UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

SAFETY EVALUATION REPORT

Docket No. 71-9393
Crystal River 3 Middle Package – CR3MP

SUMMARY

By letter dated September 1, 2021 (Agencywide Documents Access and Management System [ADAMS] Accession No. ML21244A485), Orano Federal Services LLC submitted an application for approval of the Crystal River Unit 3 (CR3) Middle Package (CR3MP). On February 14, 2022, the application was accepted for a detailed technical review after receiving on January 6, 2022, (ADAMS No. ML22006A365) responses to staff's October 15, 2021, request for supplemental information (ADAMS No. ML21286A798).

On December 19, 2022, Orano Federal Services LLC submitted responses (ADAMS No. ML22356A314) to staff's first request for additional information (RAI) dated June 24, 2022 (ADAMS No. ML22172A114). On June 8, 2023, Orano Federal Services LLC submitted responses to staff's second RAI letter (ADAMS No. ML23113A011) dated May 2, 2023, and also provided Revision No. 4 of the application (ADAMS No. ML23159A272)

The CR3MP packaging consists of a cylindrical 3-in. thick steel shell, and 6-in. thick top and bottom cover plates. These components and their welds make up the containment boundary. The cover plates are attached to the shell with full penetration closure welds; the top cover plate closure weld is a field weld, performed after placement of the payload into the packaging. Prior to transport, the pressure vent port is plugged by a fully threaded rod installed approximately flush to the package surface and secured shut with a closure weld.

The payload consists of the middle portion of the CR3 Reactor Pressure Vessel (RPV): reactor vessel internals components, immobilized in grout, are included in the RPV cavity. The payload rests on the bottom of the package, leaving a three-inch thick annulus around the sides, filled with low density grout, and an approximately three-inch air space over the top of the payload.

The package is 200.3-in. in diameter and 178.1-in. tall and has a maximum bounding weight of 860,000 pounds. The package will be transported in exclusive use by barge and by road to the Waste Control Specialist disposal site in Andrews, Texas.

NRC staff reviewed the application using the guidance in NUREG- 2216, "Standard Review Plan for Transportation Packages for Spent Fuel and Radioactive Material." The package was evaluated to meet the regulatory requirements of 10 CFR Part 71 and, where applicable, the requirements of 10 CFR 71.41(d) – Special Package Authorization - which states that the applicant shall demonstrate that "the overall level of safety in transport …is at least equivalent to that which would be provided if all the applicable requirements had been met."

The staff risk-informed its review by taking into account both the low-risk potential of the package contents, i.e., only activated metal, and the fact that surface contamination is fully immobilized in grout, thus lowering the consequences of any drop event. The staff finds acceptable the categorization of the package as Category II because of the low event probability associated with a one-time transport, the very low availability of dispersible radioactive material and the minuscule consequences of any potential release.

The applicant has committed to the use of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC), Section III, Division 1, Subsection ND, for the Category II CR3MP package, along with the acceptance criteria in Regulatory Guide 7.6. for the package design for stress conditions within the yield stress limits. In locations, where the demand exceeded yield stress of the package material, the applicant chose to use the inelastic analysis methods defined in ASME Section VIII, Div. 2 for local failures. Strain-based criteria were used post yielding to assess the damage and erode elements in the finite element modeling simulation. Because the package is authorized for a one-time transport, the staff finds this approach of using two Code sections in the analysis appropriate to capture the elastic-plastic behavior of the package drop response in the material. Similarly, the staff finds also acceptable that the applicant did not strive to maintain containment boundary integrity, but, rather, chose to demonstrate compliance with the required regulatory dose limits in accordance with 10 CFR 71.51 (a)(2). The load combinations continue to be the same, with only the acceptance criteria changing from stress to strain.

Based on the statements and representations in the application, the staff concludes that a Special Package Authorization is acceptable and meets the requirements of 10 CFR Part 71. Accordingly, the package is authorized for a one-time only shipment for disposal.

Reference

CR3MP Transport Package Safety Analysis Report, Revision No. 4, June 2023.

1.0 GENERAL INFORMATION

1.1 Special Package Authorization

The application was reviewed to meet the requirements of 10 CFR Part 71 and, where applicable, the requirements of 10 CFR 71.41(d) – Special Package Authorization. This provision of the regulations is intended to apply only in limited circumstances and only to one-time shipments, as is the case for the CR3MP package.

As required by 10 CFR 71.41(d), "packages for which compliance with other provisions of these regulations, i.e., 10 CFR Part 71, is impracticable shall not be transported, except under special package authorization." The provision states that a special package authorization may be issued if the applicant demonstrates the following:

(1) compliance with the other provisions of the regulations is impracticable,

(2) requisite standards of safety established by the regulations are demonstrated through means alternate to the other provisions, and

(3) the overall level of safety in transport for these shipments is at least equivalent to that which would be provided if all the applicable requirements had been met.

The review of the CR3MP application considered the above stated requirements and noted where the provisions of 10 CFR 71.41(d) are applicable.

1.2 Package Description

The CR3MP Type B(U)-96 package is designed to transport the segmented middle section of the decommissioned Crystal River Unit 3 (CR3) Reactor Pressure Vessel (RPV) and Reactor Vessel Internals (RVI). The CR3MP package is transported, via exclusive use, from CR3 to the licensed low-level waste disposal facility of Waste Control Specialists near Andrews, Texas.

The CR3MP consists of a 3-in. thick steel body assembly shell, 6-in. thick top and bottom covers, and a closure joint weld. Each top and bottom cover is groove welded to the shell wall along the circumference. A ½-in. square backing ring under the top cover helps to facilitate welding of the top cover in the field. A Low-Density Cellular Concrete (LDCC) grout fills the annulus between the RPV shell exterior and the CR3MP shell. RVI components are set within the RPV by built-up layers of LDCC grout and form one rigid monolith. There is a nominal 3-in. air gap between the top surface of the RPV and the bottom surface of the top cover. However, the radial 3-in. nominal annular gap between the shell inner wall and the RPV outer diameter is filled with LDCC.

The materials of construction of the package are carbon steel plate and cementitious grout. Due to material property limits, a Lowest Service Temperature (LST) of 0°F is established as a condition for this letter authorization during the entirety of the transport. As outlined in NRC Regulatory Guide 7.12, an equivalent level of safety for the 10 CFR 71.71 and 10 CFR 71.73 Normal Conditions of Transport (NCT) and Hypothetical Accident Conditions (HAC) initial test conditions is applicable for brittle fracture criteria of the bounding 6-in. thick CR3MP top and bottom covers at the LST identified.

A complete evaluation of the materials and their acceptance criteria under both NCT and HAC conditions is covered in section 2.2, Materials, of this SER.

The dissipation of heat from the CR3MP package is entirely passive. Containment of the radioactive waste in the package is provided by the main cylindrical shell, top and bottom covers, and weld joints of the CR3MP. Shielding is provided by the steel located in walls of both the shell body and top and bottom covers, while the RPV steel shell primarily provides radial shielding on the sidewalls of the package. The CR3MP transports fissile exempt material; thus, there is no criticality concern.

Four threaded holes, set on the top cover and used to facilitate lifting the top cover, will be eventually plugged by set screws. One of the holes, acting as a pressure vent port which is part of the containment boundary, is also plugged by a fully threaded rod installed flush to the package surface and secured with a closure weld prior to transport.

The overall height of the package is 178.1-in. while the overall diameter is 200.3-in. The package is designed to be transported with its cylindrical axis vertical. The overall package gross weight is a maximum of 860,000 lb.

1.3 Contents

The radioactive contents are of normal form. Table 1.2-1 of the application lists the package radionuclide activity levels.

The CR3MP activation source term is modeled solely as 30,000 Ci Co-60 since the other two significant contributors to activity (Ni-63 and Fe-55) are weak radiation sources relative to Co-60. A neutron activation analysis provides the activated segment specific activity (Ci/g), weight, and material density input for all the components. A concentration for both fixed and loose surface contamination is conservatively determined.

None of the source contents contain fissile content, therefore the payload is fissile exempt per the provisions of 10 CFR 71.15(b). The Criticality Safety Index (CSI) described in 10 CFR 71.59 does not apply.

2.0 STRUCTURAL AND MATERIALS EVALUATION

This application was submitted as a special package authorization under the provisions of 10 CFR 71.41(d), for which the applicant must demonstrate that the overall level of safety of the package is at least equivalent to that which would be provided if all the applicable requirements of 10 CFR Part 71 had been met. The structural review evaluates the structural configuration of the CR3MP transportation package to ensure that it meets the safety objectives of 10 CFR Part 71 by compliance with the stated regulatory requirements. And, where the requirements cannot be met, the applicant’s approach to demonstrate safety is evaluated using the provisions of 10 CFR 71.41(d). In performing this evaluation, the staff has used the information provided by the applicant in the SAR and other documents submitted as a part of the license application.

The staff ensures that the application contains general information required for cask transportation via public transportation routes. This part of the review confirms compliance with the General Requirements of 10 CFR 71.43. The staff reviews the performance of the cask under NCT and HAC using the sequence of tests prescribed in 10 CFR 71.71 for NCT and 10 CFR 71.73 for HAC conditions, respectively. The demonstration of compliance with a regulatory requirement is evaluated using the acceptance criteria in 10 CFR 71.41. In addition, the staff reviews the structural integrity of the package for lifting and transportation loads using the regulatory guidance provided in NUREG-0554 and NUREG/CR-0128. The applicant has utilized the guidance in NUREG/CR-6407 to assign cask component safety categories based on their importance to safety.

The staff used this categorization and the American Society of Mechanical Engineers (ASME) design rules identified by the guidance in NUREG/CR-3854 to determine if the material and design process selected for a package component is commensurate with its importance to safety.

2.1 Description of the Structural Design

The CR3MP package is a 3-in. thick steel cylindrical shell, with 6-in. thick top and bottom cover plates. These components and their welds make up the containment boundary. The base metal is ASTM A516 Grade 70 or optionally ASME SA516 Grade 70 for all three components. The cylindrical shell and each cover plate may have multiple full penetration welds connecting constituent plates. The cover plates are attached to the shell with full penetration closure welds. The top cover plate closure weld is field welded, after placement of the payload in the steel cylinder. The package is closed by welding the top cover plate, which has with no closures, seals, or vent ports. The package is 200.3-in. in diameter and 178.1-in. tall and has a maximum bounding weight of 860,000 pounds.

The payload is the middle portion of the CR3 Reactor Pressure Vessel (RPV) along with Reactor Vessel Internal (RVI) components, and a grout immobilizes the contents inside the containment. The RPV payload rests on the bottom of the package, leaving approximately a three-inch annulus around the sides, and approximately 3-inch-high space over the top of the payload. The annulus is grouted with low density cellular concrete (LDCC) grout, leaving a nominal air space of 3 inches at the top of the payload. The CR3MP design does not include any impact limiters, or any other features specifically designed to absorb free drop energy.

The package is designed to be resistant to fracture at the lowest service temperature (LST) and provide containment of the radioactive material under NCT and HAC. The package does not have any external structural lifting attachments. The tie-down lug on the lifting frame is only to hold the package in place during transportation. The package is transported as exclusive use by barge and by road between the Crystal River Unit 3 site and the Waste Control Specialists disposal site. A summary of overall component weights and cross-section is shown in SAR table 2.1-2 along with its geometric dimensions. The CR3MP assembly is shown in SAR Drawings 3024427, 2 sheets.

2.1.1 Material Properties

The staff reviewed the material properties used in the structural design and analysis to verify they are appropriate for the safety assessment. This includes consideration of the temperature range to which the package material is exposed during transportation. The CR3MP package uses two dissimilar materials in the packaging and uses a steel containment and cementitious grout to immobilize the contents.

The applicant identified that the cask will be made of ASTM A516 Grade 70 or optionally ASME SA516 Grade 70 steel for all three components that make up the containment. Staff comparison of the mechanical properties of the two materials is shown in the table below.

Mechanical Properties	ASTM A516 Grade 70	ASME SA 516 Grade 70
Ultimate Tensile Strength	70.3-89.900 ksi	70 -90 ksi
Yield tensile strength	37.7 ksi	38 ksi
Elongation at Break	17% - 21%	17 % -21%
Modulus of Elasticity	29,000 ksi	29,000 ksi

The staff agrees that one material is acceptable as an alternate for the other due to their close mechanical properties. Table 2.2-1, list the mechanical properties of both materials across the temperature range of interest.

The staff reviewed the ASTM/ASME material selected for use in the shell and the top and bottom cover plates in ASME BPVC Division II, “Materials,” Part D,” Properties,” and finds that the material properties shown in table 2-2.1 are derived from those in the ASME Code. In addition, the applicant has considered the requirements for brittle fracture in accordance with the staff position in Regulatory Guide 7.11, “Fracture Toughness Criteria of Base Material for Ferritic Steel Shipping Cask Containment Vessels with a Maximum Wall thickness of 4 Inches.”

The staff reviewed the methodology presented and finds that the applicant has used the guidance in NUREG/CR-6491 in establishing the temperature at non-ductile transition (T-NDT) and has used that to establish the LST and associated material properties. In SAR section 2.2.2 the applicant analyzed the interaction between dissimilar materials used in the packaging of CR3MP.

The staff reviewed the potential galvanic interactions to ensure that the material properties are not adversely affected. The review found that steel and grout are the only materials used in the fabrication of the package. Steel and grout are not known to have adverse galvanic reactions as it is extensively used in reinforced concrete structures.

The staff reviewed the procedure followed to produce the LDCC and the associated standards used in establishing the properties of the material that are produced. The staff finds that the applicant has followed the methodology of ASTM C869 and determined that the compressive strength of the LDCC is above the required 200 psi with a density of 53 pcf.

Conservatively, for modeling of the drop analysis a compressive strength of 100 psi is used and the density of 30 -60 pcf. is retained to maintain the correct over model weight in SAR appendix section 2.12.2.4.1. The actual density of the LDCC is 53 pcf. The staff notes that the applicant has chosen not to use High Density Cellular Concrete (HDCC) as a packaging material, and all grout in the package has been replaced with LDCC.

The staff finds that the applicant used material properties derived from ASTM standards duly adjusted for material embrittlement at the LST. In addition, the applicant has followed the processes specified in the ASTM for the manufacture of the grout and the determination of its properties. A more detailed evaluation of the materials used in the packaging is provided in the SER section on “Materials.”

Based on its review as described above, the staff concludes that selection of the material properties for structural evaluation of the package is consistent with the material selected using the guidance in NUREG-3854.

2.1.2 Identification of Design Codes and Standards

The applicant states in the General Information in SAR section 1.0 that the CR3MP is a onetime single use Type B (normal form) package containing Class B and Class C radioactive waste as defined by 10 CFR 61.55. It contains no fissile material, hence is exempt from 10 CFR 71.15(b)(1).

The staff considered the form of dispersible radioactivity in the package and the application of the lower standards of fracture toughness per NUREG/CR-1815 for a Category II classification, in reaching its findings. The staff finds a change from the suggested categorization acceptable because of the following factors: the low event probability associated with one time transport, the very low availability of dispersible radioactive material and the minor consequence of any potential release. With the risk (basis of the categorization) being much lower than that assumed for Category I (greater quantities of dispersible material) in the guidance, the staff accepted the applicant's categorization of Category II for this package. In evaluating the applicant's selection of design codes and standards for the fabrication of package components, the staff used the package categorization and the guidance in NUREG/CR-6407, "Classification of Transportation Packaging and Dry Spent Fuel Storage System Components," and NUREG/CR-3854, "Fabrication Criteria for Shipping Containers."

The staff evaluated the selection of the material for the welding used in the cask fabrication using the guidance in NUREG/CR-3019. The guidance in NUREG/CR-3854 recommends the design rules of ASME BPVC, Section III, Division 1, Subsection ND for Category II packages. The applicant in SAR section 2.1.2, "Design Criteria," states that the design of the cask's cylindrical shell and the top and bottom closure plates follows the design rules of ASME BPVC.III.I.ND. However, in all drops, the CR3MP experiences stresses beyond the yield strength of the material along with the containment weld, requiring an inelastic approach to simulate the plastic response of the material up to rupture strain. ASME Section VIII, Division 2 provides an approach for analysis when the stress in the element exceeds yield. Because of this, the applicant adopted ASME Section VIII Division 2 to capture the inelastic response of the package.

The staff finds this approach of using two code sections in the analysis as appropriate to capture the elastic-plastic behavior of the cask drop response in the material. Hence, all the static load combinations are evaluated in accordance with Division 1, Section III and the dynamic conditions are evaluated in accordance with Division 2, Section VIII.

The staff finds this acceptable as the applicant demonstrates compliance with the required regulatory dose limits at the surface of the cask post drop. The load combinations continue to be the same, with only the acceptance criteria changing from stress to strain. The staff evaluated regulatory implications of such a change in acceptance criteria and determined that there are no regulatory requirements limiting the use of multiple code sections or codes by the applicant.

The welding material criteria for all steel plates forming the containment of CR3MP meets the requirements of ND-2400. In SAR section 2.3.1 "Fabrication," the applicant has provided the details of the welding process to be followed in performing the containment boundary weld.

The grout used in the package is based on the guidance in ACI 523.1R for the formulation and placement of LDCC grout.

The staff finds this approach to design criteria selection acceptable for the base metal of the cask for which the risk of contamination associated with the release fraction of the Ci, is appropriate for a Category II cask.

The staff also finds that the selection of the design codes and standards for the cask components are consistent with their importance to safety. The staff evaluated design criteria for the weld which is the other component of the containment boundary. The staff finds ASME BPVC, Section III, Division 1, Subsection ND, ND-2400 is appropriate for use in the design of the CR3MP package welds as it is consistent with the design safety Category of the package base metal.

The staff noted that this classification aligns with the recommendations of NUREG/CR-3019, “Recommended Welding Criteria for Use in the Fabrication of Shipping Containers for Radioactive Materials.”

The staff did not review any design criteria for the grout used inside the CR3MP cask as it does not perform any design safety function. The grout immobilizes the pieces of the RVI and RPV from moving during transportation and storage. In addition, the surface radioactive material inside the RPV and RVI is immobilized within the grout matrix.

Based on its findings, the staff concluded that the design codes used for the CR3MP cask design meets the requirements of 10 CFR 71.31(c).

2.1.3 General Standards for All Packages

The following requirements are to be met, as defined by 10 CFR71.43.

Minimum Package Size

The applicant in SAR section 2.4.1 established that the minimum size of the package is 178 inches. The staff reviewed SAR figure 2.1-1 and confirmed that the smallest overall dimension of the package is as reported in SAR section 2.4.1. The staff concluded that the smallest overall dimension of the package exceeds the minimum size of 4 inches of the requirement hence, the application complies with 10 CFR 71.43(a).

Tamper-indicating Feature

The applicant in SAR section 2.4.2 established that the package is sealed with full penetration welds which forms the containment boundary. The staff reviewed drawing 3024427, Sheet 2 of 2, and confirmed that the package is sealed using heavy full penetration welds without any easy tampering access to the contents within. The staff concluded that the full penetration welds provide the non-tamper proof feature required of a package, hence complies with 10 CFR 71.43(b).

Secure Containment System

In SAR section 2.1.1 the applicant describes the closure of the package and identifies the welds of the containment boundary that are made in the field after placement of the contents. The staff reviewed the SAR drawing and the description of closing out the lifting hole in the top cover plate prior to shipment. The staff finds that all through access to the content is welded closed prior to shipment. The staff concludes this meets the requirements that the containment system is securely closed using a positive fastening method and hence complies with the 10 CFR 71.43(c).

Packaging Material Degradation from galvanic action, water intrusion and irradiation

In SAR section 2.2.2, the applicant states that the only two materials of packaging, steel, and grout, will not have any adverse galvanic action. This conclusion is supported by the long history of successful uses of these two materials in reinforced concrete construction. In addition, the applicant states that the sea voyage is short, and the package is painted, so no adverse chemical action is anticipated between the steel and the marine environment over this brief journey.

In SAR section 2.2.3, the applicant addresses the effect of radiation on the package material. Since the radiation from the RPV and RVI steel is primarily gamma radiation, there is no material degradation of the package. Some moisture hydrated in the grout undergoes hydrolysis, decomposing to oxygen and hydrogen, which is further discussed in SAR section 5.4.4.

Based on its review of the provided information, the staff finds that there is no degradation of the material strength used in the structural analysis resulting from galvanic action, water intrusion, or irradiation. Hence the staff concludes that the application complies with the requirements of 10 CFR 71.43(d).

Unauthorized Operation of a Packaging Device with potential to release Radioactive material.

In SAR section 2.4.5, the applicant states that there are no packaging valves or other devices on the containment boundary and the only pressure vent port is shut by plug welding. The staff's review of the notes of drawing 3024427, Sheet 1 of 2, confirmed the only vent hole is plugged and then welded shut. This ensures that there is no potential for unauthorized access to the contents of the packaging. The staff concludes that the applicant complies with the requirements of 10 CFR71.43(e).

Package Designed and Constructed for Normal Conditions of Transport

The package is designed for a specific set of conditions and tests enveloping the potential demands expected during normal conditions of transportation of the package. These conditions include the response of the package to a range of temperature changes, changes in internal and external pressure, transportation induced vibrations, exposure to water spray, and different configurations of package drops, including ones that have a potential for penetration of the package. The applicant presented information in the SAR to demonstrate that the package response meets the acceptance criteria in 10 CFR 71.43(f).

The applicant presented the analysis of the different conditions in 10 CFR71.71 in the SAR chapters 2.0 “Structural Evaluation,” for 10 CFR 71.71 (5), (7), (8), (9) and (10); SAR chapter 3.0, “Thermal Evaluation,” for 10 CFR71.71 (b), (c)(1) and (c)(2) and SAR chapter 5.0 “Shielding Evaluation,” for 10 CFR 71.71 (c)(6). The staff noted that even with the response of the package separated along the more important attributes of its response, the same exposure can have impacts on the evaluations in different chapters. The staff reviewed these referenced chapters for compliance with the requirements of 10 CFR 71.43(f) and present the findings of their evaluation in the respective chapters of this SER.

Accessible Surface Temperature Limit

In SAR section 2.4.7, the applicant identifies table 3.1-1 in section 3.1.3, “Summary Table of Temperatures,” as establishing the maximum accessible surface temperature with no insolation is bounded by 85°C or 185°F, thus satisfying the required limit set by 10 CFR 71.43(g). The staff reviewed the table for confirmation of the cited values. The evaluation of the values in the summary table is further evaluated in chapter 3.0, “Thermal Evaluation,” in the SER. Based on these evaluations the staff concludes that the application complies with 10 CFR 71.43(g).

No Continuous Venting

In SAR section 2.4.8, the applicant states that the CR3MP packaging has no provision for external venting as there is no pressure relief valve. In addition, the only vent port is plugged and welded prior to shipment. The staff confirmed this information for the description in the SAR and SAR drawings. Based on its review, the staff concludes that the application complies with the requirements of 10 CFR 71.43(h).

2.1.4 Lifting and Tie-down Standard

In SAR Subsection 2.5.1, the applicant states that the CR3MP package does not have any devices that are a structural part of the package, which could be used for lifting, in the transportation configuration. The staff reviewed the information in SAR subsections 2.5.1, and SAR chapter 7 on packaging operations. The staff finds that, in the operations involving lifting the CR3MP to the transport barge and heavy haul trucks, the applicant utilizes a custom jacking system for the transfer. As a result, there are no structural lifting devices on the package. Since the package has no lifting provisions during transportation, there are no compliance requirements under 10 CFR 71.45 (a) for the CR3MP.

The staff reviewed SAR subsection 2.5.1 on the use of tie-down devices during transportation. The options identified by the applicant establish that no structural attachments to the package will be used as tie-down points. Any flexible or steel tie-downs used in the road or barge transportation respectively will not exert a preload to the CR3MP. As the package will not be directly tied down to the conveyance, no structural tie-down criteria are required for the package, and there are no compliance requirements under 10 CFR 71.45(b) for the CR3MP.

2.1.5 Normal Conditions of Transport

SAR section 2.6 presents the analysis of NCT conditions to which the CR3MP is subject to during transportation. The drop analysis results are summarized in this section for reference. The stress limits are based on the guidance in RG 7.6 and ASME BPVC Section III, Division 1, Subsection ND, and were used for static events such as load cases for temperature and pressure variations.

Heat

The NCT heat condition as defined in 10 CFR 71.71(c)(1) is evaluated in SAR chapter 3.0. For the structural evaluation in SAR subsection 2.6.1.3, the CR3MP components are bounded by a temperature of 123.8°F in the 100°F ambient NCT condition as shown in SAR table 3.1-1. Conservatively, for the stress analysis in SAR subsection 2.6.1.3, a temperature of 1500°F is used.

A design pressure of 26.2 psig is used in the NCT stress analysis of 2.6.1.3, which is greater than the differential pressure of 25 psig resulting from the combination of Maximum Normal Operating Pressure (MNOP) and the reduced external pressure of 3.5 psia required by 10 CFR 71.71(c)(3).

The stress analysis under the given pressure and temperature of the package shell, cover plates, and the closure weld shows a large margin of safety of 9.4, and 1.65 respectively. The staff finds that these levels of margin demonstrate that the package meets the loading demands imposed by the requirements in 10 CFR 71.71(c)(3).

Cold

The CR3MP package is analyzed for cold conditions as required by 10 CFR 71.71(c)(2) for – 40°F with zero insolation and zero decay heat. This results in a uniform – 40°F throughout the package. As there is little difference in the coefficient of thermal expansion between the grout and the steel, there are no loads at the interface. As the CR3MP will be transported at a temperature above the LST of 0°F as established in SAR subsection 2.1.2.1.1, brittle fracture is not a concern.

Reduced External Pressure

The stress due to the reduced external pressure of 3.5 psia is considered in the design based on a MNOP of 3.9 psig using an enveloping value of 26.2 psig for the stress analysis. The worst stress was in the closure weld with a positive margin. The staff finds that the CR3MP meets the requirements of 10 CFR 71.71(c)(3).

Increased Internal Pressure

The loading corresponds to a minimum ambient temperature of -20°F, with no insolation, no decay heat, and minimum internal pressure. The differential gas pressure from the outside the shell corresponding to these conditions is 7.8 psi. With the package filled with grout, the grout can accommodate this pressure without crushing independently of the strength of the shell. The top cover is not supported by the grout and is designed to a pressure differential of 26.2 psig. The staff finds that the CR3MP meets the requirements of 10 CFR 71.71(c)(4).

Vibration

The CR3MP is a single use package which will undergo a small number of loading cycles during the single shipment. The massive components of the package have natural frequencies that will not be energized from the transportation vibration. Additionally, the package is filled with grout which will further dampen any vibration. Based on this information, the staff finds that the CR3MP meets the requirements of 10 CFR 71.51(a)(1).

Water Spray

The steel material used in the CR3MP is unaffected by water spray and, along with its all-welded construction, provides a water-resistant enclosure for the contents within. The staff finds this meets the requirements of 10 CFR 71.71 (c) (6).

Free Drop

The simulated NCT free drop orientations and the results are presented in SAR table 2.6-1 with detailed discussion on the simulation in SAR appendix 2.12.2. In all drops, the CR3MP experiences stresses beyond the yield strength of the material and an inelastic approach to simulate the plastic response of the material up to rupture strain, as per ASME Section VIII, Division 2. Section 2.10 for the SER evaluates the CR3MP drop scenarios. Based on the evaluation in SER section 2.10 and the summarized information in SAR table 2.6-1 the staff finds that the NCT free drop simulation meets the requirements of 10 CFR71.71(c)(7).

Corner Drop

10 CFR71.71(c)(8) applies to packages of fiberboard, wood and packages containing fissile material. The CR3MP is of steel construction with no fissile material and has not been analyzed for this drop orientation. This staff finds this assessment consistent with the requirements of 10 CFR 71.7(c)(8).

Compression

10 CFR 71.71(c)(9) requires that for packages weighing up to 11,000 lbs., a 24-hour compressive load of 5 times the package weight or 2 psi over the projected area be applied. The CR3MP weighs more than 11,000 lbs. and has not been evaluated for this requirement. This staff finds this assessment consistent with the requirements of 10 CFR 71.71(c)(9).

Penetration

In addressing the requirements for penetration by a 1.25-inch diameter, hemispherical ended,13-lb steel bar dropped vertically from a height of 40 inches, the impact energy of such a drop was analyzed. The impact energy was computed as 520 in-lb. This level of energy would not have any detrimental effect on the 6-in closure plate or the 3.75-in closure weld. This staff finds this assessment consistent with the requirements of 10 CFR 71.71(c)(10)

2.1.6 Hypothetical Conditions of Transport

SAR section 2.7 presents the analysis of HAC conditions other than drops to which the CR3MP is subject to during transportation.

Free Drop

For the free drop three worst case orientations for which maximum damage would occur was considered: on the end, the side, and CG-over-corner. To include the damage which would occur from a prior NCT one-foot free drop, the drop height of all HAC drops was set at 31-ft, with a 25 psig of internal design pressure. As the HAC drops were anticipated to cause a containment boundary breach, the HAC outcomes were not evaluated for containment boundary retention but for the contamination released based on 10 CFR71.51(a)(2) limits. The details of the HAC drop simulations are further evaluated in this SER.

Crush

The CR3MP is significantly more than the package limits of 1100 lbs. for which 10 CFR 71.73 (c)(2) requires a crush test by dropping a 500-kg (1100-lb) mass from 9 m (30 ft) onto the specimen. The mass must consist of a solid mild steel plate 1 m (40 in) by 1 m (40 in) and must fall in a horizontal attitude. Given the mass of the CR3MP of 860,000 lbs., the staff finds the requirements of 10 CFR 71.73(c)(2) do not apply to the CR3MP.

Puncture

The CR3MP puncture resistance is evaluated in two locations in accordance with the requirements of 10 CFR 71.71 (c)(3).

Puncture of the Ends

SAR subsection 2.7.3.1 addresses puncture on the ends. For the CR3MP, both ends have the same thickness and material of construction. The required puncture thickness was determined using Nelm's equation and a margin of safety of + 0.01 was established. This evaluation assumed that the bar would not fail under the applied load. The applicant evaluated the failure of the bar using its material properties and established that the bar would fail in compression well before shearing of the plate. This would result in a much higher margin of safety in puncture than the Nelm's equation predicted. The staff finds that this explanation supports the results of the calculation.

Puncture of the Package Body Shell

SAR subsection 2.7.3.2 addresses the puncture of the body shell of the package. From the computations of the puncture of the ends, both from the perspective of Nelm's equation and the maximum puncture bar load, the bar load is greater than the load required to fully shear the 3-inch shell. Thus, the side shell will be punctured. The applicant has evaluated this puncture and the consequence of the breach of the containment boundary because of this event. The consequences of a puncture on the side shell of CR3MP will be minimal as the thick wall of the RPV immediately behind the shell prevents further perforation. The applicant has established that the RPV will experience a local deformation of less than 1-inch under the puncture load. This is a conservative estimate as the package shell is assumed to be compromised and the support from the grout inside is neglected. SAR figure 2.7-1 shows the upper bound width of the opening as approximately ¾ inch through which very little grout can escape. Moreover, the grout in the annulus is not contaminated. As a result, there is little potential for any release of contamination.

Thermal

SAR subsection 2.7.4 presents the stress analysis of the CR3MP exposure to the HAC 30-minute fire as specified in 10 CFR 71.71(c)(4). The thermal exposure to this event is discussed in SAR subsection 3.4.3. The combination of the pressure and the temperature load stresses is conservatively shown to have a margin of safety of 2.0. The staff finds this assessment reasonable as both the pressure and temperature peaks will not occur at the same time; hence, the results are conservative.

Immersion

Since the CR3MP does not contain fissile material, the staff finds that the requirements of 10 CFR 71.73 (c)(5) do not apply to the CR3MP.

However, the requirements of immersion under 10 CFR 71.73 (c)(6) do apply to CR3MP. The SAR subsection 2.7.6 addresses this requirement and states that the required performance of sustaining an external pressure of 21.7 psig by the CR3MP is met by the grout fill without any assistance from the steel shell, as the compressive strength of the grout is much greater than the prescribed pressure.

The deep-water immersion test as required by 10 CFR 71.61 (an external pressure of 290 psi for not less than an hour without collapse, buckling or in leakage of water) is not required for the CR3MP package as it contains A_2 at levels lower than that for which the requirement applies.

2.1.7 Summary of Drop Analysis Approach

The NCT and HAC evaluations for dynamic events (i.e., free drop impact) were performed using an inelastic analysis method defined in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC), Section VIII, Division 2 (ASME 2017c), for protection against local failure as described in Article 5.3.3. Using the LS-DYNA software, finite element (FE) models were developed for CV components that used elastic-plastic material models, with properties obtained from both the ASME BPVC Section II, Part D (ASME 2017a) and material testing results of samples taken from the actual CV component materials used for fabrication.

The elastic-plastic material models were used to allow for realistic deformations computed using LS-DYNA and in tracking the damage at each time interval for elements along the containment boundary and comparing them to the limiting criterion. The element was considered as failed or eroded when the criterion limits were exceeded. The element was then no longer considered as a part of the FE model in the analysis for subsequent time steps. The damage accumulation methodology was adapted from ASME Article 5.3.3.2 using material specific data. The simulation was benchmarked using tensile test data of the fabrication material.

The damage accumulation material model provided a means of determining a plastic damage parameter as a function of effective plastic strain and triaxiality ratio. This was accomplished using material models available in LS-DYNA. The attachment welds between the cylindrical shell and top and bottom covers were not discretely modeled, since they were being treated as equivalent to the base materials. LS-DYNA elements that capture element erosion were used along the containment boundary to capture any element erosion. The open area of element loss was used to compute the volume of material that would be released.

The use of stress limits based on guidance in Regulatory Guide 7.6 and ASME BPVC Section III, Division 1, Subsection ND (ASME 2017b) was only for static events, such as load cases for temperature and pressure variations.

Full-size FE models were developed for four separate impact orientations, including a top-end impact configuration, a side impact configuration, a CG over top-corner impact configuration, and a tip over follow-through from a CG over top-corner configuration, each of which were half-symmetry (180°) geometry.

Three FE models underwent impact events for a 1.0-foot NCT free drop, and a 31.0-feet HAC combined free drop, while the tip over follow-through configuration was only considered as a NCT event. For the HAC combined free drop analyses, a single 31.0-feet free drop event was used to approximate the typical NCT free drop and HAC free drop sequence.

The analyses for NCT corner drop and NCT compression were not required due to weight constraints, and the analysis for NCT penetration was disregarded due to the relative size of the package compared to the size and impact energy of the requisite penetration bar.

The analysis for HAC crush was also not required due to weight constraints, and the analysis for HAC puncture was performed analytically using methods derived by Nelms (1968). Physical testing was not performed to demonstrate any regulatory compliance requirements.

2.1.8 Evaluation of Models

Packaging Material Properties

Steel

In SAR subsection 2.12.2.4.2.4 the applicant presents the properties of the packaging steel as those of ASTM A516, Grade 70 carbon steel with properties as in ASME BPVC II Part D. To establish the stress-strain curve of the fabrication steel, the applicant conducted two sets of tests at different temperatures for the shell and cover steel. The temperature variation did not change the steel behavior.

The elastic properties from the tests are shown in SAR figure 2.12.2-7. The results of the second series of test, shown in SAR figure 2.12.2-8 reflect the stress-strain behavior in the plastic region out to fracture. The resultant stress-strain values shown in SAR table 2.12.2-4 are used in LS-DYNA along with the true stress-strain curve shown in SAR figure 2.12.2-9.

The staff finds that the material input file for LS-DYNA is consistent with the test values of the packaging material and demonstrates that these input steel properties will be able to capture the response of the containment material to package drops required under 10 CFR 71.71 and 10 CFR 71.73.

Acceptance Criteria

In SAR subsection 2.12.2.2.1 the applicant has presented the acceptance criteria used in the drop analysis of the CR3MP package on an unyielding surface. In the drops, the package undergoes different levels of material deformation leading to the damage of the containment and loss of confinement. The acceptance criteria are used in the material model to capture the progression of material deformation and establish when accumulated damage leads to loss of confinement.

The acceptance criteria examined the state of stress (via triaxiality criterion (TF)) and strain (via the limiting triaxial strain) at limiting points in the containment and assessed the combined effect using the damage accumulation procedure in ASME. When the maximum stress intensity remains within acceptable limits the plastic deformation is not sustained, and the material behavior is essentially elastic. When points are reached where drop energy is absorbed by sustained plastic deformation, the Effective Plastic Strain (EPS) is calculated using the material test data.

The triaxial strain limit is determined at each of these controlling points using the methodology in subarticle 5.3.3.1 of Section VIII, Division 2 of the ASME BPVC and compared to the EPS. For regions where the plastic strain does not change, and the EPS limit is not exceeded, damage is not accumulated. The acceptance criteria also assess element erosion using the damage accumulation method of ASME BPVC, VIII, Div.2, subarticle 5.3.3.2. This allows for an accumulated strain limit damage to be computed at the controlling points, from which a margin of safety against accumulated strain damage is determined.

The staff finds the acceptance criteria is acceptable for capturing the response of the package material.

Low Density Cellular Concrete (LDCC)

SAR subsection 2.12.2.4.2.2 presents the information on LDCC. The LDCC is used in two separate zones of the package. The LDCC in the package has a compressive strength of 100 psi and meets the requirements of table 3.1 of ACI 523.1R.

Material Models in LS-DYNA

Steel:

The staff finds that the use of LS-DYNA damage accumulation features and the input material information with the acceptance criteria are acceptable to determine that the response of the material will be adequately captured for the impact loads from the different drop conditions required by 10 CFR 71.71 and 10 CFR 71.73 and provide a reliable estimate of the resulting damaged.

The applicant simulated tensile tests using these modeling features to confirm that the package model would truly reflect the material behavior. The results of such tests are presented in SAR Figures 2.12.2-10 through 2.12.3-13. The results demonstrate that the simulated results are close to the test results and can track the damage to the specimen during necking.

LDCC:

For the reactor fill LDCC grout, a simple elastic material model was used based on nominal properties obtained from open literature. The material properties of the LDCC are not vital as this is a filler material and is not an Important-To-Safety component. For the LDCC in the annular region, an elastic-plastic material model was adapted for use by incorporating a “generic” concrete model. The generic concrete model resulted in internally derived parameters for a tabulated compaction equation of state, including volumetric strain, compressive pressure, and bulk unloading modulus. This material model allowed for plastic deformation beyond a 100-psi unconfined compressive strength and provided stable and uniform results at locations of high compressive and shear loading.

The staff finds that the LDCC model in LS-DYNA can capture its response to the impact loads within the package. The LDCC model in LS-DYNA was further confirmed by a simulated compression test of the material. The stress-strain curve from this simulation is shown in SAR Figure 2.12.2-6 and shows a reasonable match with the compressive strength.

Finite Element Model

Mass and geometry

In SAR subsection 2.12.2.4 the applicant provided information on the finite element model that represents the package structure. The staff reviewed the process and the checks made to ensure that the finite element model used in the simulations captures the physical and geometric properties of the package.

The comparison of the model geometry and mass with those of the package are presented in SAR table 2.12.2-2 and 2.12.2-3 respectively. The comparisons show that the model represents the package in both these aspects.

Element Formulation and Discretization

The applicant used the solid element formulation in LS-DYNA in developing the FE model mesh for the CR3MP steel containment. Hourglass stabilization is used to reduce non-realistic deformation of the solid elements that produce zero strain and no stress. Hourglass controls were defined for all deformable elements/materials in the FE models. The SAR included a table that specified the hourglass ID for all components, except for the horizontal drop pad. A standard solid element with exact volume integration was used for all elements, and an hourglass coefficient was used for all but the reactor fill component.

The size of the element and their ability to capture the analysis parameters was selected using a series of mesh sensitivity analysis. The results of the mesh sensitivity runs are presented in SAR subsection 2.12.2.4.3.1 to demonstrate that the size of the elements is sufficient while maintaining reasonable computational times.

The packaging grout validation analysis used a fully integrated selectively reduced element formulation, though this material in the rest of the analyses uses a constant stress solid element formulation. This difference the staff finds is of minor importance, with little impact to the conclusions of the FE analyses.

The applicant performed a mesh sensitivity analysis particularly for regions near the attachment weld between the cylindrical shell and the cover plates. SAR table 2.12.2-5 lists the parameters and results of the element sizing runs. SAR figures 2.12.2-15 through 2.12.2-22 present the results in a graphical format and using the Five-Step Procedure for Uncertainty Estimation from Section 2 of ASME V&V 20-2009 to produce an extrapolated estimation of parameters for comparison.

The staff finds that the finite element model representation of the package in LS-DYNA is acceptable and demonstrates that the package when subject to the conditions required under 10 CFR 71.71 and 10 CFR 71.73 will be capable of capturing the response of the package to the respective loading conditions.

Drop Simulation Results

NCT Analysis

In SAR subsection 2.12.2.5 the applicant presents the results of the NCT drop analysis. For the End Drop, the simulation was set with an initial velocity of 96.2 in/s and an appropriate problem time to capture the secondary impact of payload against the top cover. The maximum stress intensity is shown in SAR figures 2.12.2-23 and 2.12.2-24. Since the peak stress was greater than the yield stress, plastic strain limits were determined. The maximum accumulated damage was only a small fraction of the fracture initiation limit as shown in SAR figure 2.12.2-29. No elements eroded from the model and the maximum accumulated strain limit damage margin of safety was computed as 19.8.

The NCT Corner Drop results are reported in SAR subsection 2.12.2.5.3. SAR figure 2.12.2-5 has the CR3MP oriented with the top cover down and the shell cylindrical axis oriented at 47.8°

from the horizontal. The drop is set with an initial velocity of 96.3in/s. The maximum stress intensity of the model is shown in SAR figure 2.12.2-39 located at the bottom outer edge of the top cover (SAR figure 2.12.2-40). The maximum accumulated damage is 17.8% of the fracture initiation limit. The accumulated strain limit damage margin is 3.8. The CR3MP impact force shown in SAR figure 2.12.2-49 has an initial impact peak force of 2.77x10^6 lbf., which is bounded by the secondary impact of the payload on the top cover inner surface peaking at 4.0493x10^6 lbf.

The NCT Corner drop tipover is reported in SAR subsection 2.12.2.5.4. In this section the damage to the CR3MP after the corner drop reaches its final resting state is analyzed. Any further damage was added to the top cover which experienced the highest strain on 17.9%. The energy available for the tipover is the sum of the potential energy of the CG change and the residual kinetic energy from the corner drop. SAR figures 2.12.2-57 and 2.12.2-58 show that the maximum accumulated damage in the top cover is 3.2%. The combined accumulated damage from the corner drop tipover is cumulatively computed as 21.1%. The corner drop tipover accumulated strain limit damage provides a margin of 3.7.

HAC Analysis

The HAC analysis considered the End, Side and CG-over-corner drops and are in SAR subsections 2.12.2.6.1 through 2.12.2.6.3, respectively.

The HAC End Drop simulation was oriented with the top cover down and parallel to the drop pad (SAR figure 2.12.2-5) with initial velocity of 536.2in/s and an appropriate problem time to capture the secondary impact of the payload against the top cover. SAR figure 2.12.2-69 shows that the maximum accumulated damage on the outside surface of the shell as 4.53% of the fracture initiation limit, with a maximum accumulated strain limit damage margin of safety of 12.5.

The HAC Side Drop was simulated with an orientation as shown in SAR figure 2.12.2-5 with an initial velocity of 536.2in/s; SAR figures 2.12.2-71 and 2.12.2-72 show that the maximum stress intensity is reached in the lower edge of the top cover, with similar stress in the bottom cover. The maximum accumulated damage in the bottom cover is 11.2% of the fracture initiation limit, with a maximum elemental accumulated strain limit damage margin of safety of 6.1. The accumulated damage reported is insufficient to erode any element from the model.

The HAC Corner Drop is oriented as shown in SAR Figure 2.12.2-5 in the simulation with an initial velocity of 536.2 in/s. Total damage accumulation was sufficient to erode elements in the CR3MP shell. The location and the erosion are shown in SAR figure 2.12.2-82, figure 2.12.2-83 and Figure 2.12.2-84. As a result, any other elements with an accumulated strain limit damage that is below a safety margin of 3 was considered as eroded. This led to a length measuring 45.2 inches on the symmetry plane with the widest gap of 4.13 inches. This resulted in a rectangular open area of 373 square inches as the area of possible LDCC content release.

Model Energies

SAR subsection 2.12.2.7 provides the applicant’s assessment of the model energies from the different simulated drop conditions. For each simulation, the applicant shows in a graphical format the distribution of energy in different forms as the drops proceeds over the duration of the simulation. The model energies are reasonably well balanced and led to a maximization of the containment boundary damage. All cases are within the range of computed potential energies of 5.17×10^6 in-lbf and 1.602×10^8 in-lbf during NCT and HAC respectively.

LDCC Released

SAR subsection 2.12.2.8 provides the applicant's assessment of the flow of the LDCC through the damaged section of the containment. The LDCC from within the RPV passes between the RPV and the closure plate through the narrow crack, as shown in SAR figure 2.12.2-84. The area of the gap is 373 square inches.

Summary of the Results of the Drops

The CR3MP acceleration is computed from the contact force curve between the outer steel of the containment and the drop pad. The NCT drop results are summarized in SAR table 2.12.2-7. The results show no significant accumulation of damage in the models with significant margins of safety, thereby maintaining the integrity of the containment boundary for all NCT drop cases.

The HAC drop results are summarized in SAR table 2.12.2-8 and show that plastic strain has occurred in all cases. Only in the case of the corner drop did the damage erode elements in the containment boundary, which occurred at the interior of the CR3MP shell adjacent to the inner surface of the cover. Conservatively, the opening was sized as 373 square inches.

Evaluation of Drop Simulations

The staff finds that all FE models appear to show a good representation of the load cases defined, providing reasonable and expected results for overall deformation, stresses and strains within individual components, and element erosion due to damage accumulation.

For some load cases, the packaging grout experienced significant plastic strain, resulting in dramatic component deformations. The side impact configuration during HAC resulted in significant accumulation of the packaging grout within the clearance (gap) near the top of the CV. Though some lack of sufficient contact issues were found, it likely has little effect on the results. The CG over top-corner impact configuration during HAC resulted in only minor deformation of the packaging grout, which was limited by the movement of the RPV components. The deformation of the packaging grout during these analyses seems reasonable for the application.

For all load cases except the CG over top-corner impact configuration, the damage parameter does not exceed the critical threshold, indicating that some plastic deformation and subsequent damage may have been accumulated, but not to the point of material failure. Though the critically damaged elements were only on the inside surface of the CV, a through-thickness failure across a wider region of elements was assumed, and the total loss of radioactive materials was calculated based on that opening (gap) size.

2.1.9 Conclusion

Based on the unique nature of the package, the crush test, the effect of puncture and fire as evaluated by the applicant has little or no effect when combined with the overall HAC drop analysis. As a result, the staff finds the package's overall target safety objective is met.

The staff based on the findings of their review concludes that the package's structural design information presented in the SAR meets the requirements of the applicable sections of 10 CFR Part 71, and, where applicable, the requirements of 10 CFR 71.41(d) – Special Package Authorization - which states that the applicant shall demonstrate that "the overall level of safety in transport …is at least equivalent to that which would be provided if all the applicable requirements had been met" is demonstrated by the information presented in the application.

2.2 Materials Evaluation

The CR3MP package consists of a 3-inch-thick steel shell, a 6-inch-thick steel top and bottom cover, closure and other fabrication welds. The top cover plate closure weld is a field weld, performed after placement of the RPV and RI contents into the packaging. A low-density cellular concrete (LDCC) grout fills the annulus between the contents and the CR3MP shell. The contents have no fissile material and only consist of highly activated metal. Shielding from gamma radiation is provided by the thick shell wall and top and bottom covers.

The package is welded closed with one pressure vent port in the top cover, which is subsequently plugged and welded flush prior to transportation.

The applicant has proposed two license conditions related to the materials review,

- LST of the transport is discussed in this SER and is established at 0°F. For the duration of the transport, the LST shall be greater than or equal to zero.

- No Pressure test is performed as required by 10 CFR 71.85(b), which stipulates the containment system to be tested to at least 50 percent higher than the maximum normal operating pressure (MNOP), if the MNOP exceeds 5 psi. The MNOP for this vessel under NCT is 14.8 psig, establishing the pressure test minimum at 22.2 psi. The applicant evaluated this vessel using a higher pressure of 26.2 psi to show an adequate safety margin as described in SAR section 2.6.1.3.1.

2.2.1 Drawings

The applicant provided drawings in SAR section 1.3.2 that describe the materials specifications, component dimensions, weld fabrication and examination requirements. The staff reviewed the drawings with respect to the guidance in NUREG/CR-5502, "Engineering Drawings for 10 CFR Part 71 Package Approvals," and confirmed that the drawings provide adequate details of the design features considered in the materials review. The staff concludes that sufficient information is provided in the drawings to satisfy the requirements of 10 CFR 71.33.

2.2.2 Codes and Standards

The applicant provided references to codes and standards in SAR section 2.1.4 for material specifications, welding procedures, inspection methods and acceptance criteria. The package is classified as a Category II package and, per the guidance of NUREG/CR-3854, "Fabrication Criteria for Shipping Container," is designed in accordance with ASME Boiler and Pressure Vessel Code (B&PV) Section III, Division 1, Subsection ND, "Class 3 Components." Design of the containment boundary is based on the methodology of NRC Regulatory Guide 7.6.

The staff reviewed the materials specifications for the containment boundary and noted that the applicant cited either ASME or ASTM standards (SA- or A516, Grade 70), which is consistent with the guidance in NUREG-3854 for Category II containment materials. In addition, the welding requirements are discussed in section 2.2.3 below.

Based on the staff's verification that the applicant's design, fabrication, and testing is in accordance with the codes and standards recommended in the staff guidance, the staff finds the package criteria to be acceptable to meet the requirements of 10 CFR 71.31(c).

2.2.3 Weld Design and Inspection

As stated in SAR section 2.3.1, all welding procedures and personnel are to be qualified in accordance with ASME Section IX. In SAR section 2.3.1, the applicant stated that all weld filler metal heats will be impact tested using welding coupons in accordance with ASME Section III, Division 1, ND-2400 and Table ND-2331(A)-2. All weld filler materials and welding procedure qualifications shall be per ASME Code Section III, Division 1, ND-4335.

In SAR section 2.1.4, the applicant states that the package is classified as a Category II package and, in accordance with NUREG/CR-3854, the appropriate design criteria for this category containment is ASME Code Section III, Division 1, Subsection ND. All nondestructive examination is performed per ASME Code Section III, Division 1, Subsection ND. All welds are visually inspected per Article ND-4123 with the acceptance criteria of ND-4424. Welds are identified to be inspected using surface techniques on the root layer, final pass of inner and outer surface and volumetrically inspected on the finished outer surface, and acceptance criteria shall be in accordance with Article ND-5300 and Section V, Article 4, Article 6, or Article 7.

In SAR section 2.3.1, the applicant also notes that closure joint welds between the top and bottom cover and the outer shell are all full penetration Category C welds per requirements of ASME Code Section III, ND-4243.1, Figure ND-4243-1(j).

The staff reviewed the welding criteria and verified that the Import to Safety (ITS) welds are designed, fabricated, and examined in a manner that is consistent the ASME B&PV Code and the guidance in NUREG/CR-3854, and therefore the staff concludes that the fabrication criteria meet the requirements of 10 CFR 71.31(c).

2.2.4 Mechanical Properties

The applicant provided mechanical properties of the steel materials of construction in SAR Table 2.2-1. The staff reviewed these properties against the referenced ASME code edition and found these to be acceptable. The applicant outlined additional requirements for materials used as containment boundary in SAR section 2.3.1 for minimum carbon content, weld metal tensile strength, and maximum nil ductility temperature (NDT).

LDCC consists of Portland cement per ASTM C150, "Standard Specification for Portland Cement" and is mixed with foaming agents per ASTM C869, "Standard Specification for Foaming Agents Used in Making Preformed Foam for Cellular Concrete" and follows the guidance of American Concrete Institute (ACI) 523.1R (Guide for Cast-in-Place Low Density Cellular Concrete).

In SAR section 2.3.2 the applicant set a minimum compressive strength requirement for LDCC of 100 psi at 28 days using the testing guidance from ASTM C495, Standard Test Method for

Compressive Strength of Lightweight Insulating Concrete. The applicant used this minimum LDCC compressive strength value in the analysis for NCT and HAC conditions.

The staff verified that the properties used in the structural analysis are consistent with applicable ASME, ASTM, and ACI codes and standards, and therefore the staff concludes that the mechanical properties meet the requirements of 10 CFR 71.33, and 71.51(a).

2.2.5 Brittle Fracture

The ASTM A516 and ASME SA-516 steel containment materials are fine grain steels designed for LST. To address the brittle fracture performance of these steels, the applicant describes the fracture testing that will be performed on the containment materials to demonstrate their performance at the LST of the package during transportation. The applicant used the guidance specified in NUREG/CR-6491 to establish the LST as 0°F. The applicant set the requirements for material to be drop weight tested in accordance with ASTM E208 to ensure the NDT would be -20°F or lower. Due to material properties being limited, a license condition is established for the LST to be greater than or equal to 0°F during the entirety of the transport.

Additionally, in SAR section 7.1.3 related to package operation and preparation for transport, the applicant set forth the requirement that a continuous ambient temperature monitor sensor shall be used as part of the transport if there was any possibility for the ambient temperature to reach 0°F during the transportation window. Transportation shall be halted if the temperature reaches a range between 0°F and 5°F. Transportation can only resume once the ambient temperature is above this temperature requirement.

The staff reviewed the details provided and concludes that, based on the testing requirements that will establish adequate brittle fracture performance at the LST, the applicant satisfies the requirements of 10 CFR 71.51(a).

2.2.6 Radiation Effects

There are no fissile materials in this package and the only radiation associated with the RPV and RVI is gamma radiation. The staff notes that gamma radiation is not expected to have any effect on the mechanical properties of the containment boundary steels or the integrity of the grout material. For the grout material, some radiolysis of the moisture in the grout may release hydrogen and oxygen gas. This is discussed in Chapter 4 of this SER and in SAR section 5.4.4.

The staff verified the information provided and concludes that it meets the requirements of 10 CFR 71.43(f), and 71.51(a).

2.2.7 Corrosion Resistance and Protective Coatings

The applicant stated that the steel and concrete materials of construction will not have a significant chemical, galvanic or other reaction, neither internally nor externally. The applicant supported this position by citing the facts that the outside of the package is painted, the transportation over water to the waste disposal site will be of relative short duration, and the package is only designed for one-time use.

The staff reviewed the information provided and verified that the painted carbon steel components are not expected to experience significant corrosion during the one-time shipment in the outdoor air environment. The staff also noted that painted carbon steel transportation packages are commonly used, and the staff is unaware of any operating experience in which corrosion has challenged a welded steel confinement boundary.

Based on staff's review of the information provided, the staff finds that the package design for corrosion performance meets the requirements of 10 CFR 71.43(d).

2.2.8 Content Reactions

SAR section 5.4.4, "Radiolytic Gas Generation," and Appendix 3.5.2, "Evaluation of Pressure in CR3MP," provide the applicant's analyses of the potential for radiolytic decomposition and vaporization of the moisture in the grout to generate a combustible hydrogen gas mixture and increased internal package pressure.

The applicant calculated the maximum quantities of total gas and hydrogen gas that may be generated due to water radiolysis and determined that it would take an estimated 429 days for generated hydrogen to reach flammable concentrations of 5% by volume in the air space inside the canister (i.e., the flammability threshold in NUREG-2216).

In SAR section 7.1.3 the applicant states that, to keep the hydrogen concentrations to 5% or less by volume, the shipment window after the package closure shall be set to a maximum of 1 year.

The staff reviewed the applicant's evaluation of water radiolysis and vaporization and concludes that the information provided by the applicant is sufficient to demonstrate that the hydrogen flammability limit will not be exceeded. Therefore, the package design satisfies the requirements of 10 CFR 71.43(d).

2.2.9 Evaluation Findings

The staff has reviewed the package and concludes that the applicant has met the requirements of 10 CFR 71.33. The applicant described the materials used in the transportation package in sufficient detail to support the staff's evaluation.

The staff has reviewed the package and concludes that the applicant has met the requirements of 10 CFR 71.31(c). The applicant identified the applicable codes and standards for the design, fabrication, testing, and maintenance of the package and, in the absence of codes and standards, has adequately described controls for material qualification and fabrication.

The staff has reviewed the package and concludes that the applicant has met the requirements of 10 CFR 71.43(d), 10 CFR 71.85(a), and 10 CFR 71.87(b) and (g). The applicant has demonstrated that there will be no significant corrosion, chemical reactions, or radiation effects that could impair the effectiveness of the packaging. In addition, the package will be inspected before the shipment to verify its condition.

The staff has reviewed the package and concludes that the applicant has met the requirements of 10 CFR 71.43(f) and 10 CFR 71.51(a) for Type B packages. The applicant has demonstrated that the package will be designed and constructed such that the analyzed geometric form of its contents will not be substantially altered and there will be no loss or dispersal of the contents under the tests for normal conditions of transport.

3.0 THERMAL EVALUATION

The staff reviewed the CR3MP application to verify that the thermal performance of the package for a one-time special authorization shipment was adequately evaluated for the tests specified under NCT and HAC, and that the package design satisfies the thermal requirements of 10 CFR Part 71.

3.1 Description of the Thermal Design

3.1.1 Packaging design features

SAR section 3.1.1 stated that the CR3MP transport package consists of a 3-inch-thick cylindrical shell, a 6-inch-thick bottom plate, and a 6-inch-thick top cover plate; the exterior top and shell surfaces are painted white. The content includes reactor vessel portions filled with LDCC, which are encased within the package filled with LDCC; a 3-inch air space exists at the top of the package. Heat transfer from the package is by passive means.

SAR section 1.1 stated that the LST for transport is 0°F; this is listed as a condition of the Special Package Authorization.

3.1.2 Content heat load specification

SAR section 3.1.2 stated that the thermal model's decay heat conservatively assumed 500 W; this was higher than the 358.1 W decay heat calculated in SAR section 5.2. SAR Sections 1.2.2.3 and 5.2 noted the source term was calculated to decay to this lower value on March 31, 2023; shipments after this date would be transporting contents with a lower decay heat. The thermal model assumed that the decay heat was concentrated within the centrally positioned activated and surface contaminated payload steel content.

3.1.3 Summary Tables of Temperatures

Package temperatures for NCT and HAC were provided in SAR Table 3.3-2 and Table 3.4-1, respectively. Transient temperature profiles associated with the grout, payload, and shell during the thermal HAC were provided in SAR Figure 3.4-5. All temperatures were less than the allowable values.

3.1.4 Summary Tables of Package Pressures

Package pressures during NCT and thermal HAC were presented in SAR Section 3.5.2. As noted in SAR Table 3.1.3, the MNOP and HAC pressures were calculated to be 14.8 psig and 33.4 psig, respectively.

3.2 Material Properties and Component Specifications

3.2.1 Material thermal properties

According to SAR Sections 1.2.1.1 and 2.2.1, the package shell is constructed of ASTM/ASME A516/SA516 Grade 70 carbon steel and, according to SAR Section 2.3.1, the package shell, top cover, and bottom cover welds would meet ASME B&PVC Code requirements. The content consists of surface contaminated and activated reactor vessel and piping portions encased in a

LDCC grout. As noted in SAR Section 2.2.1, material properties of the carbon steel are based on the ASME B&PV Code.

According to SAR Section 3.1.1, the LDCC grout would have a density range between 30 and 60 pcf; additional properties were provided in SAR Section 3.2.1 and Table 3.2-3. Thermal property values for the CR3MP package components (e.g., steel, grout, air) were provided in SAR Section 3.2 and included thermal conductivity, density, and specific heat.

SAR Table 3.1-1 indicated package component minimum temperature limits of -40°C. As noted above, the LST for transport is 0°F, such that the package would be transported in a vertical orientation at temperatures greater than or equal to 0°F.

Finally, radiolysis of water vapor within the concrete was discussed in SAR Section 5.4.3. Staff evaluation of this analysis is presented in SER Chapter 4.

3.2.2 Specification of components

As noted above, the package shell is constructed of ASTM/ASME A516/SA516 Grade 70 carbon steel and, according to SAR Section 2.3.1, the package shell, top cover, and bottom cover welds meet ASME B&PVC Code requirements.

The specifications associated with the package materials (steel, grout) were provided in SAR Section 2.2. SAR Section 2.2.1 stated that the LDCC is based on ASTM C150 (for Portland cement), ASTM C869 (for foaming agents), and American Concrete Institute (ACI) 523.3R-14 standards.

3.3 General Considerations for Thermal Evaluations

3.3.1 Evaluation by Analysis

According to SAR Section 3.3, the two-dimensional axisymmetric thermal model was constructed using ANSYS Finite Element Code Version 19.2 based on the dimensions listed in SAR Table 3.3-1. The model consisted of the carbon steel shell, top plate and bottom plate, the stainless steel RPV wall, its corresponding centrally positioned volume of payload steel, and the LDCC grout that filled the remaining void space within the package except for a three-inch air gap. Although the payload is constructed of carbon steel and stainless steel, the model applied the lower thermal conductivity for stainless steel.

According to SAR Section 3.2.1, the package's exterior top and side surfaces were painted white and had absorptivity and emissivity values of 0.34 and 0.88, respectively. These values increased to 0.8 and 0.9 during the HAC fire. The package's interior surfaces assumed a steel shell emissivity of 0.95, a concrete emissivity of 0.9, and payload steel emissivity of 0.9. SAR Section 3.3 noted radiation heat transfer was modeled across the air gap at the top of the package. SAR Section 3.5.3 discussed the natural convection heat transfer correlations applied to the package's top and side surfaces. As mentioned earlier, thermal properties (e.g., thermal conductivity, specific heat, density) of steel, LDCC, and air were presented in SAR Section 3.2.1.

The ambient temperature boundary condition was set to 38°C. Solar insolation was applied to the top and side surfaces according to 10 CFR 71.71(c). Although the NCT steady state analysis of the large thermal mass package (860,000 lbs) averaged the insolation over 24 hours, SAR Table 3.3-2 indicated there was over 200°C margin between maximum NCT temperatures of package materials and allowable values. SAR Section 3.3 indicated that the bottom surface was modeled as an adiabatic boundary condition.

As noted in SAR Section 3.5.2, pressure calculations were based on the effects from air, water vapor, and radiolysis gases within the air gap and the LDCC of the package. Regarding radiolysis gases, SAR Section 3.5.2 considered the total gas generated that was calculated in SAR Appendix 5.5.4. In addition, SAR section 3.5.2 noted that the water vapor within the package was associated with the bound and unbound water of the LDCC grout. SAR section 2.1.3.1 listed the internal center LDCC and annular LDCC volumes and masses, which indicated that the annular LDCC volume and mass were approximately 10% of the center LDCC volume and mass.

SAR Section 3.5.2 indicated that the approximately 3-inch thick annular LDCC volume would have a one-month cure period. Likewise, the internal center LDCC was expected to have a six-month cure period during which time water vapor would diffuse and evaporate, resulting in mostly bound water vapor; earlier submittals indicated the amount of water associated with hydration of the package's cement was on the order of 100 moles. Due to variables during construction, including curing time period, LDCC density, and curing temperature, the SAR indicated an uncertainty in the final LDCC moisture quantity and, therefore, assumed saturated water vapor conditions.

To mitigate package pressure buildup, SAR Section 3.5.2 and Section 7.1.2 stated that just prior to transport, the air gap below the lid would be purged via a vacuum pump (i.e., removal of existing radiolysis gases and water vapor) and the lid vent port would be welded closed. The initial package pressure at closure was based on ambient temperature and the air gap volume. The pressure calculation at the NCT temperature for the combined open volume of the air gap and the LDCC (i.e., assuming a continuum between the two volumes) showed an NCT pressure below design pressure. According to SAR Section 2.7.4.3, the package met stress requirements based on the calculated HAC pressure. In addition, SAR section 4.3 considered the potential release effects of an assumed local rupture of the package boundary during HAC; staff notes that a rupture would reduce pressure within the package.

SAR Appendix 3.5.4.1 discussed the results of a time-step and mesh sensitivity study, which showed that changing the number of the mesh nodes by over a factor of 10 resulted in negligible temperature changes. Likewise, the time-step sensitivity study provided plots to determine the appropriate time step (which was much smaller than the default value) such that smaller time steps resulted in negligible changes of package temperatures.

3.4 Evaluation of Accessible Surface Temperature

The applicant used the thermal model described above to perform the package thermal evaluation under NCT with and without solar insolation. SAR Table 3.3-2 provided NCT temperatures which showed the maximum shell temperature with insolation was 51°C and the package surface temperature with no insolation was 40°C. Staff finds that both surface temperatures are below the 85°C limit specified in 10 CFR 71.43(g) for exclusive use shipments.

3.5 Thermal Evaluation under Normal Conditions of Transport

3.5.1 Heat and Cold

As noted above, the applicant used the thermal model described above to perform the package thermal evaluation under NCT with and without solar insolation. SAR Table 3.1-2 and Table 3.3-2 provided the NCT temperatures, which showed that payload and packaging temperatures were well below the listed allowable temperatures.

SAR Section 3.3.1 and Section 3.2.2 noted that minimum package temperatures assumed that a package with no decay heat at -40°C would reach a steady-state temperature of -40°C, which is acceptable for all components according to the component specifications. As noted earlier, SAR Section 1.1 stated that the lowest service temperature (LST) for transport is 0°F; this is listed as a condition of the Special Package Authorization.

3.5.2 Maximum Normal Operating Pressure

SAR Appendix 3.5.2 described the MNOP calculation to compute the maximum normal operating pressure of 14.8 psig based on an average air temperature of 50°C. The calculation considered the increase in air pressure due to the temperature rise from ambient temperature to NCT temperature, the effect of water vapor pressure, and the pressure associated with moles from radiolysis gases. The calculated 14.8 psig MNOP is less than the 25 psig internal design pressure and the 26.2 psig pressure used in the NCT structural analysis described in SAR Section 2.6.1.3.1.

The calculation of hydrogen concentration due to radiolysis of water vapor within the concrete was discussed in SAR Section 5.4.3. Results showed concentrations would reach 5% (volume) for a time period of more than 400 days, which is greater than the six-month transport period's Special Authorization condition. Further staff's evaluation of this analysis is presented in Chapter 4 of this SER.

Finally, SAR Section 2.6.1.2 noted that there were no impacts due to differential thermal expansion.

3.6 Thermal Evaluation under Hypothetical Accident Conditions

3.6.1 Initial Conditions

According to SAR Section 3.4.1, the initial package temperatures for the HAC fire were based on the hot (38°C ambient and insolation boundary conditions) NCT maximum package temperatures described earlier. It was stated that the package was modeled in a horizontal orientation during the fire, with all sides exposed to the fire. Prior to the fire and during the post-fire conditions, the package was modeled in a vertical orientation to have higher insolation input and lower heat removal. The insolation input to the package after the fire was increased due to a higher surface absorptivity of 0.8 in order to account for oxidation and soot accumulation as a result of the fire. Thermal fire input considered radiation heat transfer and convection heat transfer from the fire. Radiation heat transfer was based on standard radiation heat transfer energy balance between the fire source temperature and the package surface temperature. Convection thermal input was based on being a fraction of the total heat flux from the fire. The effects of the radiation heat transfer and convection heat transfer on package temperatures during the fire was considered sufficiently modeled for this package considering the conservative decay heat value and the large thermal mass of the fixed solid content of the one-time shipment package.

3.6.2 Fire Test Conditions

According to SAR Section 3.4.2 and based on structural analyses described in SAR Section 2.7.1.3, the HAC thermal model was slightly modified from the NCT thermal model by assuming a crack formed at a lower package corner after the HAC drop tests such that a hypothetical 3-inch section of internal grout was exposed to the fire. SAR Section 3.4.2 indicated that a package surface emissivity of 0.9 was applied to the surface during the fire.

An ambient temperature of 38°C was applied after the 30-minute fire. A post-fire period of one day was analyzed to obtain transient temperatures; no convection heat transfer was assumed during this period. In addition, a steady-state model that considered convection heat transfer was also analyzed using post-fire conditions.

3.6.3 Maximum Temperatures and Pressures

Results of the maximum package temperatures during the fire HAC were provided in SAR Section 3.4.3, Table 3.4-1, Figure 3.4-3 during the fire transient, and Figure 3.4-4 for the post-fire steady-state condition. SAR Figure 3.4-5 provided the transient temperature profiles for grout, payload steel, and the shell. All temperatures were below allowable values.

SAR Section 3.5.4 discussed the pressure calculation during the thermal HAC. Pressures were calculated to be 33.4 psig and considered water vapor pressure, pressure from the radiolysis gases, and the effect of increased HAC temperatures of the gaseous phases.

Finally, SAR Section 3.4.4 noted that maximum thermal stresses during HAC were discussed in SAR Section 2.7.4, which found that differential thermal expansion was not an issue.

3.7 Evaluation Findings

Based on review of the statements and representations in the application, the staff concludes that the thermal design has been adequately described and evaluated and that the package design meets the Special Package Authorization requirements of 10 CFR 71.41(d).

4.0 CONTAINMENT REVIEW

The objective of the containment review was to evaluate the package design for a one-time Special Authorization shipment against the containment requirements of 10 CFR Part 71, under both NCT and HAC.

4.1 Description of the Containment System

According to SAR Section 4.1 and Section 1.2.1.1, the containment boundary of the CR3MP package consists of the bottom closure plate cover, the cylindrical shell, the top closure plate cover, pressure vent plug, and full penetration and volumetrically inspected welds that are classified as either Category A, B, or C per Subparagraph ND-3352.1 of the ASME Boiler and Pressure Vessel Code. The containment boundary is made from ASTM A516/ ASME SA516, Grade 70 carbon steel. According to SAR Section 1, the top plate cover, bottom plate cover, and shell are 6 inch thick, 6 inch thick, and 3 inch thick, respectively; SAR Figure 1.1-1 shows the CR3MP package cross-section.

SAR Section 4.1.2 states that there are no valves, ports, bolted closures, or seals in the containment boundary and the package is permanently welded closed for the one-time shipment. SAR Section 2.4.8 and Section 4.1.3 indicated there is a vent port located on the top closure plate; SAR Section 1.2.1 stated that a vent port plug is installed flush to the package and welded closed prior to transport.

4.2 General Considerations for Containment Evaluations

As noted in SAR Section 1.1, the application is for a Special Package Authorization in accordance with 10 CFR 71.41(d) for one-time shipment of the CR3MP package.

According to SAR Section 1.2.2, the content consists of sectioned portions of reactor pressure vessel and its internals. The activity associated with the content includes neutron activation of the metal content and surface contamination. As noted in SAR Section 1.2.2.3, Section 2.1.2, and Table 1.2-1, the content's activity that is greater than 30,000 Ci is nearly all associated with metal activation with only less than 25 Ci of Co-60 associated with fixed and loose surface contamination; the surface contamination was based on samples of the reactor coolant system and was mostly fixed. The chosen bounding package A_2 value, including due to activated metal, was approximately 3,000 A_2 with the fixed and loose surface contamination being approximately 2.5 A_2, according to SAR Section 4.3. Although a large portion of the surface contamination was found to be fixed, the containment analysis conservatively assumed all surface contamination as potentially being releasable.

SAR Section 5.5.3 discussed the radiolytic hydrogen generation (G_{H2}) and total gas generation (G_{total}) values due to the presence of water and foaming agents in the LDCC grout. The SAR indicated that foaming agent G values were bounding by using conservative assumptions during their calculation. According to the analysis presented in SAR Section 5.4.4, the applicant calculated that the hydrogen concentration in the package would reach 5% volume during a period greater than 400 days.

As noted in the SER Shielding Evaluation, the gas generation calculation was based on the payload having 358.1 W decay heat, of which a fraction was calculated to be absorbed in the grout. SAR section 1.2.2.3 and section 5.2 noted the source term was calculated to decay to this value on March 31, 2023; shipments after this date would be transporting content with a lower decay heat and, correspondingly, lower radiolytic hydrogen and total gas generation.

The analysis indicated that the approximate 400-day period was based on the amount of air within the internal LDCC (after subtracting the volume taken up by the reactor pressure vessel and reactor vessel internals) when calculating the hydrogen concentration; the LDCC grout is made to ensure at least 40% air volume, as indicated in SAR section 3.1.1. The SAR noted that the volume of air for determining hydrogen volume concentration did not consider the dilution effect of certain volumes within the package.

SAR section 3.5.2 and section 7.1.2 noted that, prior to shipment, the package's top air gap is purged via a vacuum pump and then, the top cover pressure vent port plug is seal welded. SAR section 7.1.3 stated there is a shipment window of one year after the port plug is welded close. Recognizing the SAR did not state a time period between purging of the air gap and subsequent welding of the port plug, such that radiolysis gases may accumulate in the air gap prior to welding of the port plug, the Special Authorization condition states that shipment must be complete within six months after the air gap purge to account for uncertainties in analysis assumptions and potential transport conditions.

4.3 Containment Evaluation under Normal Conditions of Transport

As noted in SAR Section 1.2.2, the releasable content is associated with surface contamination rather than volatiles or gas. The surface contamination is bonded to the LDCC grout that fills the welded-closed package and thus would have a negligible release fraction. According to SAR Section 4.2, the NCT structural and thermal analyses described in SAR Section 2.6 and Section 3.3 indicated there was no structural failure through which grout could be released and, therefore, there is no loss of radioactive contents exceeding the 10^{-6} A_2 per hour limit of 10 CFR 71.51(a).

4.4 Containment Evaluation under Hypothetical Accident Conditions

SAR Section 4.3 performed an analysis to show the effect of a potential release based on a hypothetical opening after a structural HAC. The analysis assumed a conservatively sized weld opening based on results from a dynamic finite element analysis of the structural HAC drops described in SAR Section 2.7.1.3. The SAR noted a number of conservative assumptions of the release calculation, including the activity and form of the released grout and its pathway for exiting the opening.

The results of the calculation showed a potential release less than an A_2, which is less than the A_2/week requirement of 10 CFR 71.51(b).

4.5 Leakage Rate Tests for Packages

The CR3MP package is used for a one-time exclusive use shipment special package authorization. There is no leakage test for the CR3MP one-time special package authorization because of package design and fabrication procedures, structural examinations and inspections, numerical dynamic finite element drop analysis results, and the small release fraction of the limited loose surface contamination activity encased within the LDCC grout.

4.6 Evaluation Findings

Based on review of the statements and representations in the application, the staff concludes that the containment design has been adequately described and evaluated and that the package design meets the Special Package Authorization requirements of 10 CFR 71.41(d).

5.0 SHIELDING REVIEW

The objective of the review is to verify that the shielding of the package provides adequate protection against direct radiation from its contents and that the package design meets the external radiation requirements of 10 CFR Part 71 during NCT and HAC. This application was also reviewed to determine whether the package fulfills the acceptance criteria listed in Section 5 (Shielding Review) of NUREG- 2216, “Standard Review Plan for Transportation Packages for Spent Fuel and Radioactive Material.”

5.1 Shielding Design Description

5.1.1 Design Features

The applicant designed the CR3MP to transport the Crystal River Unit 3 RPV and RVI. The CR3MP had an overall height of 178.1 inches and an overall diameter of 200.3 inches. The CR3MP transport package shielding design featured a three-inch thick right circular cylinder steel shell. The package also has both a six-inch (minimum) top cover and a six-inch (minimum) bottom cover. The applicant stated that the steel RVI would be encased within the RPV using LDCC fill material (i.e., grout). The applicant also stated that, after encasing the RVI in grout, the RVI and RPV would be placed inside the right circular steel shell leaving an approximately three-inch annulus between the RPV and the inner surface of the right circular cylinder shell as well as a gap between the top of the RPV and the top of the right circular steel shell.

The applicant stated that the annulus would be filled with grout up to the top of the RPV and the top cover would subsequently be welded to the right circular steel shell thereby creating a three-inch air gap between the RPV top and the bottom of the top cover. The staff reviewed the SAR drawings and text describing the package shielding features. The information described the shielding features, materials, and dimensions with tolerances; therefore, the staff finds that the applicant adequately described the package with sufficient detail to support an evaluation of the package's shielding capabilities.

5.1.2 Maximum Radiation Levels Summary

The applicant performed shielding analyses to demonstrate that the package meets the 10 CFR 71.47(b) regulatory requirements for exclusive use transport as well as the 10 CFR 71.51(a)(2) regulatory requirements. The applicant summarized the NCT dose rates for the package top, side, and bottom surfaces in SAR Table 5.1-1 as well as the dose rate two meters from the package radial surface. In addition, the applicant provided a dose rate for occupied locations in SAR Table 5.1-1. The applicant summarized the HAC dose rates in SAR Table 5.1-2. After reviewing both the SAR Table 5.1-1 dose rates and the SAR Table 5.1-2 dose rates, the staff finds that these values meet the regulatory dose rate requirement for NCT in 10 CFR 71.47(b) and HAC in 10 CFR 71.51(a)(2).

5.2 Shielding Radiation Source Term

The applicant utilized an activation source term that was generated by the original equipment manufacturer (OEM). The OEM generated location- and energy-specific neutron fluxes in accordance with the NRC approved methodology outlined in BAW-2241NP-A, Revision 2, "Fluence and Uncertainty Methodologies" (ADAMS Accession No. ML073310660). Then, using the computed fluxes and component materials, the OEM calculated the activation isotopes and decayed them based on a shipment date of June 30, 2021. The applicant subsequently increased the calculated value by more than fifty percent to 30,000 Curies to account for uncertainties.

The staff reviewed the proprietary approach used to determine the activation source term and found it acceptable for the following reasons: first, the OEM followed an approved NRC methodology; second, the applicant increased the calculated activation source term by more than fifty percent (50%) to be conservative which exceeded the acceptable uncertainty identified in the NRC methodology. The staff also determined that basing the activation source term on a

June 30, 2021, shipment date versus a shipment date of March 31, 2023, was conservative because shorter cooling times increase calculated dose rates.

The OEM calculated an activation source term which was predominantly Co-60. The remaining activation source term isotopes included Ni-63, Fe-55, and trace amounts of other isotopes. The OEM also determined that the activation source term did not include neutron sources. The applicant chose to model the activation source term as solely Co-60 and provided the gamma energy spectrum in SAR Table 5.2-1.

The staff finds the assumption that Co-60 is the only isotope present conservative because, of all the source term isotopes, the energetic photons emitted by Cobalt-60 are most able to penetrate the steel shielding material of the package and contribute to both worker and public exposure. Therefore, the staff finds that the applicant has adequately described the activation source term.

In estimating the surface contamination source term, the licensee obtained coupons from all available Reactor Coolant Systems as surrogates since the reactor interior was not accessible. The licensee chose to obtain surrogate coupons from the Reactor Coolant Systems because they shared a similar operating environment (i.e., temperature, pressure, duration) to the RVI and RPV interior surfaces. The staff finds this approach reasonable because the reactor coolant could deposit contamination from the RVI in the Reactor Coolant Systems.

The licensee analyzed the coupons to determine the types and quantities of surface contamination present. The empirical samples demonstrated that the surface contamination is composed primarily of Co-60 (58%), Ni-63 (30%), Cs-137 (5%), and Fe-55 (5%). Since Co-60 was the predominant surface contamination isotope, the applicant modeled the entire surface contamination source term as Co-60 and provided the gamma energy spectrum in SAR Table 5.2-1. The staff finds using only Co-60 for the contamination source term conservative because, of all the source term isotopes, Co-60 will contribute the most to exposure since it has the ability to penetrate several inches of steel.

The analysis identified both a minimum and a maximum surface contamination value. Using the empirical data provided by the licensee, the applicant estimated the surface contamination on the RPV and RVI components to be approximately 24.8 Curies. The applicant developed this estimate by increasing the empirical data by more than ten percent above the maximum contamination value identified in the licensee’s analysis. The staff found increasing the surface contamination source term by more than ten percent conservative. Therefore, the staff finds that the applicant has adequately described the contamination source term.

5.3 Shielding Model

5.3.1 Source and Shielding Configuration

The applicant generated a three-dimensional, quarter-symmetry model utilizing reflective x- and y- axes with the Monte Carlo N-Particle® (MCNP), Version 6.2 computer code. Because the packaging and payload are symmetric across the x- and y- axes (radial axes), the staff found this simplification acceptable. The applicant explicitly modeled the RVI and RPV steel and LDCC in the CR3MP payload by importing the three-dimensional RPV and RVI geometry created by the OEM’s computer code into the MCNP code. The applicant included neither a description of the RPV geometry, the RVI geometry nor the activation source term in the sample

MCNP input file provided with the application because the lines of code generated by the OEM to model these payload aspects were too numerous.

The applicant modeled the RPV and RVI as reduced density carbon steel (approximately 432 lb/ft^3) because the volume calculation methodology employed by the OEM's code increased the volume of these components in the model versus the actual RPV and RVI volumes. The applicant also modeled the air gap between the top of the payload and the package lid interior surface as void.

The staff determined that modeling the RVI steel at a density of 432 lb/ft^3 versus the typical carbon steel density of 488 lb/ft^3, as well as modeling the air pocket above the RPV as void, are conservative because these assumptions provide less radiation attenuation versus the actual payload configuration. In modeling the LDCC, the applicant used the minimum allowable density of 30 lb/ft^3. The staff determined that modeling the grout at the minimum density is conservative since this assumption provides the least possible radiation attenuation for the payload configuration.

The applicant modeled the packaging as carbon steel with a density 488 lb/ft^3. The staff determined that using this density is reasonable since it depicts the actual payload properties. The staff also reviewed the applicant's sample input file. The staff determined that the applicant correctly input the Co-60 gamma spectrum in SAR Table 5.2-1.

5.3.2 Material Properties

The applicant modeled all steel as carbon steel. SAR Table 5.3-2 identified the steel composition used in the MCNP model. SAR Table 5.3-3 listed the grout composition used in the MCNP model. The staff confirmed that the applicant correctly input the carbon steel and grout compositions identified in SAR Tables 5.3-2 and 5.3-3 respectively to the MCNP model.

5.4 Shielding Evaluation

5.4.1 Methods

The applicant calculated dose rates for the CR3MP using photon cross-sections based on ENDF/B-VI.8 nuclear data in the MCNP computer code, Version 6.2. Given the capabilities and the extensive application of the MCNP code within the nuclear industry, the staff found the code acceptable for this application. To calculate the NCT dose rates, the applicant modeled the payload and packaging as undamaged based on the results of NCT analyses. After reviewing the application, the staff determined that the CR3MP NCT shielding model reasonably depicted the package configuration described in SAR Section 2.6.

Although the HAC analytical results identified no significant damage to the CR3MP shielding components, the analyses indicated that surface welds may fail in limited areas which could result in a significant release of grout. Therefore, to calculate the HAC dose rates, the applicant modeled the payload without grout between the RPV and the packaging inner radial surface. Staff found this approximation acceptable because it would lead to higher dose rates due to a maximum loss of material.

In determining package dose rates, the applicant performed two calculations. The first calculated the dose rate due solely to the activation source term, and the second calculated the dose rate due solely to the contamination source term. The applicant determined the total dose rate by summing the results of the two calculations. The staff found that summing the dose rates for the neutron activation source and the surface contamination source acceptable since dose rates from different sources are cumulative. For NCT dose rates, the applicant calculated CR3MP surface dose rates using tallies at the top, bottom, and radial surfaces.

The applicant also calculated dose rates two meters from the radial surface. In addition, the applicant calculated the occupied location dose rate with a radial tally located 25 feet from the CR3MP centerline. For HAC, the applicant calculated dose rates one meter from the top, bottom, and side surfaces using three tallies. The staff reviewed the tally information in the sample MCNP input file. Staff determined that the tallies were appropriately located and appropriately sized to identify the maximum package dose rates.

5.4.2 Flux-to-Dose-Rate Conversion

The applicant used the American National Standards Institute ANSI/ANS-6.1.1-1977 photon flux-to-dose rate conversion factors in their analyses. Staff finds this acceptable since it follows guidance. The applicant provided the conversion factors in SAR Table 5.4-1.

5.4.4 External Radiation Levels

The applicant identified the maximum dose rates calculated by the applicant for the side, top, and bottom package surfaces due to activation and contamination for both NCT and HAC in SAR Table 5.4-2. The applicant also identified the uncertainty, one of the ten statistical checks used by the MCNP code to determine if a result is valid, associated with each MCNP calculation in SAR Table 5.4-2. SAR Table 5.4-2 identified that the uncertainty for each calculation result was less than ten percent except for the package bottom surface which was thirteen percent. The staff determined that the external radiation levels were reasonable because, even though the uncertainty value for all calculations was not less than the MCNP code acceptance criteria, the values are less than ten percent of the regulatory limit.

5.4.3 Confirmatory Calculation

Using the MAVRIC module in SCALE 6.2.3, the staff developed a three-dimensional model of the package using the packaging dimensions shown in the SAR drawings and proprietary RVI dimensions. The package payload consisted of the RVI, LDCC and the RPV. Because the staff did not have the information necessary to explicitly model the RVI, the staff modeled the RVI and grout as three distinct homogenized regions stacked axially to match the proprietary description of the axial steel variation within the RVI provided by the applicant.

For the activation source term, the staff specified an axial source term distribution using proprietary information provided by the applicant with uniform radial and angular distributions within the homogenized steel and grout regions. For the contamination source term, the staff used a uniform radial, angular and axial distribution based on the applicant's description of contamination distribution in SAR Section 4.3.

The staff modeled the space between the RPV and the packaging wall as LDCC, the RPV as carbon steel with a density of 432 lb/ft^3 and the space above the RVI, grout and RPV as air with a standard density of 0.080 lb/ft^3. The staff also modeled the packaging surrounding the payload as carbon steel with a density of 488 lb/ft^3.

The staff used mesh tallies to calculate all dose rates. The staff calculated NCT dose rates of approximately 4.7 mrem/hr, 1.3 mrem/hr and 63 mrem/hr on the top, bottom and radial package surfaces respectively. The staff also calculated a dose rate of approximately 6.4 mrem/hr two meters from the package surface in the radial direction and 1.8 mrem/hr 25 feet from the center of the package in the radial direction.

The staff calculated HAC dose rates of approximately 3.8 mrem/hr, 0.9 mrem/hr and 17 mrem/hr one meter from the top, bottom and radial package surfaces respectively. The staff calculated higher dose rates primarily due to modeling the RVI steel and LDCC as homogenous mixtures because this reduced the RVI steel density from the 432 lb/ft^3 used by the applicant to a maximum of 139 lb/ft^3 in the staff's model. These dose rates are acceptable because they are below the regulatory limits.

5.5 Gas Generation

5.5.1 Gas Generation Model

The applicant modified the MCNP shielding model to calculate the energy absorbed in the grout by maximizing the grout density (i.e., 60 lb/ft^3). The staff determined that increasing the grout density was reasonable since modeling the maximum LDCC density increases energy deposition due to increased mass. In evaluating gas generation, the applicant only utilized the activation source term because it was roughly 1,000 times larger than the contamination source term.

The staff evaluated the decay heat contribution of the surface contamination radionuclides using the ORIGEN module within SCALE 6.2.3 and found that they produced very little decay heat; therefore, the staff finds ignoring the contamination source term a reasonable approximation.

In addition, the applicant assumed that the activation source term only emitted Co-60 photons asserting that this would allow more energy deposition in the grout. The staff determined that assuming the activation source term only emitted Co-60 photons is reasonable because the range of Co-60 photons is much greater than the range of beta particles making it more likely that radiation would escape the RVI steel and deposit energy in the grout.

The applicant determined the payload decay heat using the Co-60 Curie payload calculated by the OEM for a June 30, 2021, shipment date versus the 30,000 Curies Co-60 used in the shielding calculation. However, to account for uncertainty in the OEM's flux calculations, the decay heat from isotopes other than Co-60 as well as contamination, the applicant conservatively increased the decay heat and used a bounding payload decay heat of 358.1 watts.

Although the applicant did not use the bounding Co-60 shielding source term to evaluate gas generation, the staff finds using the value calculated by the OEM for a June 30, 2021, shipment date reasonable because shorter cooling times increase the payload's heat production capabilities and increasing the value to account for uncertainties appropriate.

In addition, using the ORIGEN module within SCALE 6.2.3, the staff calculated a decay heat value that was very close to the applicant's decay heat value; therefore, the staff finds the decay heat value used to evaluate gas generation reasonable. In addition, the staff reviewed the sample input file and determined that the applicant used the correct factor for converting MeV to Joules.

The applicant's results indicated that 11.6% of the emitted radiation energy is deposited in the grout.

5.5.2 Confirmatory Calculation

As stated in SER Section 5.4.3 above, the staff specified an axial source term distribution using proprietary information provided by the applicant. The staff plotted a flux distribution using the axial source term distribution that reasonably mimicked the gas generation flux distribution shown in proprietary SAR Figure 5.4-2. As stated in SER Section 5.4.3 and the paragraph above, the staff found the MCNP model for evaluating gas generation, as well as the assumptions and inputs used to develop the model, acceptable. For these reasons, the staff finds the applicant's assertion that 11.6% of the emitted radiation energy is deposited in grout reasonable.

5.6 Evaluation Findings

The staff reviewed the application and performed confirmatory analyses of the package shielding design. Based on its review of the statements and representations provided in the application, the staff determined that there is a reasonable assurance that the Crystal River Reactor Unit #3 Middle Package meets the regulatory requirements 10 CFR 71.47 and 71.51. The staff also considered the regulation itself, appropriate regulatory guides, applicable codes and standards, and accepted engineering practices, in reaching the following findings:

> The staff finds that the application adequately describes both the package contents, and the package design features that affect shielding in compliance with 10 CFR 71.31(a)(1), 71.33(a), and 71.33(b), and provides an evaluation of the package's shielding performance in compliance with 10 CFR 71.31(a)(2), 71.31(b), 71.35(a), and 71.41(a). The packaging and the contents descriptions are adequate to allow for evaluation of the package's shielding performance. The evaluation is appropriate and bounding for the packaging and the package contents as described in the application.
>
> The staff has reviewed the application and finds that it demonstrates the package has been designed so that under the evaluations specified in 10 CFR 71.71 (normal conditions of transport), and in compliance with 10 CFR 71.43(f) and 10 CFR 71.51(a)(1), the external radiation levels do not significantly increase.
>
> The staff has reviewed the application and finds that it demonstrates that under the evaluations specified in 10 CFR 71.71 (normal conditions of transport), external radiation levels do not exceed the limits in 10 CFR 71.47(b) for exclusive-use shipments.
>
> The staff has reviewed the application and finds that it demonstrates that, under the tests specified in 10 CFR 71.73 (hypothetical accident conditions), external radiation levels do not exceed the limits in 10 CFR 71.51(a)(2).
>
> The staff has reviewed the application and finds that it identifies codes and standards used in the package's shielding design and in the shielding analyses in compliance with 10 CFR 71.31(c).
>
> The staff has reviewed the application and finds that it includes operations descriptions, acceptance tests, and maintenance programs that will ensure that the package is

fabricated, operated, and maintained in a manner consistent with the applicable shielding requirements of 10 CFR Part 71.

6.0 CRITICALITY

The CR3MP contents are limited to fissile material quantities that meet the exemption standards in 10 CFR 71.15. The applicant estimated the amount of fissile material to be less than two grams. Therefore, criticality is not a concern for this package.

7.0 PACKAGE OPERATIONS

The CR3MP Type B package is used for a one-time shipment and disposal of a portion of the CR3 RPV and RI at a licensed disposal site.

Since the package is permanently sealed and will be disposed of with its contents, the "Preparation of Empty Package for Transport", as defined in Regulatory Guide 7.9, does not apply to this package. For the same reason, package opening instructions as stated in 10 CFR 71.89 are not applicable. In addition, operational controls and precautions as described in 10 CFR 71.35(c) for fissile material packages do not apply since the package is fissile exempt.

Procedures for both loading and unloading the package are proprietary in nature and will not be described in this SER.

To organize and coordinate all of the transportation activities, a Transport Emergency Response Plan shall be in place before shipment can proceed. Such a controlling document includes exclusive use instructions, details such as the transportation route, mode of transportation and transfer locations, distances, processes, and equipment, compliance with letter authorization conditions. It also identifies responsibilities and interfaces for each transportation activity, including transfer from one conveyance to the next, tie-down instructions and inspection, radiological controls, and package delivery to the disposal site. Additionally, guidance for interaction with appropriate local and federal agencies in the event of an accident is provided.

8.0 ACCEPTANCE TESTS

The containment shell and top and bottom covers consist of a welded steel enclosure: plate material used in the fabrication of the packaging is to be procured with certified mechanical and chemical test reports. Material tests of the base metal and weld filler metal are to be completed in compliance with the SAR drawings.

The welds, used to fabricate the shell, the top and bottom covers, along with the closure joint welds between the shell and these covers, are examined per SAR Sections 8.1.1, Visual Inspection and Measurements and 8.1.2, Weld Examinations.

The surface contamination is fixed in place by the LDCC within the RPV. There is no gaseous or liquid radioactive material in the package. As demonstrated in SAR Section 4.2, the package integrity under NCT provides assurance that the radioactive materials will remain contained in the package and that there is no release of radioactive materials under NCT. In addition, SAR Section 4.3 demonstrates that, in the event of a partial loss of containment under HAC, the released radioactivity levels are within the regulatory limits. As a conclusion, leakage rate tests are not applicable to the CR3MP package.

The density and compressive strength of both the LDCC within the RPV and between the CR3MP interior shell and the outside of the RPV shall be confirmed with a minimum of two samples in accordance with ASTM C495 guidance. The wet-cast density is measured and recorded at the point of placement. The mix is adjusted, as required, in order to obtain the specified wet-cast density. The minimum compressive strength of the LDCC shall be 100 psi at 28 days when tested in accordance with ASTM C495. A minimum LDCC air fraction of 40% shall be obtained.

Shielding tests prior to final acceptance for shipment are not required for the CR3MP package. The package is constructed in compliance with the design requirements described in the SAR, the procedures for package loading, the weld examinations, and the pre-shipment dose rate surveys performed as part of the preparation of the package for transport confirm the adequacy of the shielding as required by the package design. In addition, the calculated dose rates are well below the regulatory limits defined in 10 CFR 71.47.

Tests to demonstrate the heat transfer capability of the CR3MP package are not required because the thermal evaluations presented in the SAR are based on conservative heat transfer properties and methodologies. As such, the CR3MP package is capable of withstanding temperatures within its design envelope, therefore thermal testing is not applicable.

No maintenance program is applicable for the CR3MP package because the package is a one-time only single-shipment package.

CONDITIONS

In addition to the requirements of Subpart G of 10 CFR Part 71, the following conditions apply:

(1) The package is a one-time only exclusive use shipment.

(2) The package is constructed and assembled in accordance with Licensing Drawing No. 3024427, Revision No. 3, 2 sheets.

(3) The package must be conspicuously and durably marked with the trefoil symbol and the following information: Type B(U), Model No. CR3MP, Package Identification Number USA/9393/B(U)-96.

(4) The package authorized by this letter must be transported by road and by barge in a conveyance assigned for the sole use of the shipper.

(5) The package must be prepared for shipment and transported in accordance with Chapter 7 of the application. Due to material property limits, a Lowest Service Temperature of 0°F is established for the entirety of the transport.

(6) The package must be acceptance tested in accordance with Chapter 8 of the application.

(7) Lifting of the CR3MP is performed exclusively via direct external jacking of the package from below or jacking while the package is resting on a skid or beams. Tie-downs for the CR3MP are only hold-down devices, placed over or around the

package, that are fastened either to the transport skid or directly to the conveyance.

(8) Prior to shipment, package dose rates shall be measured at all locations necessary to demonstrate compliance with 10 CFR 71.47.

(9) A Transport Emergency Response Plan to coordinate all transport activities shall be in place before the shipment can proceed.

(10) Transport duration is limited to 6 months after purging the CR3MP air gap (Step #6 in Section 7.1.2 of the application) has been completed.

(11) The Special Package Authorization will expire on August 31, 2027.

CONCLUSION

Based on the statements and representations contained in the application, and the conditions listed above, the staff concludes that the CR3MP package meets the requirements of 10 CFR Part 71.

Issued with a letter of approval on August 4, 2023.