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Finite Element Analysis of Bulk Tritium Shipping Package

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ABSTRACT

The Bulk Tritium Shipping Package was designed by Savannah River National Laboratory. This package will be used to transport tritium. As part of the requirements for certification, the package must be shown to meet the scenarios of the Hypothetical Accident Conditions (HAC) defined in Code of Federal Regulations Title 10 Part 71 (10CFR71). The conditions include a sequential 30-foot drop event, 30-foot dynamic crush event, and a 40-inch puncture event. Finite Element analyses were performed to support and expand upon prototype testing. Cases similar to the tests were evaluated. Additional temperatures and orientations were also examined to determine their impact on the results. The peak stress on the package was shown to be acceptable. In addition, the strain on the outer drum as well as the inner containment boundary was shown to be acceptable. In conjunction with the prototype tests, the package was shown to meet its confinement requirements.

INTRODUCTION

Shipping packages for radioactive materials must meet the criteria for the Hypothetical Accident Conditions (HAC) specified in the Code of Federal Regulations Title 10 Part 71 (10CFR71). The accident conditions occur sequentially and the cumulative damage must meet acceptable limits. The sequential accident scenarios are:

1. A free drop of the package through a distance of 9 m (30 ft) onto a flat, essentially unyielding horizontal surface. The orientation is such as to produce maximum damage.
2. The package is placed on a flat, essentially unyielding horizontal surface and struck with an 1100 lb plate. The orientation is that which will produce maximum damage for the package.
3. The package is dropped through a distance of 40 in onto a steel bar with a diameter of at least 6 in.

The model that was developed had to evaluate the combined effect of the residual stresses caused by the torque load and the cumulative damage caused by the sequential dynamic impacts. The sequential accident conditions are required to be performed in the orientation that would produce maximum damage. Due to the complexity of the dynamic impacts, determining the orientation of maximum damage is not an easy task. A series of different orientations was chosen to challenge the package under the accident conditions. The analytical results were compared to experimental test data to verify the model.

DISCUSSION

Finite Element Model

As part of the finite element model the package and the load conditions are symmetrical with respect to the x-y plane. Principles of symmetry were applied, and only half of the package was generated in the finite element model. It is assumed that the response of the portion of the package that is not modeled is identical to the portion of the package that is included in the finite element model.

The overall finite-element mesh used for the BSTP is shown in Figure 1. The model of the packaging contains 182,038 nodes and 129,872 elements. As stated, principles of symmetry were applied, so only half of the package was included in the finite element model. The finite element meshes of the part instances were generated using versions 6.6-1 and 6.7-1 of the Abaqus/CAE finite element program. The analysis was performed using version 6.7-1 of Abaqus.

The finite element model representation of the containment vessel cylindrical section, drum body, and contents consist of 4- and 8-node 3-dimensional shell elements (Types S4R and SC8R in the Abaqus® finite element code). These elements are highlighted in Figure 2. The steel crush plate is represented by 4-node 3-dimensional shell elements (Type S4R in the Abaqus finite element code).

The containment vessel body, containment vessel bolts, drum bolts, and drum insulation are modeled using 8-node 3-dimensional solid elements (Type C3D8R in the Abaqus finite element code). These elements are shown in Figure 3.

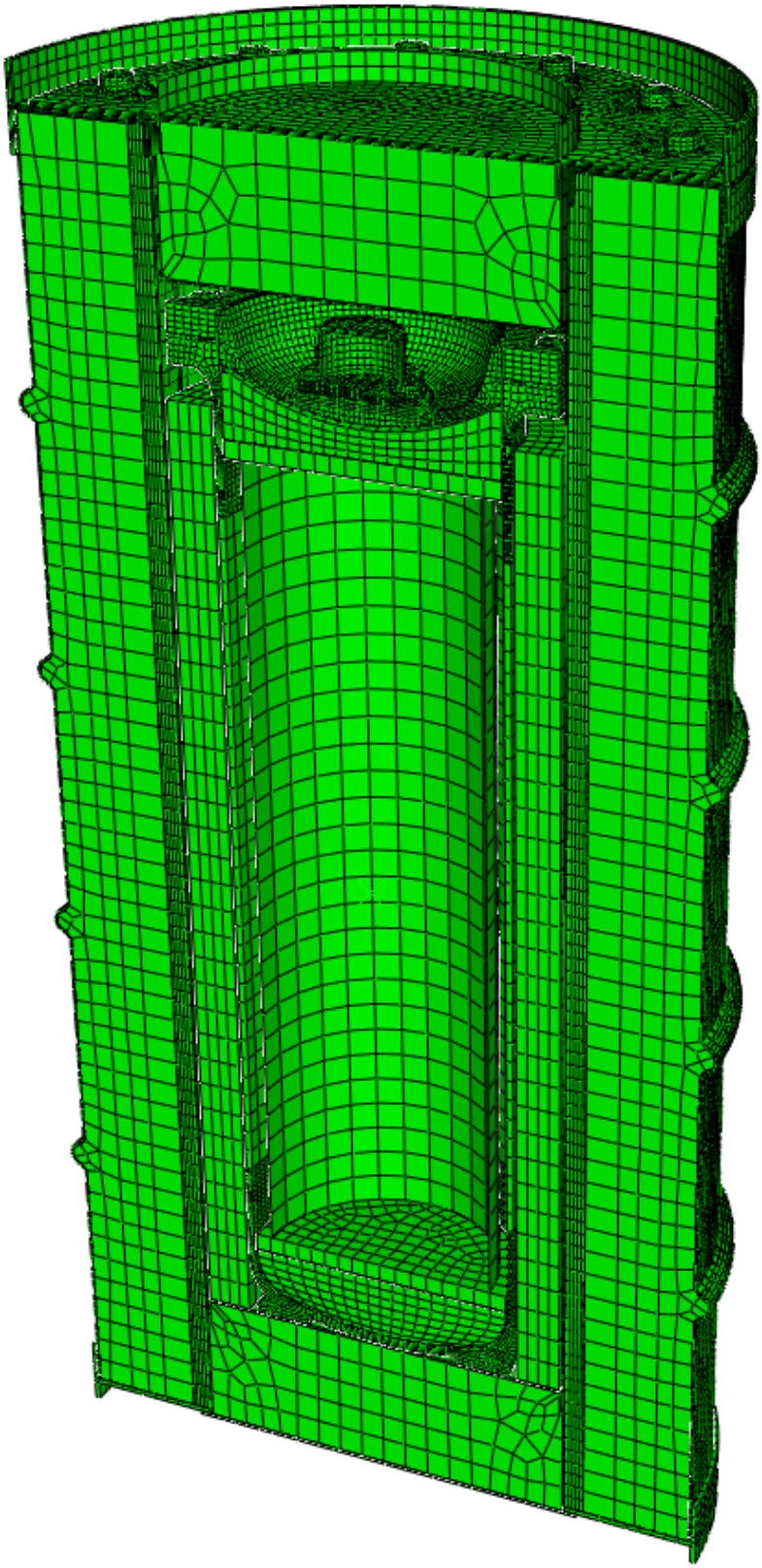

Figure 1 – Finite Element Model of Package

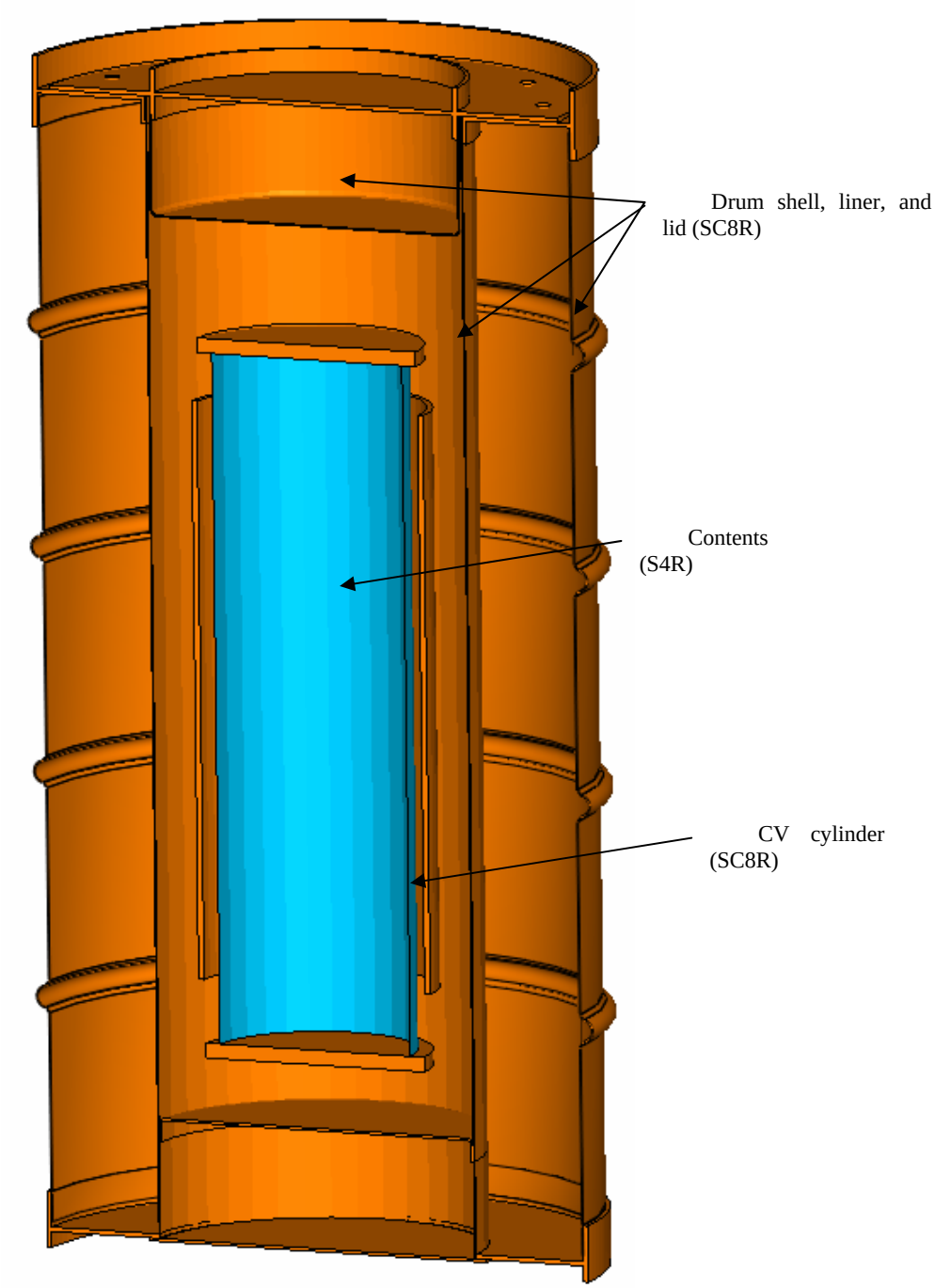

Figure 2 – Shell Elements in BTSP Finite Element Model

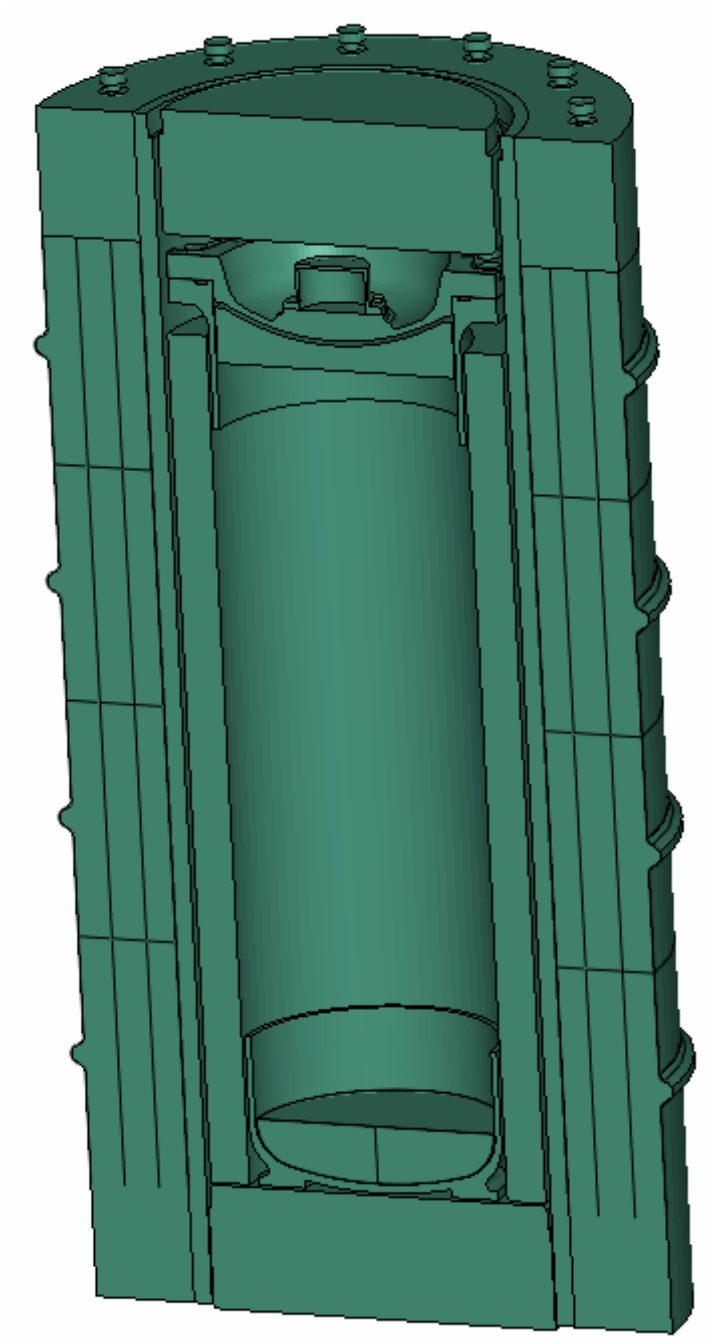

Figure 3 – Solid Elements for Finite Element Model

Applied Loads and Initial Conditions

Gravitational Load

The downward gravitational load of the falling package and crush plate is represented by a gravitational load of 386.4 in/s^2 in the negative vertical direction.

Initial Conditions for 30-ft free drop

The free drop of the package is completed during the first load step of the finite element simulation. In all finite element models, the package is initially located near the target floor so that the initial velocity of the package model is equal to the velocity of the package after a 30-ft free fall. The initial velocity of the package model is calculated using Eq. 1.

$$V_0 = \sqrt{2gh} = \sqrt{2 \times 386.4 \frac{\text{in}}{\text{s}^2} \times 12.0 \frac{\text{in}}{\text{ft}} \times 30\text{ft}} = 527.5 \frac{\text{in}}{\text{s}} \qquad \text{Eq. 1}$$

The same initial velocity calculated in Eq. 1 for the package is used for the crush plate just prior to the impact with the package. However, the application of the initial velocity in the model is different as discussed in further detail below.

Initial Conditions for 30-ft crush

The crush plate is located near the package, opposite the floor, such that it will not interfere with the package during the drop event. At the onset of the crush step, the crush plate has an initial velocity of 527.5 in/s, representative of the velocity after a fall of 30 ft. To preclude any unintended acceleration that might be the result of numerical calculations, the crush plate velocity is specified as a constant value of 527.5 in/s during a short intermediate time step. The velocity specification is removed and replaced with just a gravitational load at the start of the crush step. The crush plate contacts the package during this third step.

Initial Conditions for Puncture

After the crush event, the crush plate and floor are moved out of the way and the package is allowed to free fall 40 in onto a 6-in diameter pin. The pin is located near the package so that the applied velocity of the package model is equal to the velocity of the package after a 40-in free fall. As with the crush plate, the velocity is applied during a short intermediate time step. The velocity specification is removed and replaced with a gravitational load at the start of the puncture step. The applied velocity of the package model is calculated using Eq. 2.

$$V_0 = \sqrt{2gh} = \sqrt{2 \times 386.4 \frac{\text{in}}{\text{s}^2} \times 40\text{in}} = 175.8 \frac{\text{in}}{\text{s}} \qquad \text{Eq. 2}$$

Boundary Conditions

As stated previously, only half of the package is modeled. Symmetry conditions are applied to ensure no rotation or movement across the symmetry boundary.

The bolts and threaded inserts of the package are modeled as a tied connection defined by surfaces of the two parts in the model (Type “Surface to Surface” as defined by the Abaqus finite

element code). The preload is achieved by applying a temperature constraint to the bolt stem to achieve a stress in the bolt equal to the stress associated with torquing the bolt to the maximum design value.

Acceptance Criteria

The dynamic load associated with a 30-ft drop, a 30-ft crush, or a puncture of a BTSP package is classified as a Level D Service Load defined in the ASME B&PV Code, Section III, Appendix F 1341.2. The stress limits are specified as follows:

$$P_m \leq 0.7S_u$$

$$P_L \leq 0.9S_u$$

where P_m = General primary membrane stress intensity
P_L = Local primary membrane stress intensity
S_u = Ultimate strength of material

Orientations

The configurations that were modeled included different drop and crush orientations as well as different environmental conditions designed to challege different aspects of the package. The drop and crush configurations are listed in Table 1.

Table 1 – Orientation of Package in Finite Element Model

Drop Orientation	Crush Orientation	Temperature
Top Down	Side	77 ºF
Side	Side	-20 ºF
Side	Side	77 ºF
Side	Side	150 ºF
CGT	CGB	77 ºF
CGT	CGB	150 ºF
CGT	CGT	77 ºF
Bottom Down	Top Down	77 ºF
Slap Down	Side	77 ºF
Slap Down	Side	-20 ºF

Results

The interior vessel of the package is required to remain leak-tight after the sequential loading. The outer portion of the drum must confine the inner vessel, but is not credited as a containment boundary. As such, the stress criteria are applied to the containment vessel boundary. Cumulative plastic strain was also evaluated for the containment vessel and the exterior portions of the drum. The results of each orientation were evaluated. As part of the evaluation, it was determined that different orientations challenged different areas of the package. The most challenging orientation for the containment vessel body, may not be the most

challenging orientation for the containment vessel bolts. In addition to different orientations, different temperature conditions were also modeled. After review, all of the criteria were met for each of the different orientations.

Test Comparison

The package was tested under the same sequential loading conditions as the models. As a validation for the models, the cumulative damage from the models was compared to that of the tests. While exact stresses and strains can not be compared between the models and tests, similar cumulative damage indicates that the model is accurately predicting the physical phenomena occurring during the dynamic impacts.

As an example, on a center of gravity over bottom corner crush, the relative damage to the package is similar, see Figure 4. This type of comparison, including comparing depths of indentations and deformation, was performed for all of the different orientations. Based on this review, the analytical predictions agree well wit the experimental results.

Figure 4 – Model Comparison to Test Results

CONCLUSION

The stress results obtained from this analysis show that the ASME limits for maximum stress intensity are met. The results for the effective plastic strain show that the maximum effective plastic strain in the containment vessel body, containment vessel bolts, and lid cap bolts are all within acceptable limits. The results for the effective plastic strain of all other metal components show that the drum will withstand the drop, crush, and puncture events. The models were validated against similar experimental tests.