Mechanical Sensitivity Considerations for Finite Element Analysis Supporting Type A Package Licensing

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ABSTRACT

Fissile shipping packages are fabricated from materials governed by recognized international standards to ensure that consistent, traceable components constitute the package design and fabrication. These standards typically identify material property minima or range values enabling the designer to fully assess the material for design capability and expected performance. However, construction materials are rarely, if ever, fabricated purposely to specification minimum. In addition to stated mechanical properties, materials exhibit temperature dependent characteristics which may impact the material behavior when subject to Normal and Accident transport conditions.

Type A fissile shipping packages are governed by SSR-6 as well as 10CFR71 ensuring structural integrity is maintained when subject to the transport conditions. Since regulatory test articles are not fabricated to the most limiting material properties, shipping package designers frequently utilize dynamic, large strain capable software to evaluate the package's structural robustness supporting a license application.

Package designers must identify which package safety components are not at a limiting condition and provide justification that the package's structural robustness is not compromised. Justification may be demonstrated by testing, analysis, or both. Finite Element Analysis (FEA) software assessed the Westinghouse Traveller fresh fuel shipping package for recent licensing efforts when considering limiting material conditions. The results of the FEA demonstrate that the initial Traveller package robust design provides adequate margin against manufacturing tolerances, temperature-dependent material property variability, and a combination thereof.

1. INTRODUCTION

Shipping package mechanical design requires structural assessments governed by SSR-6 [1] as well as 10CFR71 [2]. Regulations describe hypothetical accident conditions as well as normal conditions of transport; both of which require the package demonstrate compliance by analysis or testing. For relatively heavier fresh fuel packages, the 9-meter free drop tends to structurally stress the packaging globally, while the 1-meter pin-puncture tends to induce localize mechanical stresses.

Construction materials are specified by internationally recognized standards or by equivalent design engineering specifications. Such standards and specifications state minimum material requirements such that structural integrity is maintained during the packaging lifetime. However, fabrication rarely, if ever, results in materials at specification minimum. For this reason, sensitivity analysis are often performed to determine the structural effects of reduced material properties as a result of raw material properties, temperature dependent properties, reduced material thickness, or a combination of reduced material properties.

The Westinghouse shipping package, named the "Traveller", has been in service globally since 2004. Since that time there have been design upgrades, requests for additional information (RAIs), and other licensing changes requiring structural evaluations. Sensitivity evaluations have been subsequently performed.

2. MECHANICAL DESIGN CONSIDERATIONS

Regulatory compliance is demonstrated by testing, analysis or a combination thereof. The Traveller was originally licensed with both testing and analysis, but more recent amendment update requests have been demonstrated using FEA techniques. The use of FEA was preferred to physical hardware testing as it permits numerous material property variations, repeatable boundary conditions, and a more cost-effective analysis. Furthermore, discrete material properties can be evaluated since manufacturing will not necessarily obtain the most limiting condition. Dynamic, high-strain FEA software was utilized assessed the Traveller package structural integrity for the 9-meter free drop and the 1-meter pin-puncture drop tests. Figure 1 provides a picture of the Traveller package. The Traveller structural behavior was evaluated considering the conservative aspects of the principle materials such as minimum metal thicknesses, variable foam crush strength, and reduced metal strength in order to evaluate both drop conditions.

Figure 1: Westinghouse Fresh PWR Fuel Traveller Package

The Traveller package design incorporates three primary structural components: a 6000 series Aluminum internal structure (called the “Clamshell”) housing a fresh fuel assembly and a protective Outerpack comprised of an inner and outer Type 304 stainless steel barrel surrounding polyurethane foam. The Clamshell tightly packages the fresh fuel assembly and prevents significant fuel assembly deformation or lattice expansion in the event of imposed accident conditions. The Outerpack is designed to absorb the impact energy from accident conditions through skin plastic deformation as well as impact limiting polyurethane foam. A cross-section showing primary construction constituents is provided in Figure 2.

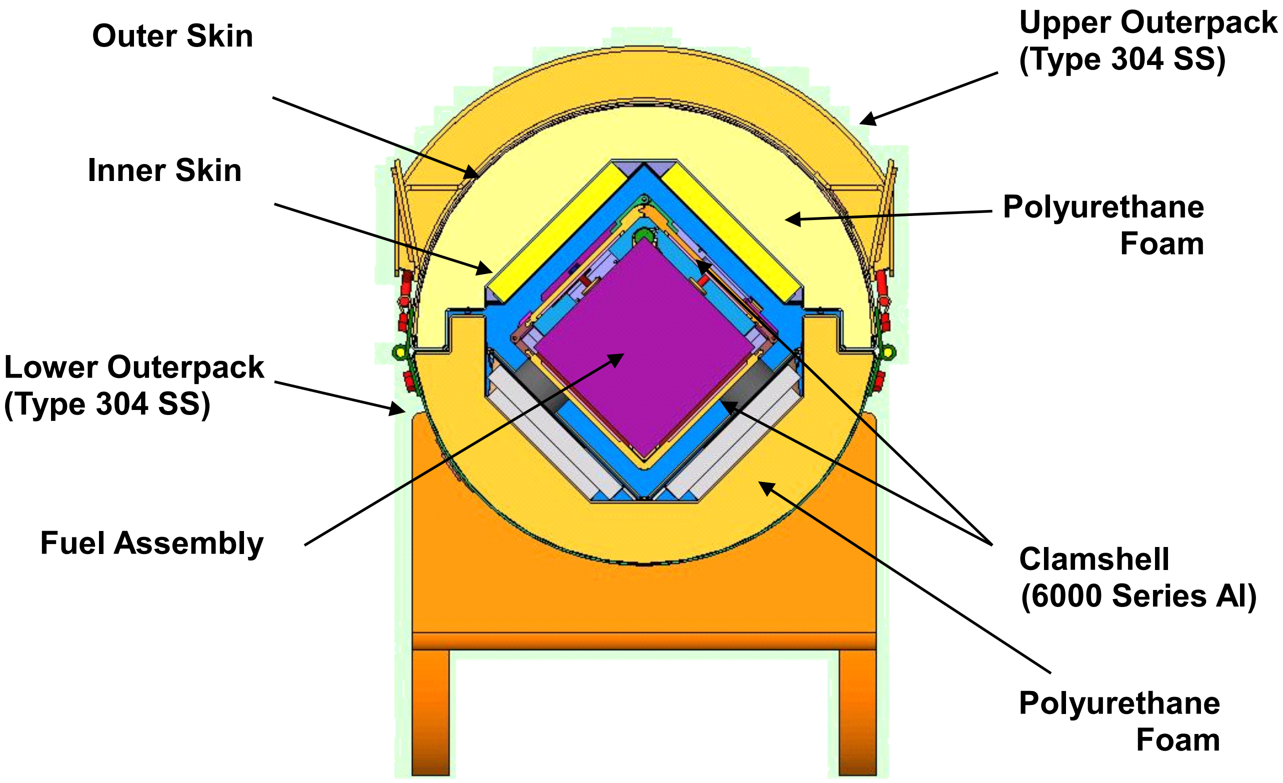


Figure 2: Traveller Cross-Section and Primary Construction Constituents

2.1 Impact Limiter Temperature/Density Effects on Mechanical strength

Case-study: Impact Limiting Foam Behavior for the 9-meter free drop

2.1.1 Background

Temperature dependent polyurethane foam mechanical characteristics are well documented from manufacturing literature [3]. These curves are used in non-linear Finite Element (FE) sensitivity studies to evaluate the most damaging 9-meter free drop test orientation for both the packaging and fissile contents. Other considerations that may affect performance include foam density variance and physical geometry. Typically, as temperature increases crush strength decreases, and as density decreases crush strength decreases. At higher temperatures and lower densities, the foam will have the lowest crush strength. Conversely, at low temperatures and higher densities the foam will have the greatest crush strength. However, as density decreases, the foam is more compliant resulting in greater energy absorption and lower acceleration impact forces assuming the foam does not bottom-out. Since the Traveller package has 3 different foam densities, the study became quite extensive.

2.1.2 Evaluation

The mechanical behavior of the Traveller Outerpack was evaluated for variable foam properties considering the most damaging 9-meter free drop orientations. Using the LS-DYNA finite element analysis (FEA) model to evaluate the performance of the package during the Center-of-Gravity over Corner and Vertical drop orientations, variations of mechanical characteristics of polyurethane foam materials in the Traveller package were evaluated for cold (-40°C), hot (70°C), and nominal conditions, as well as variable density. This study was performed since the most damaging Outerpack orientation is a Center-of-Gravity over Corner impact, and the most damaging drop orientation for the fuel is a vertical impact.

A variable foam density and temperature foam crush strength curve for 10±1 pound per cubic foot (pcf) foam is shown in Figure 3 and represents expected crush strength performance for the other foam densities used in the Traveller.

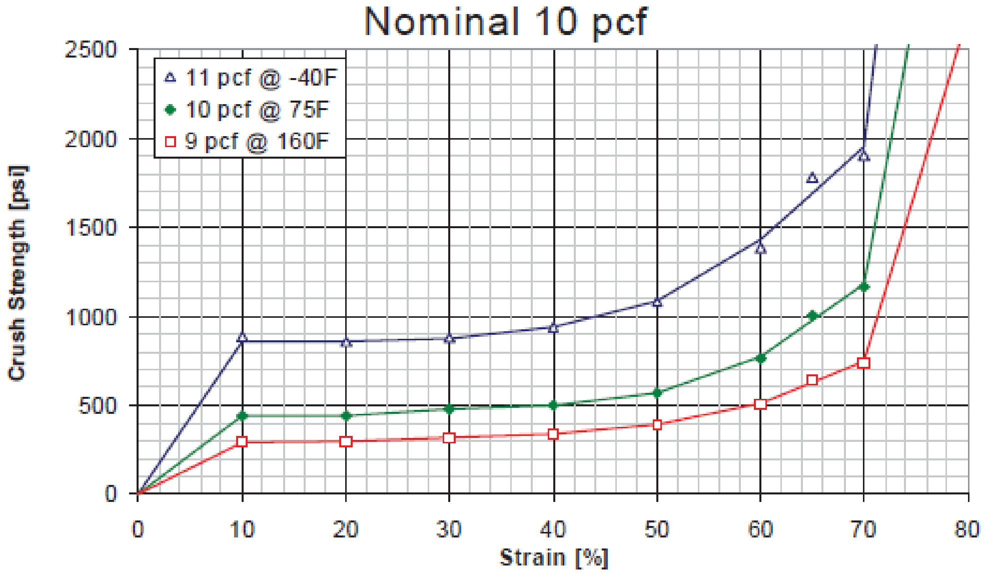


Figure 3: Typical Variable Foam Crush Properties

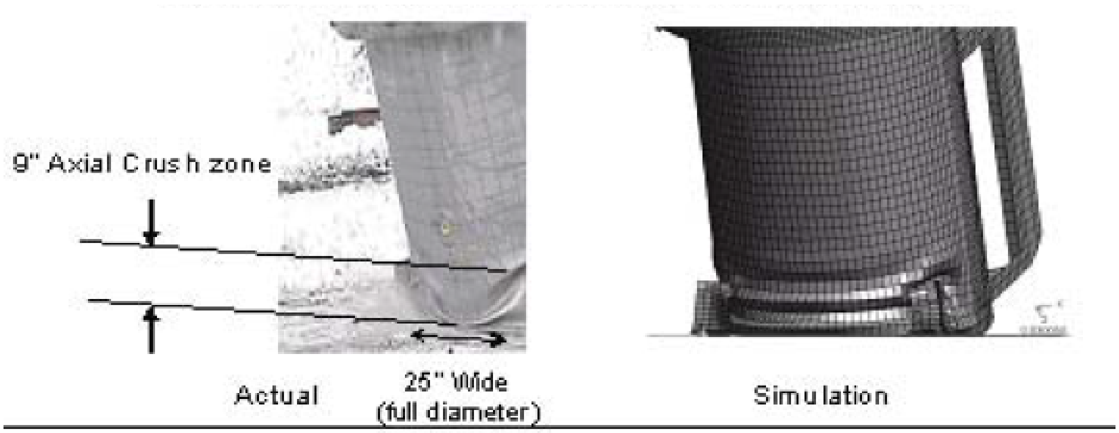
2.1.3 Evaluation Results

Variable foam crush strengths were determined to have minimal effects on the Traveller global mechanical behavior. Furthermore, the Traveller maintained its structural integrity in the 9-meter free drop tests when various crush strength were evaluated.

When those variable foam properties were evaluated using FEA for the most limiting Outerpack drop orientation, the cold case at high density resulted in slightly more acceleration impact force than nominal, and was nearly the same as the hot case at low density (Table 1). This phenomenon is attributed to the relatively small overall end cap impact limiter thickness for the Traveller design, and the fact that the stainless steel outer skin plastic deformation absorbs a high portion of the kinetic energy. Figure 4 shows the actual versus simulated drop test CG Over-Corner FE with good agreement of the model to test results.

Table 1: Outerpack CG Over-Corner Foam Crush Sensitivity Results

	Polyurethane Foam Condition		
Output	Low density foam/Hot	Nominal	High density foam/Cold
Acceleration Force	49.3g	47.3g	49.6g



(b) Overpack Deformation at the Top Nozzle End of the Package

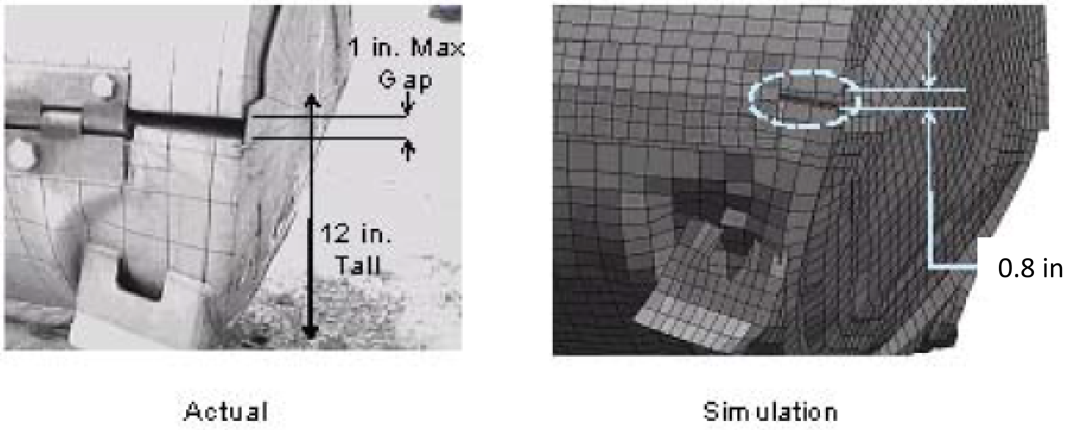


Figure 4: 9-meter CG Over-Corner Outerpack HAC Drop Test Comparison

Figure 5 shows that in the Vertical drop case, the cold case at high density resulted in a similar impact force compared to nominal, and greater than the hot case at low density. These results show that high temperature foam is softer than cold (or nominal) foam and resulted in less impact force as expected (at primary impact). The numerical normal impact force results are presented in Table 2 for clarity.

Table 2: Vertical Foam Crush Sensitivity Numerical Results

	Polyurethane Foam Condition		
Output	Low density foam/Hot	Nominal	High density foam/Cold
Impact Force	1.5E6 N	2.8E6 N	2.9E6 N

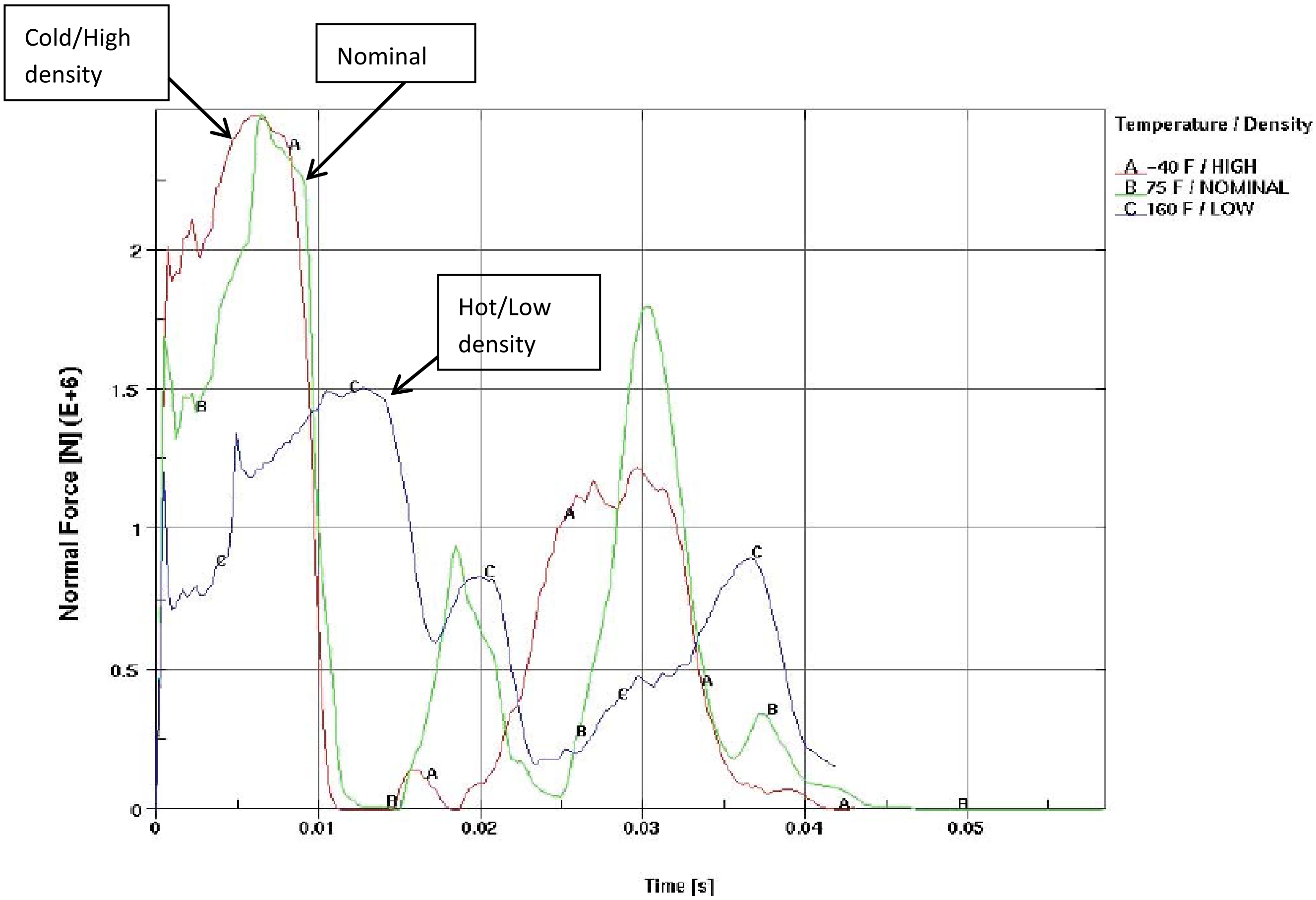


Figure 5: Foam Density/Temperature Variation Effect on 9-meter HAC Drop Test (Outerpack, Vertical)

2.2 Reduced Material Thickness/Analysis at Specification Minima

Case-study: 1-meter Pin-puncture test

2.2.1 Background

A sensitivity study was initiated primarily to evaluate the structural effect of reducing skin thickness 10% for the 1-meter pin-puncture test. As with other evaluations, other conservatisms were incorporated into the study in addition to reduced outer skin thickness. With respect to Outerpack components, three primary conservatisms were incorporated into the pin –puncture finite element analysis (FEA):

1. Reduced acceptance strain failure value from 60% down to 46.7%;
2. Type 304 Stainless steel tensile and ultimate strength specifications reduced;
3. Based upon previous case study, the most limiting polyurethane foam density values.

Physical testing was performed on the Traveller package during its licensing phase. Of note is the 2-7/8" deep indent resulting from the angled impact (Figure 6).

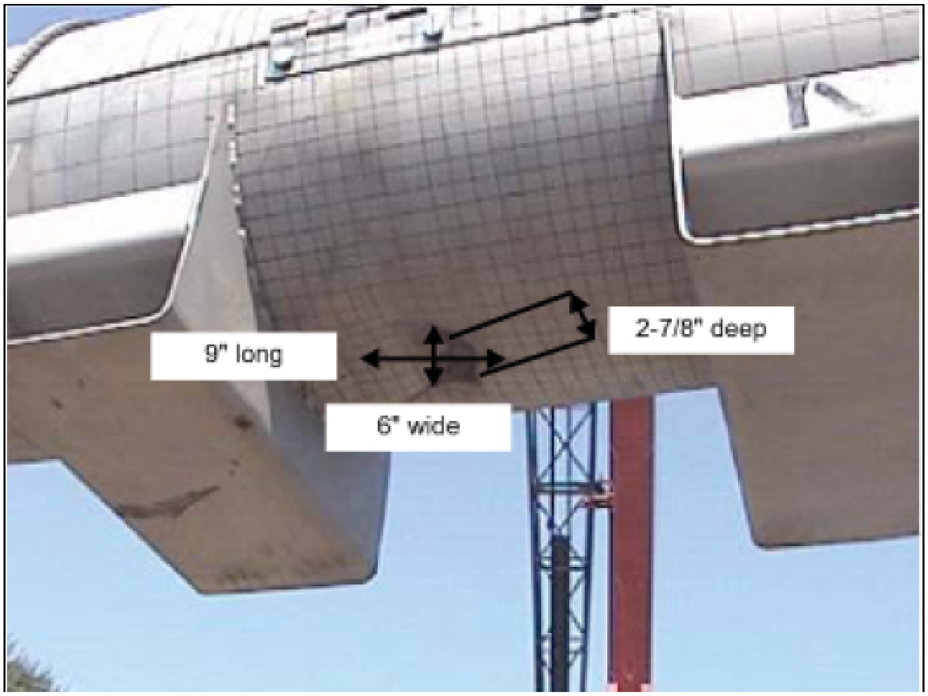


Figure 6: Traveller 1-meter Pin-Puncture Test Results

The mechanical characteristics of the Outerpack stainless steel and foam were used in sensitivity studies to evaluate the most damaging Outerpack drop test orientation. Type 304 Stainless steel mechanical characteristics were evaluated at 70°C by lowering the nominal (24°C) tensile yield and ultimate tensile strengths by 10%. At reduced temperature, austenitic stainless steel is slightly stronger; as a result tensile yield and ultimate tensile strengths were increased to 112% and 132% of their respective 24°C values. In addition, the failure strain acceptance criteria were lowered from 60% nominal to 46.7%. Case study 1 provided the foam sensitivity study results.

2.2.2 Evaluation

The Outerpack stainless steel material property conservatisms were incorporated into the pin-puncture FEA to ensure impact loads were maximized. Since the pin-puncture test is best described as a local event, higher density meshing is suitable for the analysis (i.e. global effects can be ignored). Figure 7 depicts the 1-meter pin-puncture drop test simulation. Regulatory pin-puncture FEA was performed at a 20° orientation relative to horizontal; the drop height is 1-mteter from the lower package surface to the upper pin surface. To reduce computation time, the initial velocity is set from the first principle calculation free drop equation.

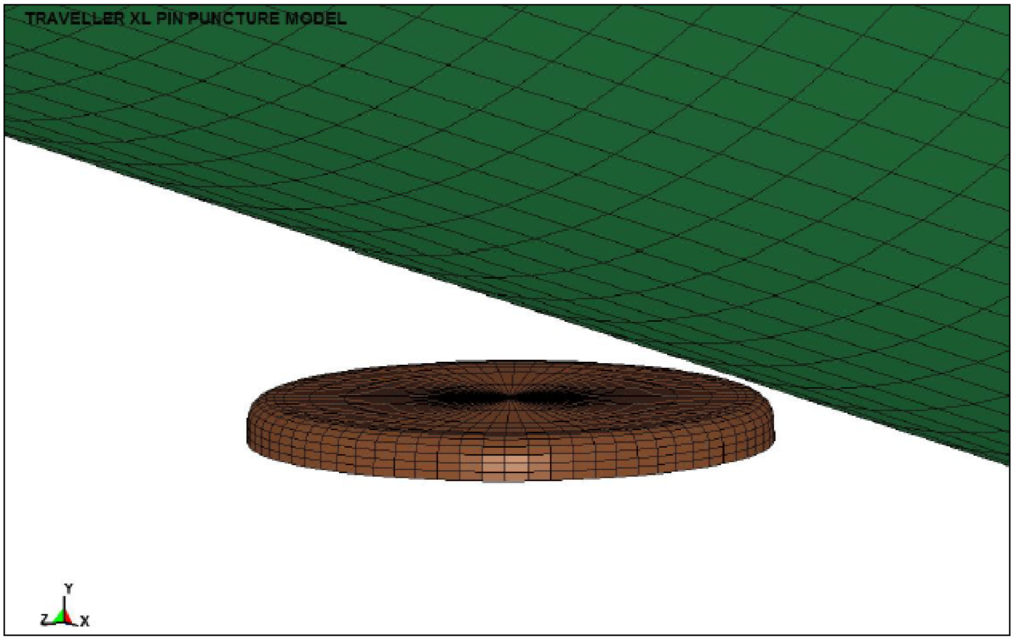
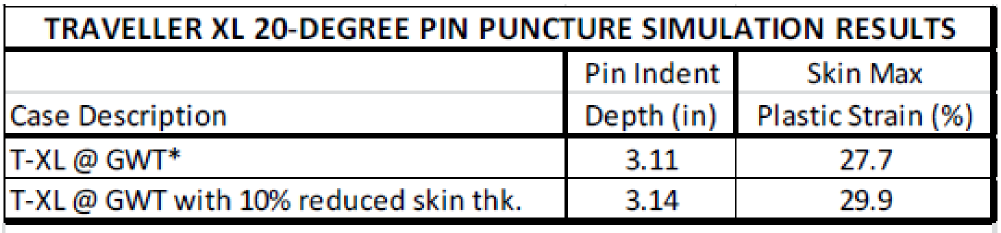


Figure 7: Traveller 1-meter Pin-Puncture FEA Model

2.2.3 Evaluation Results

The subsequent FEA indicated a maximum predicted strain of 27.7% and 29.9% for the nominal and reduced thickness cases, respectively, as shown in Table 3. Figure 8 provides a snapshot of the resulting skin deformation resulting from the pin-puncture impact. Of importance is the skin does not perforate.

Table 3: Traveller 1-meter Pin-Puncture FEA Plastic Strain Values, 20° Orientation



TRAVELLER XL 20-DEGREE PIN PUNCTURE SIMULATION RESULTS

Case Description	Pin Indent Depth (in)	Skin Max Plastic Strain (%)
T-XL @ GWT*	3.11	27.7
T-XL @ GWT with 10% reduced skin thk.	3.14	29.9

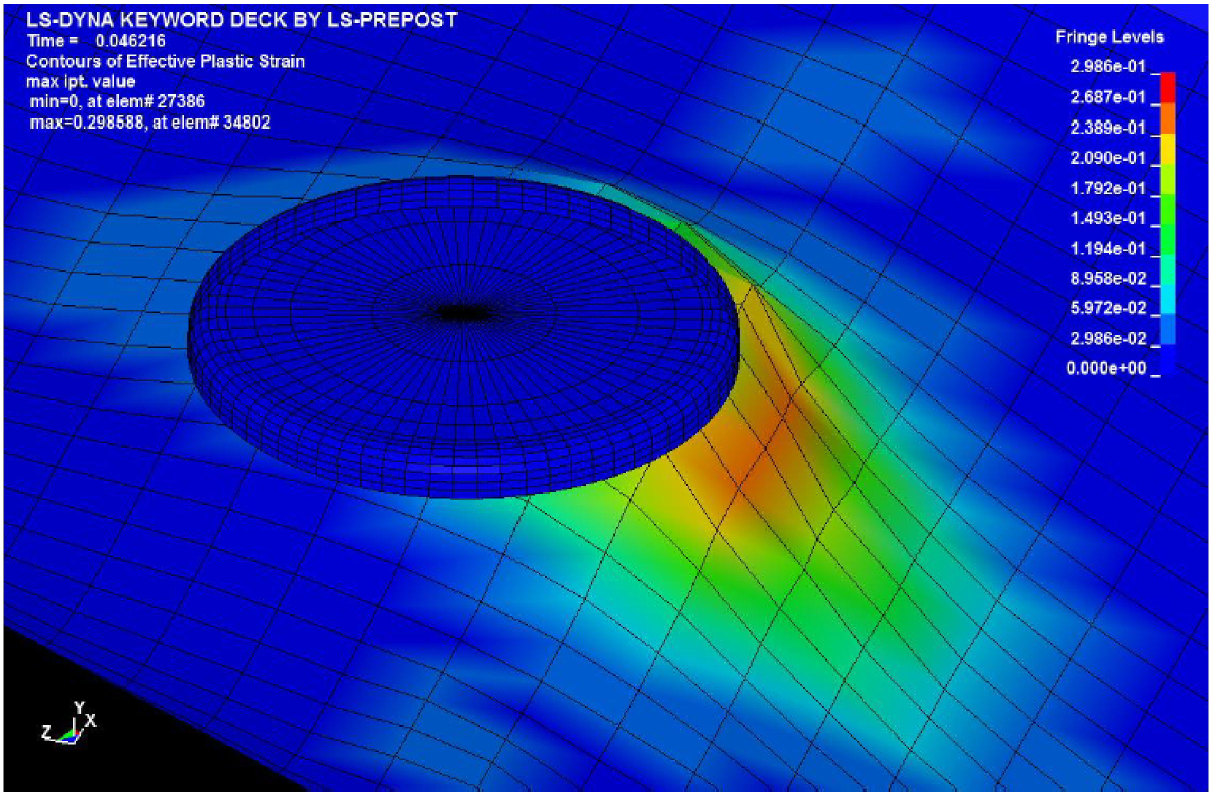


Figure 8: Traveller 1-meter Pin-Puncture FEA Plastic Strain Results, 20° Orientation

When those material conservatisms are compared to the reduced failure strain of 46.7%, there is 41% and 36% margin against Outerpack skin perforation for the nominal and reduced thickness cases, respectively. Note that when compared to strain failure value of 60%, there is 54% and 50% margin against Outerpack skin perforation for the nominal and reduced thickness cases, respectively.

2.3 Combined Evaluation

Case-study: HAC 9-meter free drop test to Evaluate Mass Increase

2.3.1 Background

The Traveller package required an evaluation for increased transportation masses of 130 pounds. A FEA was conducted for the 9-meter free (as well other regulatory requirements) to verify structural integrity and robustness. The FE model was developed as a benchmark to the physical testing, and nominal properties input as the "base" case. For the increased content mass case study, the most limiting foam crush strengths and reduced mechanical properties from previous sensitivity studies were combined with the limiting, conservative material conditions or joint geometry during a vertical free drop test.

2.3.2 Evaluation

A FEA model was developed for the vertical drop test orientation as this had been determined most structurally challenging for the fuel assembly and Clamshell structure. With the following sensitivity considerations, this case is referred to as the "heavy Clamshell" case.

Figure 9 shows the composite Traveller upper portion consisting of the fuel assembly, Clamshell, impact pillow and Outerpack impact limiter which is comprised of stainless steel shells and polyurethane foam. An objective of this evaluation was to determine the resulting deceleration forces applied to the Clamshell and subsequently the fuel assembly.

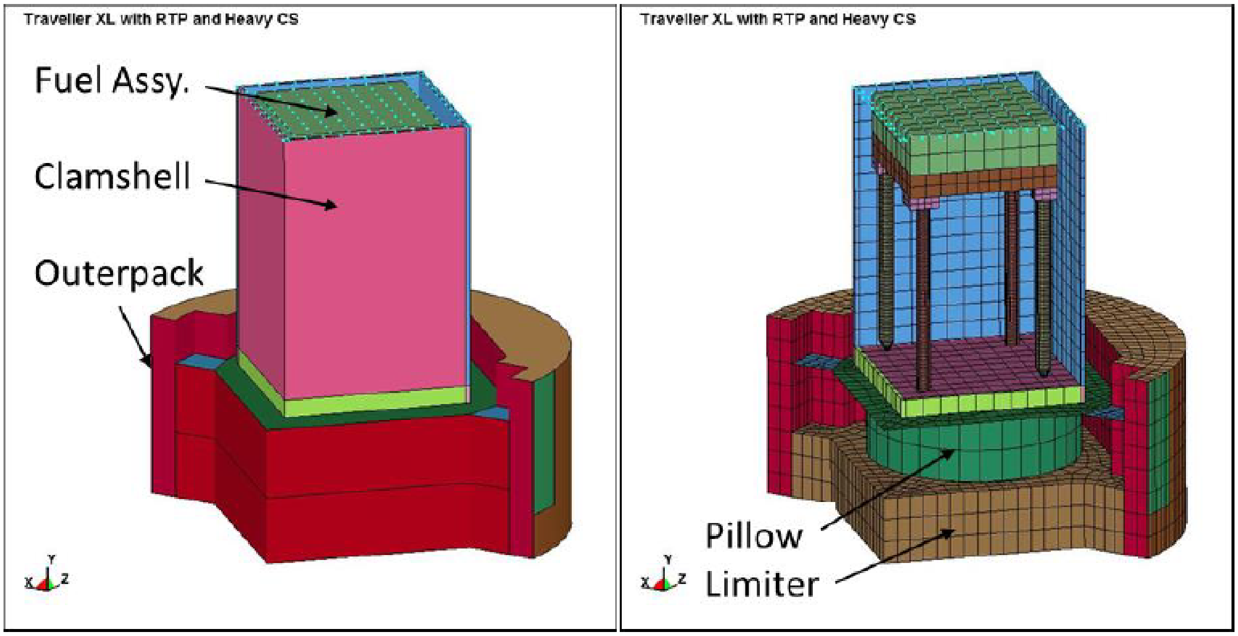


Figure 9: Traveller 9-meter Vertical Free Drop FEA Model (Upper Portion)

ASTM A240 Type 304 Stainless steel

Type 304 Stainless steel mechanical characteristics were evaluated at 70°C by lowering the nominal (24°C) tensile yield and ultimate tensile strengths by 10%. The Outerpack sheet metal was reduced 10% for this case study since that reduction results in a maximum predicted strain increase from 0.08 in/in to 0.09 in/in; or 11% for 9-meter impacts.

ASTM B209/B221 Type 6005-T5 Aluminum

The Clamshell thickness was reduced 11% at the localized "pocket areas" and 41% in the primary structural wall itself for the HAC FEA. The 6005-T5 aluminum alloy did not have available temperature dependent mechanical data. Since 6061-T6 is similar with respect to tensile properties and elongation it was used as a basis to evaluate the 6005-T5 alloy. For conservatism, the temperature effects were doubled for each temperature dependent property as compared to the respective 24°C value. At 70°C, 6005-T5 alloy tensile yield and ulitmate strengths are reduced 6% and 4% respectively; thus, 6005-T5 aluminum alloy values were reduced 12% and 8%. At -40°C, 6005-T5 alloy tensile yield and ulitmate strengths are increased 4% and 6% respectively; thus, 6005-T5 aluminum alloy values were increased 8% and 12%.

Polyurethane Foam

Case studies were performed on the variable foam properties as well as impact orientation to evaluate the most potentially damaging drop condition. Variable foam crush strengths were determined to have minimal effects on the Traveller global mechanical behavior. As previously stated, the cold case at high density resulted in slightly more acceleration impact force than nominal, so the base case utilized nominal properties and the heavy case cold properties (Table 1). It is noted that using denser foam will have a similar effect at equal temperatures since the stress-curves are an explicit model input.

2.3.2 Evaluation Results

It is expected that the force history would be similar for the base and heavy Clamshell cases since the physical phenomena are highly similar. The Outerpack and Clamshell are essentially a de-coupled system with respect to the vertical drop test. Figure 10 presents the rigid wall (i.e., ground impact force) force history of the impact event from the Outerpack impact until the fuel assembly impacts the inner impact limiter.

As expected, the initial Outerpack impact resulted in slightly greater rigid wall forces for the heavy case as compared to base case. This is attributed to the slightly more rigid foam as opposed to the mass increase. That effect is apparent at approximately .007seconds after the heavier Clamshell impacts the inner impact limiter and additional crushing occurs.

The global Clamshell deceleration force increased from 124g to 135g, or 8.1%. These results were incorporated into a structural analysis to ensure key Clamshell components maintained a positive safety margin.

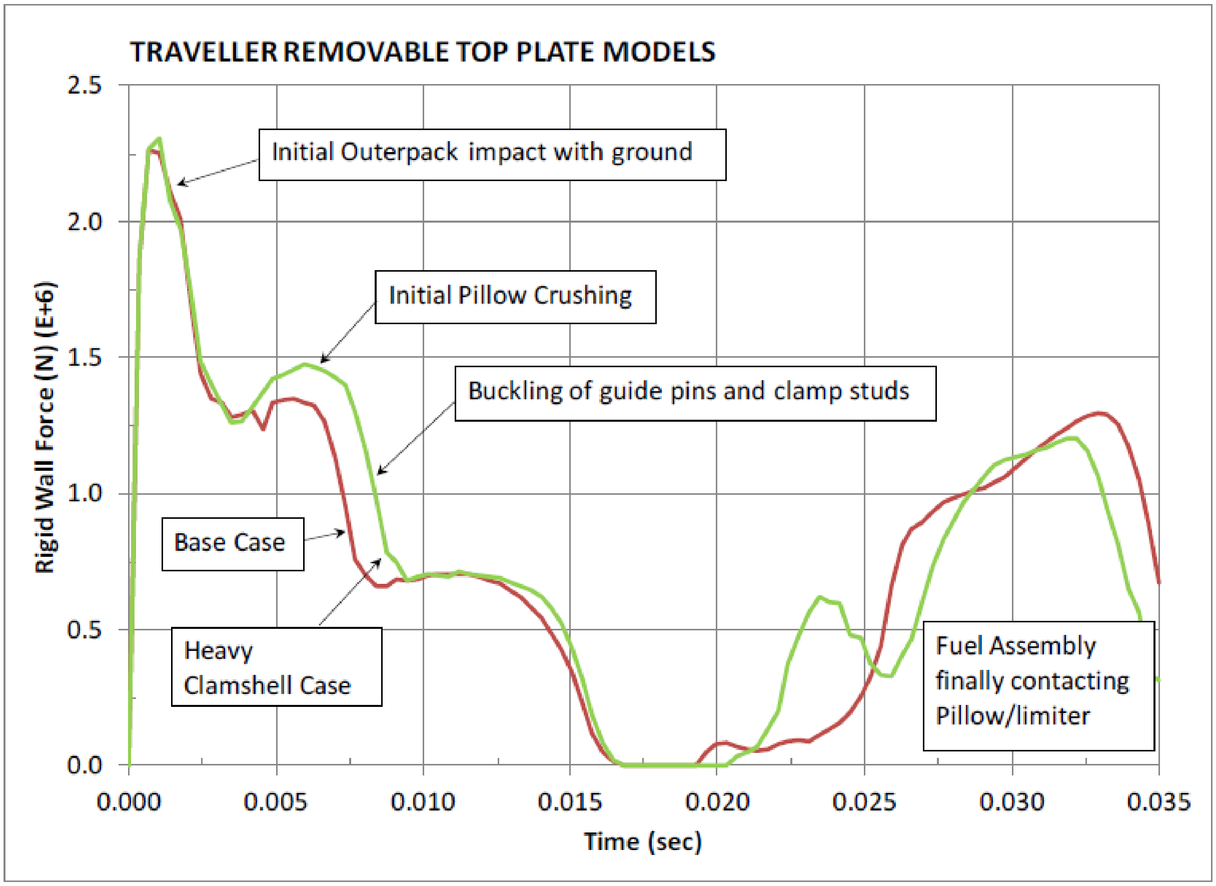


Figure 10: Traveller 9-meter Vertical Free Drop FEA Rigid Wall Force Results

3. CONCLUSIONS

Using FEA, the Westinghouse Type A Shipping package underwent numerous sensitivity studies to determine the effects of construction material variations on compliance to regulatory accident conditions. Since physical testing of each package construction material at specification minima is not practical, use of FEA for these sensitivity studies is warranted. This methodology is also recommended for material and geometric design optimizations during the design phase for margin assessment and even cost benefits.

4. REFERENCES

1. IAEA Safety Standards Series TS-R-1, Regulations for the Safe Transport of Radioactive Material, 2009 Edition, Page 89.
2. United States Nuclear Regulatory Commission Regulations, Title 10, Code of Federal Regulations, Part 71, Subpart F.
3. General Plastics Last-A-Foam ®FR 3700 for Crash and Fire Protection of Nuclear Material Shipping Containers, General Plastics Manufacturing Company, Tacoma WA.