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TN-B1 Container Thermal Analysis Applicability

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REVISIONS

REVISION	DATE	EXPLANATORY NOTES
2.0	See 1rst page release date	Incorporated additional information to address the USNRC RSI (Reference [20]), including minor text changes in Section 2 and 6, added Section 7, added current fuel design data to Table 2, deleted Table 3, deleted Appendix 1 and added References 18 – 20.
1.0	12/8/15	New document

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TABLE OF CONTENTS

LIST OF TABLES

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1. INTRODUCTION

The introduction of the ATRIUM™[1] 11 fuel assembly design in reload quantities has necessitated a resubmittal of the TN-B1 shipping container Safety Analysis Report (SAR) (Reference [1]) as this design is outside of the previously evaluated parameters. The evaluations supporting the new submittal have been split into separate documents. This document specifically addresses the thermal evaluation documented in Section 3 of the SAR. Since the container design and construction are unchanged, the thermal protection characteristics of the container are also unchanged. Therefore, this evaluation is limited to the fuel design, and the results will be incorporated into a revised Section 3 of the SAR.

2. SUMMARY OF RESULTS

The thermal evaluation documented in the current SAR encompasses the TN-B1 container and the fuel assembly. Since the container design is unchanged, the existing thermal evaluation for the container in Section 3 of the SAR remains applicable. Therefore, only the fuel assembly designs were evaluated.

The thermal evaluation for the AREVA fuel assembly designs was completed for the 9x9, 10x10 and 11x11 arrays, and the results are shown in Table 2. Fuel designs from other fuel fabricators were not evaluated. These designs, when shipped in the TN-B1, shall meet the current requirement defined by the product of the maximum pre-pressure and the maximum Inside Radius/Thickness of 10.18653MPa absolute (9.14 x 1.1145 MPa) or less.

The evaluation results, shown Table 1, are the bounding example fuel designs to replace the designs in Table 3-5 of the current SAR. The values for the 8x8 fuel design are directly copied from SAR Table 3-5 with the exception of a correction to the maximum allowed cladding inside radius to thickness ratio. The other fuel assembly design values are being revised to reflect the evaluation results of liner clad fuel rods. The maximum allowed initial pressures for these designs have been reduced due to the thermal evaluation methodology conservatively neglecting the thickness and strength of the liner in the stress analysis. Therefore, a lower initial fuel rod fill pressure is required to achieve the cladding stress limit.

A qualitative evaluation of the influence of the cladding initial stress state, due to Hypothetical Accident Condition (HAC) drop tests, on the capability of the cladding to maintain containment is provided in Section 7.

The current SAR example design values are bounding for fuel designs with non-liner cladding.

No other changes to Section 3 of the SAR are recommended.

3. DESIGN DESCRIPTION

This evaluation includes AREVA ATRIUM fuel assembly designs with 9x9, 10x10 and 11x11 lattices for use in boiling water reactors (BWR). All are similar in construction with differing rod and spacer grid quantities and associated dimensional variations. The fuel assemblies consists of a lower tie plate (LTP), an upper tie plate (UTP), fuel rods, spacer grids, a cage assembly and miscellaneous assembly hardware.

A full description of the TN-B1 packaging is provided in Section 1.2 of the SAR.

4. ASSUMPTIONS

No assumptions were made beyond those presented in the Section 3 of the SAR. The assumption specifically applicable to this evaluation is that the thickness and strength of the liner material in liner cladding is conservatively neglected.

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[1] ATRIUM is a trademark of AREVA Inc.

5. COMPLIANCE

In accordance with Section 3.1 of the SAR, the TN-B1 package is designed to provide thermal protection as described in Subpart F of 10 CFR 71 for transport of two BWR fuel assemblies with negligible decay heat. Compliance is demonstrated with 10 CFR 71 subpart F. The TN-B1 protects the fuel through the use of an inner and outer container that restricts the exposure of the fuel to external heat loads. The insulated inner container further restricts the heat input to the fuel through its insulation. The fuel requires very little thermal protection since similar fuel has been tested to the 800ºC temperature without rupture.

The primary features that affect the thermal performance of the package are 1) the materials of construction, 2) the inner and outer containers and 3) the thermal insulation of the inner container. The multi walled construction of the combined outer and inner containers reduces the heat transfer as well as reduces the opportunity for the fire in the accident conditions to impinge directly on the fuel. The thermal insulation also greatly reduces the heat transfer to the fuel from external sources.

Given negligible decay heat, the thermal loads on the package come solely from the environment and solar radiation for Normal Conditions of Transport (NCT), as described in Section 3.4 of the SAR, or a half-hour, 800ºC (1,475°F) fire for Hypothetical Accident Conditions (HAC), as described in Section 3.5 of the SAR. Since the fuel cladding is designed for thermal transients greater than what is found in the NCT and the fuel rod is allowed to expand in the fuel assembly without interference, the fuel cladding stresses are evaluated at the maximum temperature seen during a HAC thermal event.

6. MAXIMUM PRESSURE EVALUATION

Section 3 of the AREVA TN-B1, Docket No. 71-9372, SAR was used as the bases for the thermal evaluation of the ATRIUM 11 fuel rod. Also considered in this evaluation was the replacement of the 9x9 and 10x10 fuel designs previously analyzed and reported by Global Nuclear Fuel in Table 3-5 of the SAR. Though the replacement is not required for example purposes, reporting the AREVA fuel designs that are the most limiting was determined to be technically appropriate. A consistent method of modifying the current fuel design characteristics was applied to create bounding cases with a target of maximizing the fuel rod pressure at HAC and minimizing the allowed cladding stress margin. These changes do not restrict the bounding designs exclusively to AREVA designs. Fuel supplied by other manufacturers is acceptable provided that the design meets the requirements specified in the SAR Table 3-5 note.

Table 3-5 “Maximum Pressure” was updated using the method described in Section 3.5.3.2 of Reference [1]. The parameter values for each design were determined using an iterative process with the initial fuel rod fill pressure as a variable and the temperature and cladding thickness as constants. All other parameters are dependent on the fill pressure, temperature and cladding thickness. The initial fill pressure was modified (reduced from 1.1145 MPa absolute) until bounding cladding diameters were derived for the current cladding designs within each fuel array. The sequence of the parameter calculations is in the order of the paragraphs below.

Bounding fuel designs within a single array were determined based on the following:

- Highest cladding inside radius to thickness ratio
- Smallest maximum inside and outside cladding diameters
- Smallest allowed cladding thickness

As necessary, the initial pressure may have been further reduced on the bounding fuel design to result in calculated cladding diameters that bound the other cladding designs within a single array.

The updated SAR Table 3-5 is shown in Table 1. In addition to the new column for the 11x11 fuel design, the bounding example 9x9 and 10x10 fuel designs shown in the SAR were updated to reflect the results for liner cladding in these fuel designs. The use of liner clad reduces the maximum allowed internal pressure due to the thickness and strength of the liner material being conservatively excluded in accordance with the methodology detailed in the SAR. Therefore, the liner cladding stress results are conservative and limiting for the initial fuel rod fill pressures.

6.1. INITIAL PRESSURE

The maximum initial fuel rod pressures were determined by an iterative process for each fuel array and cladding type using bounding parameters for the current fuel rod designs to ensure that sufficient margin existed to the allowed HAC stress limit. The resulting values are shown in Table 2, and the values for the bounding design for each array were populated into Table 1.

To verify that the current fuel rod design initial fill pressures are bound, Table 2 compares the calculated bounding values to the current design values. The comparison shows that the bounding initial fuel rod fill pressures are limiting.

6.2. FILL TEMPERATURE

The fuel rod fill temperature of 20°C is defined by the methodology specified in Section 3.5.3.1 of Reference [1].

6.3. HAC TEMPERATURE

The HAC fill temperature of 648°C is defined by the methodology specified in Section 3.5.3.1 of Reference [1].

6.4. MAXIMUM ALLOWED CLADDING INSIDE RADIUS TO THICKNESS RATIO

All fuel designs shipped shall be limited in design by a value of 10.18653 MPa, determined by the product of the initial pressure (Section 6.2) and maximum allowed cladding inside radius to minimum cladding thickness ratio (Table 3-5 note of Reference [1]). The radius to thickness ratio is calculated for each fuel array and cladding type using the following equation:

Maximum r/t = 10.18653 / initial pressure

The results of the calculation, shown in Table 2, are rounded down to two decimal places and the values for bounding design (defined in Section 6) for each array were populated into Table 1.

Applying this method to determine the radius to thickness ratio for the 8x8 results in a value of 16.75 (10.18653 / 0.608) rather than the 20.20 shown the SAR Table 3-5. Table 1 was updated to show this correction. All other values were verified to be correct.

6.5. MINIMUM ALLOWABLE CLADDING THICKNESS

[redacted]

[redacted]

The primary units are metric and are rounded up to three decimal places. Values in inches are obtained by dividing the values in millimeters by 25.4.

The values for the current designs and the results of the calculation for the bounding values are shown in Table 2. The values for the bounding design for each array and cladding type were populated into Table 1.

6.6. MAXIMUM ALLOWABLE CLADDING INSIDE DIAMETER

The maximum allowable cladding inside diameter is based on the previously calculated cladding inside radius to minimum cladding thickness ratio (Section 6.4) and the minimum allowed cladding thickness (Section 6.5). The equation is as follows:

I.D. = 2 * maximum r/t * minimum allowed cladding thickness

The primary units are metric and are rounded down to two decimal places. Values in inches are obtained by dividing the values in millimeters by 25.4.

The values for the current designs and the results of the calculation for the bounding values are shown in Table 2. The values for the bounding design for each array and cladding type were populated into Table 1.

6.7. MAXIMUM ALLOWABLE CLADDING OUTSIDE DIAMETER

The maximum allowable cladding outside diameter is based on the previously calculated maximum allowable cladding inside diameter (Section 6.6) and minimum allowed cladding thickness (Section 6.5). The resulting outside diameter is directly related to the r/t value (Section 6.4) and, therefore, the design is bound by the allowable stress limit. The equation is as follows:

O.D. = maximum allowed cladding I.D. + 2 * minimum allowed cladding thickness

The primary units are metric and are rounded down to two decimal places. Values in inches are obtained by dividing the values in millimeters by 25.4.

The values for the current designs and the results of the calculation for the bounding values are shown in Table 2. The values for the bounding design for each array and cladding type were populated into Table 1.

6.8. PRESSURE AT HAC

The pressure at HAC is based on the previously calculated initial pressure (Section 6.1), the HAC temperature (Section 6.3) and the fill temperature (Section 6.2) as follows (see Sections 3.5.3.1 and 3.5.3.2 of Reference [1]):

Pressure @ HAC = max initial absolute pressure * max absolute temperature / ambient absolute temperature

The values for the current designs and the results of the calculation for the bounding values are shown in Table 2. The values for the bounding design for each array and cladding type were populated into Table 1.

6.9. APPLIED PRESSURE AT HAC

The applied pressure at HAC is the pressure at HAC (Section 6.8) at gauge pressure. The equation is as follows:

Applied Pressure @ HAC = Pressure @ HAC – 1 atmosphere

The values for the current designs and the results of the calculation for the bounding values are shown in Table 2. The values for bounding design for each array and cladding type were populated into Table 1.

6.10. CLADDING STRESS

The cladding stress is based on the previously calculated applied pressure at HAC (Section 6.9), cladding inside radius (Section 6.6) and minimum cladding thickness (Section 6.5). The equation is as follows (see Table 3-5 of Reference [1] for method):

Cladding stress = Applied Pressure @ HAC * max allowed inside diameter / min thickness / 2

The values for the current designs and the results of the calculation for the bounding values are shown in Table 2. The values for the bounding design for each array and cladding type were populated into Table 1.

6.11. MARGIN

The margin to the maximum allowed cladding stress at HAC (31.1 MPa, Section 3.5.3.2 of Reference [1]) is calculated as follows (see Table 3-5 of Reference [1] for method):

Margin = maximum allowed cladding stress at HAC / cladding stress – 1

The values for the current designs and the results of the calculation for the bounding values are shown in Table 2. The values for the bounding design for each array and cladding type were populated into Table 1.

7. INFLUENCE OF INITIAL STRESS STATE

Certification testing of the TN-B1 package is summarized in Section 2.12.1 of the SAR (Reference [1]). Two tests were performed on CTU 1, a 9-meter (30-foot) slap-down on the lid and a 1-meter (40-inch) oblique puncture test on the lid. A 9-meter (30-foot) end drop was performed on CTU 2. The testing resulted in no failure of the cladding as verified by leak tests. Illustrations of fuel rod deformations in CTU 2 tests are shown in Figures 2-40 through 2-43 in the SAR. While there is plastic deformation to the fuel rods, the magnitude of these deformations are not large as can be seen from the relatively small angles of fuel rod deflections. Such deformations are expected to be limited due to the presence of the fuel pellets within the fuel rods. The deformations observed during the drop tests are consistent with those calculated in the ATRIUM 11 Fuel Assembly Shipping Container Drop Analyses (Reference [18]).

The qualitative result of such deformations is to impart cold-work into the cladding material thereby increasing its yield stress (which would be beneficial in that the cladding would be more resistant to further deformation) and decreasing its ductility (the cladding would be less able to sustain further large deformations without failure). Section 3.5.3.1 of the SAR indicates that the peak fuel rod temperature (conservatively assumed to be the same as the peak package inner wall temperature) reaches a maximum of 1198°F (648°C, 921 K) at the end of the fire or 1,800 sec (30 min) after the start of the fire (see SAR Figure 3-3). This peak temperature is somewhat similar to a recrystallization/stress relief temperature (e.g., Reference [19]) that might be used during cladding manufacture, perhaps for a longer exposure time. The impact of such a thermal cycle to the deformed cladding material would be to partially relieve residual stresses resulting from the HAC drop event. At elevated temperatures, the yield stress of the cladding material decreases (plastic deformation is easier) and its ductility increases (failure of containment is less likely).

From a theoretical point of view, the deformation of the fuel rods during the drop event is mainly a slight bending in the axial plane. Therefore, after the drop event, a permanent bending axial strain is present along the fuel rods. It is possible that some of the bending is still elastic and an associated distribution of residual axial stresses across the thickness of the cladding exists; however, as described above, these residual axial stresses will be quickly relaxed during the heat up period.

More importantly, the axial bending deformation has a negligible impact on the deformation mode during the heat up. The loading during the heating period is due to increased internal gas pressure, which acts primarily in the radial direction and causes a principal hoop stress. The prior drop event does not create significant stresses and strains in the radial and circumferential directions of the transverse cross-section, which is the loading plane for the heating period. Therefore, the mechanical deformation during the heating period can be considered independent of the prior small axial bending during the drop event. This is the basis for the analysis in SAR Section 3.5, where results of the closed tube pressure ballooning tests have been used to assess the avoidance of clad rupture due to internal gas pressure.

Overall, failure of the deformed cladding during the thermal cycle considered is not expected. This expectation is supported by the GNF-J certification tests discussed in SAR Section 2.12.2 which are summarized in Table 2-13. As with the certification testing of the TN-B1 package, no failure of the cladding occurred during these tests either. It should be noted that the testing of CTU 2J included a NCT free drop test from 1.2 m, followed by a 9 m HAC free drop, followed by a 1 m HAC puncture drop, followed by an HAC thermal test (which resulted in no failure of the simulated fuel assembly cladding).

Table 1: Maximum Pressure

Parameter	Units	8 x 8 Fuel	9 x 9 Fuel	10 X 10 Fuel	11 X 11 Fuel
Initial Pressure, Max	MPa absolute	0.608	0.861	0.800	0.851
Fill temperature	°C	20	20	20	20
Temperature during HAC	°C	648	648	648	648
Outside Diameter Maximum	mm	12.5	11.38	10.59	9.72
	inches	0.492	0.448	0.417	0.383
Minimum Allowable Cladding Thickness	mm	0.68	0.444	0.386	0.375
	inches	0.0268	0.0175	0.0152	0.0148
Cladding Inside Diameter Maximum	mm	11.14	10.50	9.82	8.97
	inches	0.439	0.413	0.387	0.353
Pressure @ HAC	MPa absolute	1.91	2.71	2.51	2.67
	psia	277	393	365	388
Applied Pressure @ HAC	MPa	1.81	2.61	2.41	2.57
	psig	262	378	350	373
Stress Pr/t	MPa	14.82	30.8	30.7	30.8
	psi	2149	4468	4452	4464
Margin, (allowed stress / actual stress) – 1	None	1.10	0.010	0.013	0.010
Max Allowed Cladding Inside Radius / Thickness	None	16.75	11.83	12.73	11.97

Note: The cladding thickness and diameters are for example purposes and represent current bounding fuel designs. However, all fuel to be shipped must have a maximum pre-pressure times the maximum Inside Radius/Thickness product of 9.14 x 1.1145 MPa = 10.18653 MPa absolute or less. Thus, all products must meet the maximum product of allowed pressure multiplied by Inside Radius/Thickness of 10.18653 MPa.

Table 2: Bounding vs. Current Fuel Design Thermal Evaluation

[redacted]