to the peripheral elements of the attached parts.

The applicant, in section 2.6.7, cites the use of element erosion of the weld between the cover plates and the cylindrical shell. The elements used for the attachment welds between the individual elements of the weld are deleted if the effective plastic strain within the element exceeded the plastic strain limit.

The deleted elements expose openings (gaps) between the welded parts initiating a discontinuous deformation sequence.

This information is required by the staff to evaluate compliance with 10 CFR 71.71 and 71.73 drop tests.

RAI 2-7 Response:

The original purpose of allowing for erosion in the welds in the LS-DYNA® finite element simulations was to allow for failure of the welds in the drop event. It was believed that in adjacent regions where the strain exceeds the limiting triaxial strain criteria, the loading is primarily compressive. Since the failure, if any, was assumed to only occur in the weld joint, it was believed that it would be sufficient to give erosion to the weld elements only. After further review of the LS-DYNA® simulation, not extending the basic erosion criterion to the peripheral elements of the attached parts was deemed generally imprecise. Therefore, the simulation has been refined to include not only the weld regions, but the rest of the steel components as well. The revisions to the strain-based local failure criterion have been included in the response to RAI 2-6.

[changes to SAR]

In response to this RAI, SAR Appendix Section 2.12.2, *Free Drop Evaluation*, has been revised. In addition, the summary statements and sub-sections in SAR Section 2.6.7, *Free Drop*, and SAR Section 2.7.1, *Free Drop*, have been revised in response to this RAI.

<u>RAI 2-8.</u> Explain the choice of the modeling approach and discuss its influence on the non-linear behavior of the weld when subject to different drop conditions.

In section 2.12.2.4 regarding the Model, the applicant presented information on different aspects of the FEM. However, the applicant did not justify why the attachment welds in the model were simplified to two rows of elements through the 3.75-in. thickness, without definition of the compound V-groove geometry.

This information is required by the staff to evaluate compliance with 10 CFR 71.71 and 71.73 drop tests.

RAI 2-8 Response:

As outlined in response to RAI 2-7, since material erosion is now considered in the entirety of the CR3MP steel containment boundary, a distinct weld region is no longer required. Instead, the weld region is homogenous with the shell and cover components. Therefore, for a full penetration weld joint, detailed dimensioning of the weld region geometry is no longer necessary.

[changes to SAR]

The LS-DYNA drop impact models in SAR Appendix Section 2.12.2, *Free Drop Evaluation*, and model descriptions in SAR Appendix Section 2.12.2.4, *Model* have been revised in response to this RAI.

RAI 2-9. Provide a dimensional check for the model and model weights.

In section 2.12.4 the applicant did not provide any basic checks of the model to the information in the SAR. The staff's review identified that the total height of the package (i.e., length of the cylindrical shell) is 178.63 in in the FE models, though the SAR describes it as 178.1 in multiple locations.

For the NCT free drop and HAC combined free drop center of gravity (CG) over top corner impact orientations, the FE models have the package oriented with an angle of 42.2° between the axial centerline of the package and the horizontal drop pad instead of the 47.8° as defined in the SAR.

This information is required by the staff to evaluate compliance with 10 CFR 71.71 and 71.73 drop tests.

RAI 2-9 Response:

A dimensional check of the LS-DYNA® model and model weights has been added to SAR Appendix Section 2.12.2.4.1, *Model Geometry and Weight Check*. An inspection and comparison of the model is performed to ensure that it appropriately represents the CR3MP. SAR Appendix Table 2.12.2-2 provides a comparison of the nominal dimensions shown in the SAR drawing 3024427 to the LS-DYNA® model values. Variances are demonstrated to be small, considered within reason and provide results which do not appreciably change overarching outcomes of the drop analysis.

Because the SAR limit dimensions are not symmetric about the nominal, the LS-DYNA® dimension may justifiably represent a true average between the two tolerance limits. For example, the 178.63-in. overall CR3MP height mentioned in the RAI represents the average height, given a nominal between the two tolerance limits. Regarding the drop impact angles, 47.8° mentioned in the SAR is the angle formed between the horizontal drop pad and the cover of the CR3MP when in a top-down corner orientation. The LS-DYNA® model has the same angle, it was just reported as the opposing co-interior angle (42.2°), measured between the drop pad and theoretical cover perpendicular line. For clarity, a new Figure 2.12.2-5 has been added to the SAR to depict the angles used in the NCT and HAC corner drop cases.

[changes to SAR]

In response to this RAI, SAR Appendix Section 2.12.2.4.1, SAR Appendix Table 2.12.2-3, and Figure 2.12.2-5 have been added to the SAR.

<u>RAI 2-10.</u> Provide an explanation for the elements selected for the different parts of the package and the types of controls used to integrate non-linear behavior that may result from the different drop conditions.

In section 2.12.4, the applicant does not discuss element formulation and discretization. The SAR does not state if a mesh sensitivity was performed during the development of the FE models.

This information is required by the staff to evaluate compliance with 10 CFR 71.71 and 71.73 drop tests

RAI 2-10 Response:

As described in SAR Appendix Section 2.12.2.4.3, *Model Element Discretization and Mesh*, the CR3MP LS-DYNA® model uses exclusively solid elements that are element formulation 1 (i.e., ELFORM1), constant stress, solid elements. ELFORM1 is considered acceptable for most situations of solid materials, particularly with thick components such as used for the CR3MP. Furthermore, with this element type, no geometric, constitutive and loading assumptions are required, and boundary conditions are treated more realistically (comparatively to shells or beams). Also, when using ELFORM1, the finite element mesh visually looks like the CR3MP physical system. Most importantly, this type of element is accurate and provides a good stiffness response when the elements are highly deformed. Element formulation 2 (i.e., ELFORM2), the fully integrated, selectively reduced solid, was considered but was not selected, hence reducing any possibility of negative volume errors. In addition, ELFORM2 along with other element formulations are too stiff and are not good candidates for large strains in many situations, whereas ELFORM1 does handle severe deformations without the higher computational cost.

However, ELFORM1 necessitates hourglass stabilization. Therefore, hourglass control is implemented to reduce non-realistic deformations of the solid elements that produce zero strain and no stress. Hourglass control type 5, Flanagan-Belytschko stiffness form with exact volume integration for solid elements is assigned to all components except the drop pad. An hourglass coefficient of 0.05 is selected to minimize any nonphysical stiffening of the elements while allowing for some hourglass control. A slightly higher value of 0.1 was required to minimize hourglassing in the central region LDCC/RVI.

In terms of element mesh discretization, SAR Appendix Section 2.12.2.4.3, *Model Element Discretization and Mesh*, includes additional details. In addition, mesh sensitivity runs have been included in the revised SAR Appendix Section 2.12.2.4.3.1, *Mesh Sensitivity and Discretization*, to demonstrate that element size is sufficient while maintaining reasonable computational times. The mesh sensitivity study shows that six elements through the shell wall thickness and eight elements through the thinnest portion of the top and bottom covers produces acceptable results in comparison to coarser meshes.

[changes to SAR]

SAR Appendix Section 2.12.2.4.3, *Model Element Discretization and Mesh*, has been revised in response to this RAI. In addition, SAR Appendix Section 2.12.2.4.3.1, *Mesh Sensitivity and Discretization* has been added to the SAR.

<u>RAI 2-11.</u> **Explain the approach taken for the modeling of the package.**

The drop surface is a rigid surface compared to the cask package material and hence no surface deformation is expected. However, the model shows hourglass control for all components except for the horizontal pad.

This information is required by the staff to evaluate compliance with 10 CFR 71.71 and 71.73 drop tests.

RAI 2-11 Response:

The drop pad uses LS-DYNA® material model 20 (*MAT_RIGID), which is a non-deformable material and does not experience hourglassing. This has been noted in a revised discussion in SAR Appendix Section 2.12.2.4.3, *Model Element Discretization and Mesh*. Hourglass control for all the other solid elements is also added to SAR Appendix Section 2.12.2.4.3, *Model Element Discretization and Mesh* and discussed in response to RAI 2-10.

[changes to SAR]

SAR Appendix Section 2.12.2.4.3, *Model Element Discretization and Mesh*, has been revised in response to this RAI.

RAI 2-12. Justify the non-degradation of the base materials due to the excessive plastic strain.

The SAR identifies locations of local failure but does not provide any justifications for why they were then deemed to be acceptable and why they were not included in the maximum gap generated for the containment analysis. Justify why the base materials were not further degraded (i.e., through possible development of through-thickness cracks) because of the excessive plastic strain.

The response to this issue should also be considered in the containment analysis; similar issues are discussed and should be resolved in the other structural RAIs.

This information is required by the staff to evaluate compliance with 10 CFR 71.71 and 71.73 drop tests.

RAI 2-12 Response:

As indicated in response to RAI 2-7, in SAR Appendix 2.12.2, *Free Drop Evaluation*, the revised LS-DYNA® models for the drop impact cases now allow for the degradation of both the base materials and welds. Details of the material model and failure criteria is provided in response to RAI 2-6. As a result of the revised failure acceptance criterion, only erosion of areas not meeting the acceptance criterion result in locations of local failure. The containment analysis has been updated because of the revised evaluation.

[changes to SAR]

SAR Appendix 2.12.2, *Free Drop Evaluation* and SAR Section 4.3, *Containment under Hypothetical Accident Conditions*, have been revised because of this RAI.

<u>RAI 2-13.</u> Provide an assessment of the model energies and justification for any unexpected values to demonstrate that the model correctly captured the containment vessel's damage, and the value is maximized.

This information is required by the staff to evaluate compliance with 10 CFR 71.71 and 71.73 drop tests.

RAI 2-13 Response:

A discussion and an assessment of the model energies has been added to new SAR Appendix Section 2.12.2.7, *Model Energies*, for each drop case. A review of the results shows that the model energies are balanced within reason and that the containment boundary damage is maximized. All cases are within the range of the calculated gravitational potential energies of 5.17×10^6 lb-in and 1.60×10^8 lb-in during both NCT and HAC drops, respectively. The kinetic energy is removed from the system, as internal strain energy in the CR3MP packaging components increases. As SAR Appendix Figure 2.12.2-96 depicts and is described in response to RAI 2-5, the model energy in the central RVI/LDCC region is minimized, while conservatively maximizing damage within the containment boundary.

[changes to SAR]

SAR Appendix Section 2.12.2.7, *Model Energies*, has been added in response to this RAI.

<u>RAI 2-14.</u> Explain why the material properties of the grout were not selected based on material test data.

The material models used for the packaging grout and reactor fill grouts were a simplified elastic-plastic material model, which allowed for dramatic component deformations, resulting in some plastic strain (up to 4.06 in/in in one location).

For the HAC combined free drop side impact orientation, the internal energy for the reactor middle fill grout exceeded 21% of the total energy in the FE analysis, though the same value for the other two reactor fills and the packaging grout were no greater than 6% and 10%, respectively. Concrete-like materials are typically believed to fail by brittle fracture prior to measurable plastic deformation.

This information is required by the staff to evaluate compliance with 10 CFR 71.71 and 71.73 drop tests

RAI 2-14 Response:

As discussed in response to RAI 2-1, limited structural testing of the LDCC material has been performed. For example, the minimum 28-day compressive crush strength and wet cast density have been tested on the LDCC formula. There is however ample applicable LDCC (i.e., foam concrete) data widely available via literature that can be applied to the LDCC material model as required. For the impact drop tests, some of the pertinent data relates to properties such as Poisson's ratio and the modulus of elasticity. Such referenced literature data and the test data are referred to in response to RAI 2-5. A set of very conservative material properties are used in the LS-DYNA® model based upon testing requirements specified in Chapter 8 of the SAR. Properties for the analysis are derived from American Concrete Institute (ACI) standards using a minimum unconfined crush strength of 100 psi and density range of 30 – 60 pcf.

In order to remove the dramatic component deformations referred to in this RAI, a revised material model for both the central and annular LDCC regions have been incorporated into the revised SAR Appendix Section 2.12.2, *Free Drop Evaluation*. This has been outlined in more detail in response to RAI 2-5, but is repeated in part here.

Because the central LDCC region includes the extra RVI mass, the LDCC/RVI region is modeled as an LS-DYNA® MAT_ELASTIC material (Material Type 1). This LS-DYNA® modeling technique treats the material as an isotropic hypoelastic material, in essence providing for a more rigid effect to the region during the drop impact. Modeling as a hypoelastic material ensures that its energy absorption does not artificially dominate the response of the packaging components during the drop impact. This conservatively lends itself to more energy being experienced by the CR3MP containment boundary shell, rather than being absorbed and dissipated by the central LDCC region.

On the other hand, the annular LDCC region has no RVI, and is a thin, discrete layer between the RPV shell wall and CR3MP shell wall. The annular LDCC is significantly weaker than the steel and will crush relatively easily. Since the annular LDCC region behaves differently than the central LDCC region, a hypoelastic model is not appropriate. There are multiple options for modeling the annular LDCC that may be selected depending on the purpose of the simulation. Material Type 16 (*MAT_PSEUDO_TENSOR) is a typical LS-DYNA® model that has been used for concrete structures subject to impulsive loadings. Therefore, for the annular LDCC, LS-DYNA® Mode II of material type 16 is implemented for the annular LDCC, in order to provide a simple ‘generic’ concrete model. The 100-psi compressive strength of the material is specified along with a 0.20 value for Poisson’s ratio to automatically generate an Equation of State (EOS) for the model.

In practical terms however, the effect of LDCC confinement within the RPV specifically will yield a higher compressive strength than modeled in the drop impact simulations. Similar LDCC foam concretes have been tested, attaining compressive strains of 40% and afterwards gradually increasing in stress again until eventually locking (Ref. Figure 5.1/Section 4.1 of [1], Section 2 of [3], and Figure 4 of [2]). During this process, foam-based concretes retain excellent energy densification properties, attributed to their low density and porous void structure.

In addition, such LDCC materials have a high capacity to resist impact energy under rapid loading (i.e., high strain rate) conditions, such as that experienced during drop impact conditions (Ref. Section 6.1.2 of [1] and Figure 5/Table 5 of [2]). In an actual drop impact, during such high velocity/energy events, the resultant strain capability increases as the LDCC diminishes energy inputted into the system. Therefore, instead of all energy being isolated to deformation of the steel structures in the CR3MP, a portion of the total energy may be released through LDCC crushing and deformation.

Nonetheless, despite these central region LDCC benefits in both confined strength and high strain rate load resistance, these material aspects have been conservatively omitted in the revised material models for the LDCC (See Response to RAI 2-5). Hence, in reference to the HAC side drop impact energy, in the revised SAR Appendix Section 2.12.2.6.2, *HAC Side Drop*, only approximately 7% of the kinetic energy is being absorbed by the central region LDCC versus 33% previously (21% plus 2 × 6% for former HDCC regions).

In conclusion, as differentiated from brittle fracture failure of standard concrete-like materials, foam-based concrete materials have excellent energy densification properties that allow the material to have a high capacity to resist impact energy. These material property benefits have conservatively been diminished from the LDCC simulation models.

RAI Response References

[1] G.C. Hoff, "Shock-Absorbing Materials - Report 2 - Cellular Concrete As A Backpacking Material," U.S. Army Engineer Waterways Experiment Station, Technical Report 6-763, Vicksburg, MS, June 1971.
[2] Q. Guo et al., "Dynamic response of foam concrete under low-velocity impact: experiments and numerical simulation," International Journal of Impact Engineering, Vol. 146, December 2020.
[3] Binod Tiwari et al., "Review of State of the Practice Use of Lightweight Cellular Concrete (LCC) Materials in Geotechnical Applications," California Nevada Cement Association, July 2020.

[changes to SAR]

In response to this RAI, SAR Appendix Section 2.12.2, *Free Drop Evaluation*, has been revised. SAR Appendix Section 2.12.2.4.2.2, *LDCC* has also been added because of this RAI.

RAI 2-15. **Clarify in the SAR that the design of the welded closed vent plug port includes a recessed cover plate or some other means to ensure there are no detrimental effects during operations and transport.**

SAR section 4.1.1 indicated that a vent plug port may be part of the containment boundary. However, there was little discussion or pictorial to show that the closure design would not affect operations. The issue of snagging applies to all six of the holes; five of these are plugged or covered for transportation while the sixth one is having the threaded rod and grove weld.

The applicant did not explain the closure process to ensure that the final closure surface is prepared to eliminate these locations as potential points of attachment or that could cause any snagging during transportation and placement in its final location.

This information is needed to determine compliance with 10 CFR 71.43.

RAI 2-15 Response:

The SAR and SAR drawing have been modified to clarify that the threaded inserts used to close-off the lifting holes are installed flush to the top surface of the CR3MP top cover. This clarity will describe the intended installation process, thus ensuring that no feature on the top cover can be used as a potential attachment point nor snagged by any tiedown element.

As a result, General Note 16 on SAR drawing 3024427 has been revised to more clearly state how the cover's lifting hole plugs will be properly installed for transport. Further, General Note 22 on SAR drawing 3024427 has been revised to ensure that the hole plug will not protrude beyond the plane of the top cover surface.

[changes to SAR]

General Note 16 and 22 on SAR drawing 3024427 have been revised to clarify the vent plug installation. In addition, the wording about the vent plug in SAR Sections 1.2.1, 1.2.1.1 and 2.1.1 have been updated in response to this RAI.

<u>RAI 2-16.</u> Provide the basis for the low temperature yield strength values used in the calculation for the required brittle fracture performance of the alloy steel package components.

The calculation for the nil ductility temperature in SAR section 2.1.2.1.1, "Brittle Fracture" includes the following assumptions:

- yield strength does not increase with reduction of temperature (the calculation uses the code minimum strength at room temperature)
- the material will have the minimum required yield strength to meet the code specification (vs the typical yield strength of the supplied material which will be higher than the code specified minimum value).

Both of these assumptions make the nil ductility temperature calculation less conservative. Revise the SAR to include additional details about these assumptions

This information is needed to determine compliance with 10 CFR 71.33.

RAI 2-16 Response:

The usage of the nil-ductility temperature and determination of the Lowest Service Temperature (LST) in SAR Section 2.1.2.1.1, *Brittle Fracture*, follows the methodology provided in NUREG/CR-6491. The basis for the yield strength values used in this determination are as specified in NUREG/CR-6491. The Nomenclature section of NUREG/CR-6491 (page xi) defines σ_{ys} as "*…the ASTM minimum yield for a specific steel (units ksi).*" This is confirmed in "*Appendix A: Technical Basis*" of NUREG/CR-6491 wherein the paragraphs above equation (1A) and below paragraph (4A) state the following: "*Where σ_{ys} is the room temperature static yield strength in ksi…*" and "*For a room temperature yield strength of 60 ksi, the temperature shift…*", respectively.

As a result, the application of the yield strength values from ASTM A516, Table 2 as the room temperature value of 38 ksi for Grade 70 is appropriate when using the Figure 1 chart in NUREG/CR-6491 to ascertain the LST temperature value. Since the appropriate usage of the techniques and methods from NUREG/CR-6491 applies a room temperature yield strength in the assessment of the LST, the determination of the required brittle fracture performance of the steel materials used in the CR3MP is accurate and justified.

[Changes to SAR]

No changes to the SAR result from this RAI response.

<u>RAI 3-1.</u> Clarify the inputs to the pressure and radiolysis calculations in appendix 3.5.2 and SAR section 5.4 and confirm they are bounding.

The assumption in SAR appendix 3.5.2 was that the reference "air" volume for the pressure calculation (and radiolysis calculation) was a portion of the LDCC volume with a 40% void fraction. For example, SAR tables 3.5-1 through 3.5-3 indicate volumes associated with LDCC and HDCC are considered, however the total volumes change with each table. It is unclear whether the radiolysis and pressure calculations account for the water vapor released from the entire amount of grout within the package.

This information is needed to determine compliance with 10 CFR 71.41, 71.51.

<u>Response:</u>

Radiolysis and pressure calculations account for the water vapor released from the entire amount of LDCC within the CR3MP. The inputs to these calculations are bounding. The referenced SAR tables 3.5-1 through 3.5-3 are no longer applicable as SAR Appendix 3.5.2, *Evaluation of Pressure in the CR3MP*, has been revised as part of the response to both this RAI and RAI 3-5.

[changes to SAR]

SAR Appendix 3.5.2, *Evaluation of Pressure in the CR3MP*, has been revised as part of the response to this RAI.

<u>RAI 3-2.</u> **Provide a detailed discussion and justification of the boundary conditions applied during the 30-minute engulfing fire analysis and subsequent cool-down period.**

a. The description of the fire test boundary conditions appeared to indicate that the heat flux from the fire to the package was a function of a fire thermal component that was "reduced" due to a convection component. However, a clear definition in equation form of each thermal input of the fire thermal inputs was not clearly described. In addition, the analysis should reflect the engulfing nature of the fire condition, which includes a component due to the radiation heat transfer from the 800 deg C fire and the convection heat transfer component from the engulfing fire.
b. The discussion should include an energy balance calculation of the package surface in order to understand the derivation of the thermal input to the ANSYS model and in order to derive the package surface temperature. This calculation is a function of package decay heat, convection and radiation heat transfer into the package, and radiation heat transfer leaving the package.
c. Provide details and discussion related to the boundary conditions and modes of heat transfer associated with the CR3MP HAC post-fire steady-state temperatures provided in figure 3.4-3.

This information is needed to determine compliance with 10 CFR 71.41.

<u>Response:</u>

A detailed summary of the boundary conditions for each of the analyzed thermal cases, including the HAC fire transient, has been added in SAR Appendix 3.5.5, *Summary of Analyzed Thermal Evaluation Cases*. The summary explicitly identifies and quantifies the heat inputs, heat removal mechanisms, and any parameters associated with defining these heat transfer modes.

With regards to item (a):

The discussion of the fire heat flux in SAR Section 3.4.2, *Fire Test Conditions*, has been revised for clarity and detail. Additional equations have been added to demonstrate how the modeled fire heat flux is derived from the regulatory fire conditions in accordance with the guidance in ASTM E2230-13, *"Standard Practice for Thermal Qualification of Type B Packages for Radioactive Material*". To ensure that modeling of the fire is representative of an engulfing fire with moving hot air, the total fire heat flux includes a conservatively-calculated convection component. As a result, the radiation heat flux defined by the fire conditions in 10 CFR 71 is increased to account for convection, not reduced.

With regards to item (b):

As part of the summary added in SAR Appendix 3.5.5, *Summary of Analyzed Thermal Evaluation Cases*, the heat transfer modes with their associated values are provided for all cases. In addition, the CR3MP surface energy balance for each case is fully defined. For steady-state cases, residuals are calculated to evaluate convergence. For the HAC transient case, no residual is calculated as heat transfer at the package boundaries is not balanced (resulting in package heat-up during the fire and cooldown following the fire).

With regards to item (c):

As previously noted, the boundary conditions and modes of heat transfer related to the HAC post-fire steady-state analysis are explicitly detailed as part of the summary added in SAR Appendix 3.5.5, *Summary of Analyzed Thermal Evaluation Cases*.

[changes to SAR]

SAR Section 3.4.2, *Fire Test Conditions*, has been modified in response to this RAI, including adding Figure 3.4-2. In addition, SAR Appendix 3.5.5, *Summary of Analyzed Thermal Evaluation Cases*, has been added in response to this RAI. A summary statement has been added to the end of Section 3.1.3 to support this RAI response.

<u>RAI 3-3.</u> **Provide package temperatures (e.g., interior, package surface) as function of time during the HAC fire, including the initial conditions.**

Temperatures of package components (e.g., interior grout, air, package surface) are often used in the SAR calculations (e.g., radiolysis, pressure). Although some temperatures were noted within the SAR text, it was unclear as to which component and point in time the particular temperature was chosen as an input to the calculations.

This information is needed to determine compliance with 10 CFR 71.41.

<u>Response:</u>

Figure 3.4-5 has been added to SAR Section 3.4.3, *Maximum Temperatures and Pressure*, to show the change in CR3MP component temperatures during and after the HAC fire. The HAC fire is initialized using temperatures calculated from the NCT Hot case conditions (38 °C ambient air, maximum payload decay heat, and maximum insolation). Both average and maximum temperatures are reported in Figure 3.4-5 for different components during the 24-hour period following fire initiation. The time corresponding to maximum temperatures may be different depending on the component. Maximum temperatures reported for the post-fire steady-state condition are based on temperatures achieved once the CR3MP has reached thermal equilibrium. Where needed, the various component temperatures relative to their usage in the SAR calculations have been included in the revised SAR text and figures.

[changes to SAR]

SAR Section 3.4.3, *Maximum Temperatures and Pressure*, has been modified in response to this RAI.

<u>RAI 3-4.</u> Provide the mesh sensitivity study mentioned in SAR section 3.3 and discuss the results of a time step sensitivity study.

Section 3.3 mentioned that a mesh sensitivity study was performed; however, details of the study and its results were not provided. In addition, there was no mention that a time step sensitivity analysis of the transient HAC was performed to confirm adequate numerical time steps were applied.

This information is needed to determine compliance with 10 CFR 71.41.

<u>Response:</u>

The mesh sensitivity study mentioned in SAR Section 3.3, *Thermal Evaluation under Normal Conditions of Transport*, as well as an additional time step sensitivity have been added in SAR Appendix 3.5.4.1, *Mesh Sensitivity Study*, and Appendix 3.5.4.2, *Time Step Sensitivity Study*, respectively. To be conservative, the mesh has been slightly revised, resulting in an increase in the overall mesh density. This has resulted in a minimal variance in the CR3MP component temperatures reported in Chapter 3.0, *Thermal Evaluation*. The mesh study confirms that an appropriate number of mesh elements and nodes are modeled, such that further refinement will result in only marginal changes to model temperatures. Similarly, the time step sensitivity study confirms that adequate numerical time steps are modeled for the HAC fire transient case, such that further reduction in time step size will result in only marginal changes to model temperatures and behavior.

[changes to SAR]

SAR Section 3.3, *Thermal Evaluation under Normal Conditions of Transport*, and SAR Section 3.4.3, *Maximum Temperatures and Pressure*, have been modified in response to this RAI. In addition, in SAR sections 3.1.3, 3.3 and 3.3.2, CR3MP component temperatures have been revised because of the modification to the mesh density. In addition, SAR Appendix 3.5.4.1, *Mesh Sensitivity Study*, and SAR Appendix 3.5.4.2, *Time Step Sensitivity Study*, have been added in response to this RAI. SAR Sections 2.6.1.1, *Summary of Pressures and Temperatures*, 2.7.4.1, *Summary of Pressures and Temperatures*, and 2.7.4.2, *Differential Thermal Expansion*, 2.7.4.3, *Stress Calculations*, have been revised to support changes due to this RAI.

<u>RAI 3-5.</u> **Demonstrate in the SAR that there is no free water in the package grout material in order to confirm that the water vapor contribution to radiolysis and pressure is bounding and clarify and update the calculations and discussion in SAR appendix 3.5.2 to result in the appropriate amount of grout, and correspondingly, the water vapor that is to be used in the pressure and radiolysis analyses.**

SAR section 3.5.2.1 indicated that there is no free water within the package's LDCC and HDCC. However, there was no data or discussion within the SAR that demonstrated there would be no free water. The staff notes that, in practice, the grout slurry will contain more water than necessary to cure the concrete - to ensure sufficient water is present to hydrate all the cement and to aid workability/flow of the slurry. The evaporation of this free water from thick sections can take several months (Castro, 1998).

SAR section 3.5.2.1 states that there is no free water because the concrete is cured after 28 days; however, concrete curing is not related to the release of the excess (free) water that does not participate in the curing reaction.

In addition, the calculations in SAR appendix 3.5.2 (e.g., page 3.5-4, SAR table 3.5-5) appear to result in a total mass of LDCC and HDCC (i.e., total mass of package grout) that is below the grout amounts indicated in SAR table 2.1-2 which prevents staff from reviewing the analyses. As noted in SAR chapter 3 and chapter 5, the quantity of water vapor is an important parameter when calculating pressure and radiolysis effects and, therefore, the calculations and their inputs (e.g., fraction of cement in LDCC and HDCC, mass of grout) should be verified.

This information is needed to determine compliance with 10 CFR 71.43.

<u>Response:</u>

An assessment of the free (e.g., unbound water) in the low-density cellular concrete (LDCC) is included to draw some conclusions about potential water vapor. Since HDCC is no longer used in the CR3MP it has been completely removed throughout the SAR. It is acknowledged that in foam concrete such as LDCC a natural cured dry state occurs within 60-90 days depending on the foam density and curing temperature, since the amount of hydrated water may be considered inversely proportional to shrinkage deformation (See References [1] and [2] below). "*As the cement is hydrated, the foamed concrete comes under the composite effect of the rise of temperature and the shrinkage of chemical reaction, with the decrease of water content*" [2]. Experimental data has shown that the free water content of low-density foam concrete (like LDCC) is approximately 2% by weight [3]: "*Foamed concrete contains free water and chemically bond water. The free water content in foamed concrete depends on the density (i.e., the free water content for the 650 kg/m^3 density is 1% by weight and for the 1000 kg/m^3 density is 2% by weight based on experiment data)*".

There are two regions of LDCC in the CR3MP. The first region is the large central volumetric region which surrounds the RVI materials within the RPV walled-off middle segment. The second annular region is a narrower, thinner area which is located between the exterior RPV shell wall and interior CR3MP shell wall. Both regions will have the LDCC filler material. However, the amount of free water or rather, unbound water in the regions will vary due to the curing temperature and curing timeframe.

For the inner central LDCC region, both the curing time and the decay heat load imposed will be greater than the annular region. Based on customer schedule of operations between LDCC pouring to CR3MP package closure, the central region will have 6 months (180 days) to cure. Moreover, given both the proclivity for higher temperatures from heat of hydration due to the overall LDCC pour height and the proximity of the central internal LDCC to the highly activated RVI and associated decay heat, this will tend to accelerate the LDCC setting period. Thus, the expectation is that the interior LDCC may be considered fully hydrated prior to top cover closure.

On the other hand, the outer, annular LDCC region will be cast with approximately the standard 28-day curing period to develop full compressive strength. The curing temperature in the outer LDCC region will be lower as it is further removed from the decay heat of the RVI contents. As such, it is assumed that there could be an increased amount of unbound water available in the annular LDCC region for three reasons: 1) this LDCC is only cured for 28 days, 2) the LDCC does not have the excess RVI heat applied like the central region and 3) and the overall height is 163-in. with a relatively small open surface area.

Regarding the contribution of free water within the radiolysis analysis (SAR Section 5.4.4, *Radiolytic Gas Generation*), the utilized G-values are conservative maximum values based on a Portland cement-based concrete with similar characteristics but with shorter curing times, as identified in Table 13 of BNL-NUREG-50957, in which experiments were typically conducted with no more than 28-day cure times. The shorter curing times in BNL-NUREG-50957 would presume a conservative water content in the cementitious matrix in reference to the water content available in the CR3MP LDCC. As such, the free water content of the reference BNL-NUREG-50957 concrete should be comparatively conservative with the free water content of the LDCC and thus free water content in the central LDCC region is inherently accounted for in the resulting reference G-values.

To ensure there is neither water vapor nor radiolytic gas pressure buildup within the CR3MP prior to shipment, a vent hole is provided in the CR3MP top cover plate. This hole has been changed from optional to mandatory on the SAR drawing and will not be closed until just prior to shipment.

Regarding the contribution of free water within the pressure analysis (See SAR Appendix 3.5.2, *Evaluation of Pressure in the CR3MP*), a precise amount of free (e.g., unbound water) in the LDCC is not included. As stated above, the actual amount of unbound water available for phase changes is not readily quantifiable. However, it is known that with sufficient water and heat, that in due course there will be a saturated mix of liquid and gaseous water present. Given sufficient time, the saturated water mixture and radiolytically released gases could create a pressure on the overall CR3MP containment boundary, as the void spaces in the LDCC and the head space at the top of the CR3MP connect. Void space (e.g., porosity) in the LDCC regions will increase as the LDCC is heated. As pockets within the LDCC heat up, localized pockets will connect due to microcracking produced by the expansion of the cement paste (Section 3.2 of [3]). Vaporization of potential free water may occur at temperatures between 100 - 170°C (Section 3.1 of [3]). This water vapor will condense in cooler regions. As a result of the overall saturated mixture, the LDCC average temperature in all cases (e.g., NCT Hot, HAC fire transient and HAC post-fire steady-state) can be used to determine a known saturation pressure. Because of these changes regarding the saturation conditions in the CR3MP, SAR Appendix 3.5.2, *Evaluation of Pressure in the CR3MP*, has been revised with new pressure determinations.

Regarding variations in LDCC weight, SAR Section 2.1.3.1, *LDCC Bounding Actual Volumes and Weights*, has been added to the SAR to describe expected actual LDCC nominal volumes and weights, so they may be used in the various SAR and NRC confirmatory analyses. As a result of a new table added in Section 2.1.3.1 for RVI component volumes, previous SAR Table 2.1-2, *CR3MP Component Maximum Bounding Weights*, has been renumbered to SAR Table 2.1-3. Of note, Table 2.1-3 has a conservatively high total LDCC weight, including in the annular region. This table is primarily used in the SAR to establish a bounding maximum overall CR3MP gross weight for usage in the SAR Chapter 2, *Structural Evaluation*. For example, in Chapter 2, the overall CR3MP weight matches the 860 kips weight of SAR Table 2.1-3. Due to this conservatism, the title and column headings of SAR Table 2.1-3 has been adjusted to recognize the maximum bounding nature of these weight estimates.

<u>RAI Response References</u>

[1] Li, C.; Li, X.; Li, S.; Guan, D.; Xiao, C.; Xu, Y.; Soloveva, V.Y.; Dalerjon, H.; Qin, P.; Liu, X. "Effect of Maintenance and Water–Cement Ratio on Foamed Concrete Shrinkage Cracking," Polymers, 2022.

[2] Zhao, Wenhui; Su, Qian; Wang, Wubin; Niu, Lele; Liu, Ting. "Experimental Study on the Effect of Water on the Properties of Cast In Situ Foamed Concrete," Advances in Materials Science and Engineering, New York, 2018.

[3] Md Azree Othuman, Mydin, Y.C. Wang, "Mechanical properties of foamed concrete exposed to high temperatures," Construction and Building Materials, Volume 26, Issue 1, 2012, Pages 638-654.

[changes to SAR]

In response to this RAI, the pressure determinations in SAR Appendix 3.5.2, *Evaluation of Pressure in the CR3MP*, SAR Section 3.3.2, *Maximum Normal Operating Pressure*, and SAR Section 3.4.3, *Maximum Temperatures and Pressure*, have been revised. SAR Section 3.1.4, *Summary Tables of Maximum Pressures*, has been updated and SAR Table 3.1-3, *Summary of Maximum Pressures for the CR3MP*, has been added to support this RAI.

In addition, the SAR Drawing 3024427, *CR3MP Assembly SAR Drawing*, has been updated to exercise the vent port option as no longer being optional. Additional wording changes to SAR Sections 1.2.1, 1.2.1.1, 2.1.1, 2.4.5, 2.4.8, 4.1.3 and 7.1.2 have incorporated the vent plug as no longer being optional.

SAR Section 2.1.3.1, *LDCC Bounding Actual Volumes and Weights*, and Table 2.1-1, *Individual RVI Component Volumes Based on Solidworks Models*, have been added and the previous Table 2.1-1 has been renumbered to Table 2.1-2. In addition, Table 2.1-2 has been renumbered Table 2.1-3 and the title and weight column headings have been updated. Section 4.3, *Containment under Hypothetical Accident Conditions* has been adjusted to reflect the actual total central region LDCC available for the analysis.

A few wording changes have also been made to SAR Section 3.2.2, *Component Specifications*, and SAR Section 3.3.1, *Heat and Cold*. Wording changes have been incorporated into SAR Section 2.1.3, *Weights and Centers of Gravity*, for clarity on the nature of the overall package weight. Finally, wording changes have been incorporated into SAR Sections 2.6.1.1, *Summary of Pressures and Temperatures*, 2.6.1.3.1, *Stresses Due to Pressure Loading*, 2.6.3, *Reduced External Pressure*, 2.7.4.1, *Summary of Pressures and Temperatures*, 2.7.4.3, *Stress Calculations,* in order to support changes due to this RAI.

<u>RAI 3-6.</u> Provide the references associated with the convection heat transfer correlations listed in appendix 3.5.3.

Convection heat transfer is an important parameter for transferring the decay heat to the ambient. Although correlations were provided, the references for those correlations were not provided and their relevance to the particular surface orientation and Ra number could not be determined.

This information is needed to determine compliance with 10 CFR 71.41.

<u>Response:</u>

The convection heat transfer correlations are taken from SAR Chapter 3 Reference [8], *A Heat Transfer Textbook*. The reference is available online at the referenced link below. SAR Appendix 3.5.3, *Natural Convection Heat Transfer,* has been revised for detail and clarity regarding the origin and basis of the convection heat transfer correlations and any associated equations. In addition, cross-referenced citations of the natural convective heat transfer determinations have been documented in SAR Appendix 3.5.3, *Natural Convection Heat Transfer*.

<u>RAI Response References</u>

Lienhard IV, John H. and Lienhard V, John H., A Heat Transfer Textbook, 5th edition, Phlogiston Press, 2020, Available at: https://ahtt.mit.edu/.

[changes to SAR]

SAR Appendix 3.5.3, *Natural Convection Heat Transfer*, has been modified in response to this RAI.

<u>RAI 4-1.</u> **Provide the calculations for determining the quantity of "energy emitted by source", "energy absorbed in grout", "total gas generated" (moles) and "quantity of hydrogen gas generated" (moles) when performing the radiolysis calculation.**

Although SAR table 5.4-3 included a number of quantities, there were no corresponding calculations that demonstrated certain equation inputs (e.g., energy absorbed in grout) would result in the values found in the table for a 405 day evaluation period and, therefore, a review confirming the 5% concentration limit could not be performed.

This information is needed to determine compliance with 10 CFR 71.43.

<u>Response:</u>

A detailed step-by-step calculation of all values related to the radiolytic gas generation evaluation, including the specific values identified above, has been added to SAR Appendix 5.5.4, *Step-by-Step Radiolysis Evaluation*. As noted in the step-by-step calculation, certain values are calculated using modeling software. As provided in Section 5.2, *Source Specification*, the initial power of source (i.e., payload decay heat) is determined. The fraction of energy absorbed in the grout is calculated using MCNP models identified in Section 5.3, *Shielding Model*, conservatively modified to maximize the amount of radiation energy absorbed (as discussed in Section 5.4.4, *Radiolytic Gas Generation*). The energy emitted by the source is calculated from the integral of the decay heat over a set evaluation time period. The evaluation time period for the energy emitted has been extended to 429 days due to primarily the removal of HDCC from the CR3MP. The evaluation period is the maximum period set such that the final hydrogen concentration will not exceed 5%. Separately, the fraction of energy absorbed has changed (as have package dose rates) due to correction of an error in the MCNP shielding input source definition. The quantity of gas generated is computed in Appendix 5.5.4, *Step-by-Step Radiolysis Evaluation*, using the energy absorbed and the effective G-value of the LDCC, as modified to include the foam concentrate contribution of the LDCC effective G-value.

[changes to SAR]

SAR Section 5.5.4, *Step-by-Step Radiolysis Evaluation* has been added because of response to this RAI.

<u>RAI 4-2.</u> Demonstrate in the SAR that the G(H2) value should be reduced from its nominal value due to dose.

SAR section 5.4.4 noted that G(H2) values were reduced from nominal values to account for varying absorbed doses throughout the payload based on SAR chapter 5 Reference 11 (i.e., BNL-NUREG-50957). However, the reference indicates that G(H2) would not be expected to decrease with dose for systems that allow diffusion (such as the package interior according to SAR section 5.4.4). If a reduced G(H2) value is demonstrated to be appropriate, then provide the calculation package, including inputs, for determining the 0.23 G(H2) value. Although an equation was provided relating dose and G values in SAR section 5.4.4, it was unclear as to which dose and G values were used as input to the equation and, therefore, a review could not be performed.

This information is needed to determine compliance with 10 CFR 71.43.

<u>Response:</u>

The determination of G(H2) has been revised in SAR Section 5.4.4, *Radiolytic Gas Generation* to conservatively incorporate the maximum value of 0.35 molecules per 100 eV, published in Table 33 of BNL-NUREG-50957 (see Reference [11] in SAR Appendix 5.5.1, *References*). Conservatively, there is no reduction in G(H2) accounted for because of any effects associated with increasing absorbed dose. As mentioned in response to RAI 4-1, the G-values applied to the LDCC are further increased to account for the foaming concentrate incorporated during the LDCC formulation process. As a result of operational changes to the formulation (See response to RAI 2-1), the LDCC mixture has been altered to remove all other foaming admixtures besides the foam concentrate. As a response to RAI 4-1, all inputs, formulas, and outputs involved in the determination of CR3MP grout G-values are included in Section 5.5.4, *Step-by-Step Radiolysis Evaluation* as part of the newly added step-by-step hydrogen generation evaluation.

[changes to SAR]

SAR Sections 5.4.4, *Radiolytic Gas Generation* has been revised because of response to this RAI. To support the changes due to this RAI, wording changes have also been made in Section 4.2.1, *Hydrogen Concentration in the Package*.