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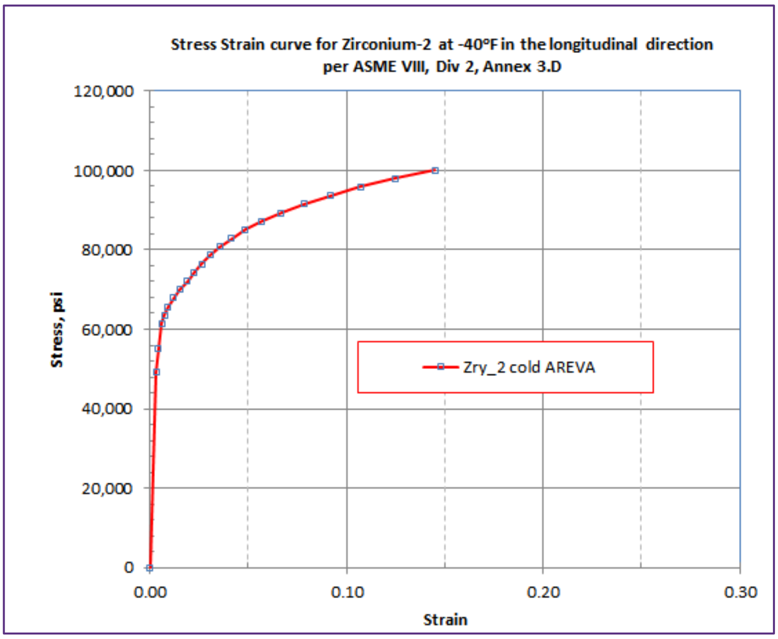
The main issue of this RAI is related to the linear and non-linear behavior of the cladding materials, as the applicant expected some plastic deformations. The staff asked where deformations of the cladding materials of the ATRIUM-11 fuel, under the accident conditions, would fall in its deformation versus strength curve. The applicant replied that the cladding material would have a 14% strain corresponding to the ultimate strength and added that the maximum strain of the cladding material after the 30 feet drop was 2.5%. The applicant also explained that it used a margin of safety of 1.4 for the theoretical load for the dynamic analysis of the fuel bundle, imposed a velocity at impact in the model, and determined the deceleration history. The staff asked the applicant to explain what is meant by applying an acceleration time history if an impact velocity is imposed and how they performed the dynamic analysis. The staff also asked the applicant to provide the assumptions used in the dynamic analyses (with rationales) and both the strain curve for Zirc-2 and the applicable references as part of the response.

AREVA Response:

The development of the stress-strain curves for the Zircaloy-2 cladding material is detailed in page 16, Section 7.3.1 of Reference 2-2-1. The stress-strain curve material model at -40°F for the cladding used in the fuel bundle analysis is represented by Figure 7.3.1-1 in page 17 of the same reference that it is shown below.



The minimum ultimate strain of the material Zirconium used for the end plug and the cladding is 14% per page 23, Figure 16, of "*Review of Zircaloy-2 and Zircaloy-4 Properties Relevant to N.S. Savannah Reactor Design*, Whitmarsh, C.L. July 9, 1962, ORNL-3281, UC-80-Reactor Technology, TID-4500, 17th Ed".. The result of the current fuel bundle drop analysis shows that the maximum plastic strain of 2.6% in the fuel cladding occurs at the weld of the heat-affected zone as shown in page B7, Figure B.5.1-2 of Reference 2-2-2. The strain plot is presented below. The maximum strain of 2.6% in the fuel rod is much less than the ultimate strain of 14% for the material Zirc-2.

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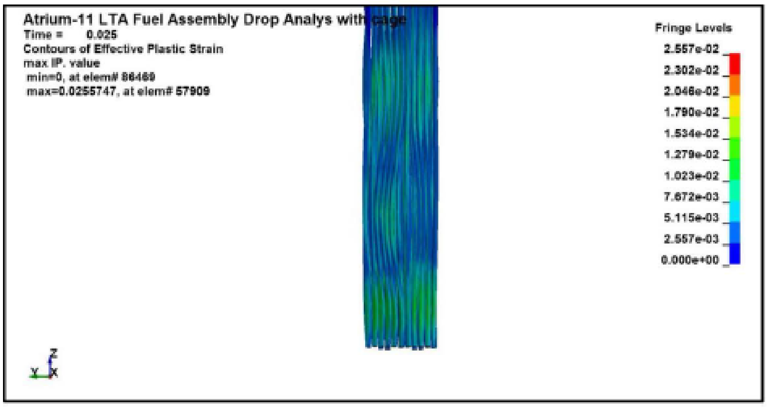

Figure B.5.1-1 Plastic Strain of the Fuel Assembly after 30-ft End Drop Accident, Case HAC-FA1

When performing the drop analyses of the TN-B1 shipping container using the LSDYNA program, the detailed fuel bundle is not included in the finite element model. Only a rigid body representing the exact weight and external enveloping dimensions of the fuel bundle is included in the finite element model of the shipping container package. An initial velocity equivalent to a 30-ft vertical drop is applied to the shipping container for the various drop orientations. A fixed rigid plane is the boundary representing the unyielding surface. The acceleration time histories of the inner container measured at the centroid of the inner container are extracted from the binary result files of the shipping container package model, as shown in Section 8.3 (page 67) of Reference 2-2-2.

When the fuel bundle end drop analysis is performed, the fuel bundle is modeled in detail along with the lumber and the thermal insulator that exist inside the inner container. The presence of the inner container is represented by a moving rigid plane below the thermal insulator. The finite element model of the fuel bundle is shown in Page B5, Figure B.4-1 of Reference 2-2-2.

To perform a dynamic drop analysis of the fuel bundle model, an initial velocity of 527 in/sec that is equivalent to a 30-ft vertical drop is applied to all parts of the fuel bundle model as well as the rigid moving plane that represents the physical boundary of the inner container shell. The initial condition simulates the entire inner container with the fuel bundles at the onset of the 30-ft drop impact. As the drop progresses, the inner container shell encounters a resistance force coming from the balsa wood and outer shell, whose movements are slowed down due to the impact of the shipping container with the fixed rigid plane. Since the outer container and the fuel bundle are not included in the same finite element model, the only common link to couple the two models is the motion of the inner container. The movement of the inner container is influenced by the movement of the outer container as evidenced by the deceleration of the inner container. In the fuel bundle drop simulation, the movement of the inner container shell of the fuel bundle model has to match the movement of the inner container shell of the shipping container model. As the fuel bundle drop simulation progresses, the movement of the inner container shell needs to be modified reflecting the presence of the resisting force from the outer container. The force resisting the motion of the inner container shell is applied as the deceleration to the movement of the inner container shell represented by the moving rigid plane. The deceleration is measured at the centroid of the inner container. The application of deceleration to the bottom shell is conservative. This assumption ignores the inherent flexibility of the inner container shell that can flex in the direction perpendicular to the shell surface that under impact can transfer the compressive force of the fuel bundle acting on the shell surface to the balsa wood below it.

In the LSDYNA input files, the deceleration is applied as prescribed motion to the inner container shell, that gradually reduces the initial velocity of 527 in/sec towards zero at the end of the impact.

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The downward movement of the inner container travels from an initial velocity of 527 in/sec to zero, and the fuel bundle impacting on the inner container shell also travels from initial velocity of 527 in/sec towards zero. The kinetic energy of the fuel bundle is dissipated by the deformation of the lumber and the thermal insulation with a very small portion of it dissipated by the inelastic deformation of the fuel cladding and the end plugs.

The deceleration of the inner container represents an impact force acting on the fuel bundle. The impact force compresses on the fuel bundle. If the compressive force is excessive, the fuel bundle cladding will deform, buckle and eventually collapse due to structural instability.

Since this is an inelastic analysis for the hypothetical accident conditions, the ASME Code 2010 Subsection III, Appendix F. Section F-1341.4 allows a collapse load analyses. The allowable compressive load is set to be 70% of the collapse load. ASME Code implies there is a built-in factor of safety of 1.4. Since it is impractical to gradually ram up the compressive load until the fuel bundle collapses, it is therefore reasonable to amplify the deceleration force 1.4 times and check if the fuel bundle can withstand the amplified deceleration force without structural stability failure. If the structure can withstand the amplified compressive force without failure, then it is confirmed that under regular unamplified compressive load, there is a safety factor of 1.4 against instability and it satisfies the ASME code requirement.

Upon integration with time, the initial velocity with integrated unmodified deceleration time history will decrease to zero signaling the end of impact. However, with the amplified deceleration time history, the positive velocity will be integrated to become reversed in direction. This is not possible in an inelastic impact condition. Therefore the time duration of the deceleration is shortened mathematically to allow the initial velocity to gradually reach zero signaling the resting of the fuel bundle. The shortening of the impact period has the net effect of reducing the reaction time of the energy absorbing material and stiffening the material property. This procedure is conservative.

References

2-2-1 FS1-0015328 “Structural Analyses of the AREVA Atrium-11 LTA Fuel Assembly in the RAJ-II Container during Normal and Accident Transport Conditions” Rev 2. This is ATKINS report NSA-DAC-AREVA-14-01 Rev 1 issued within AREVAs document control program. (Note 1)

2-2-2 FS1-0025122 “AREVA TN-B1 ATRIUM-11 Fuel Assembly Shipping Container Drop Analyses” Rev 1. This is ATKINS report ATKINS-NS-DAC-ARV-15-02 issued within AREVAs document control program. (Note 1)

Note 1: These documents were previously submitted as a part of the original application for this revision. See AREVA letter TJT:16:-36 of 18 November 2016