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RESPONSE OF THE TRUPACT-II TO EXTRA-REGULATORY IMPACTS

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ABSTRACT

Transportation risk assessments require an evaluation of the consequences of very low probability accidents that are more severe than the regulatory hypothetical accident conditions specified in 10CFR71.72. For many package types, their response to these events have traditionally been assumed or inferred from calculations of other package types. This work is the first time that a large package for the transportation of transuranic waste has been modeled to determine its response to extra-regulatory impacts. A set of seven finite element analyses of the TRUPACT-II package were conducted to determine if there would be any release from the package. Three of these analyses were of the regulatory side, end, and corner impacts that were performed during the certification testing of the package. This set of analyses was performed to calibrate the finite element model and make sure that it was providing results that were consistent with the tests. Once it was determined that the finite element model could accurately predict the response of the package, four additional analyses were performed: a 60-mph impact onto the top of the package, a 60-mph impact onto the side of the package, and 45- and 60-mph impacts onto the top corner of the package. All the impacts except the 60-mph impact onto the top corner resulted in deformations and strains in the package that indicate no loss of contents. The 60-mph corner impact resulted in strain levels that indicated that there may have been tearing in the wall of the containment vessel and possible release of radioactive material. This paper will describe the analyses performed, the validation of the finite element models, the conservative failure model adopted to indicate material tearing, and the results of the analyses.

INTRODUCTION

The most recent update of the transportation analysis for the Waste Isolation Pilot Plant (Kalinina et al. 2020) took advantage of improvements in computational modeling to assess the response of the TRUPACT-II transportation package to accidents that were more severe than the regulatory hypothetical accidents from 10CFR71.72. The TRUPACT-II package was primarily certified to meet the requirements for the regulatory impact by a series of full-scale drop tests. The data from these tests was available to calibrate the finite element model. The analyses performed consisted of lid-end, CG-over-lid end corner, and side impacts at 30 MPH to compare with the regulatory tests and extra-regulatory impacts at 45 and 60 MPH for the corner orientation and 60 MPH for the lid-end and side orientations. All of the analyses were performed using the Sandia-developed explicit dynamic finite element code SIERRA Solid Mechanics (SIERRA Solid Mechanics Team, 2019).

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TRUPACT-II MODEL

The TRUPACT-II container is a circular cylinder with a domed head transported in the vertical orientation as shown in Figure 1. The package has an outer diameter of 94 inches, a height of 122 inches, and a maximum loaded weight of 19,250 pounds. It consists of an outer confinement assembly (OCA) and an inner containment vessel (ICV). The OCA is made of inner and outer shells with the space between them filled with rigid polyurethane foam. Both the OCA and ICV are made up of upper and lower sections that are joined with a locking ring. The ICV cavity is a cylinder approximately 73 inches in diameter and 75 inches tall. The TRUPACT-II is never directly loaded with contents, but instead the contents are first loaded into one of several types of payload containers. The most common payload container is a 55-gallon (200-liter) drum, with 14 drums being transported together in two layers of seven drums each. Since the ICV is domed at each end and the payload containers are not, an aluminum honeycomb insert is installed on both the bottom of the ICV and on the lid of the ICV.

The overall finite element model used for these analyses is shown in Figure 1. In this model the individual payload containers and their contents are homogenized together to reduce the model complexity and to neglect any structural support the actual payload may add. Because of symmetry in the design and the loading, only ½ of the package needed to be modeled. The model shown contains 2,780,089 elements.

Away from the locking ring, loss of containment will be the result of tearing in the shells. This phenomenon is adequately predicted with a relatively coarse mesh of shell elements. In the region of the locking rings a more detailed mesh of hexahedral elements is required to accurately capture the interfaces between the different parts and the relative motion between them that could result in leakage through the joint. Figure 2 shows the detail of the mesh in this region of the ICV and Figure 3 shows this region for the OCA.

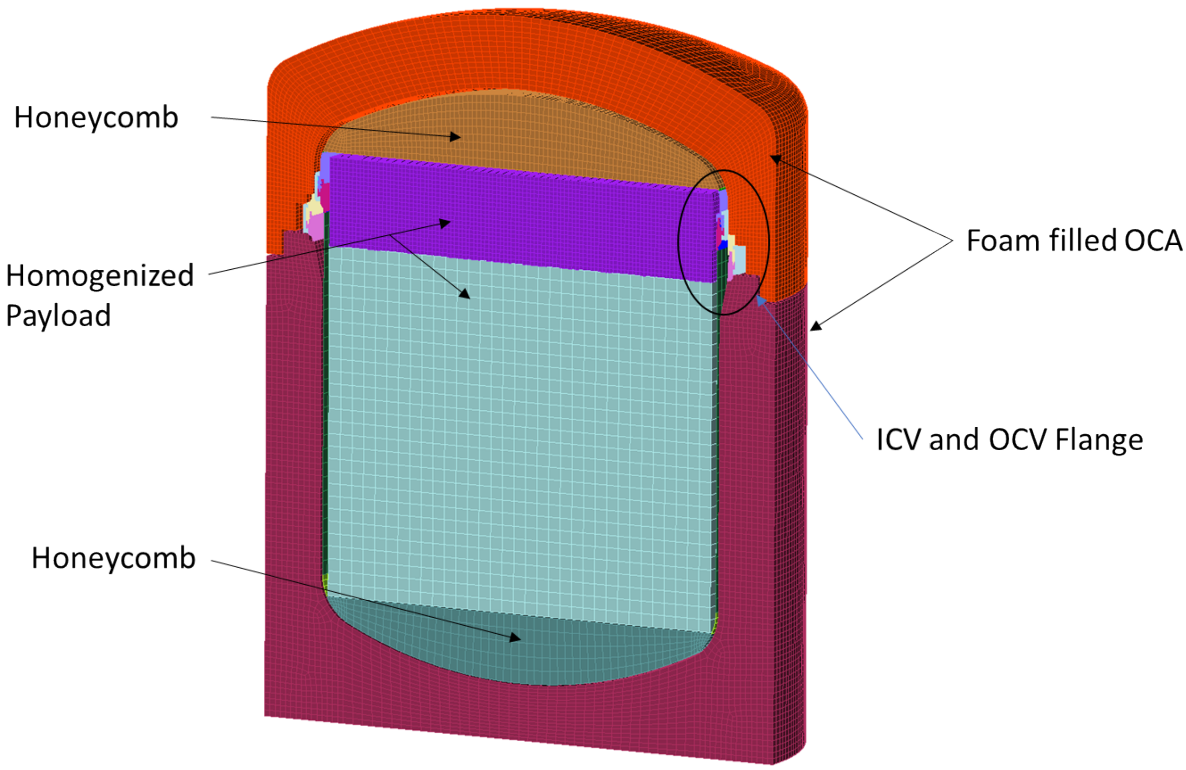

Figure 1. TRUPACT-II finite element model

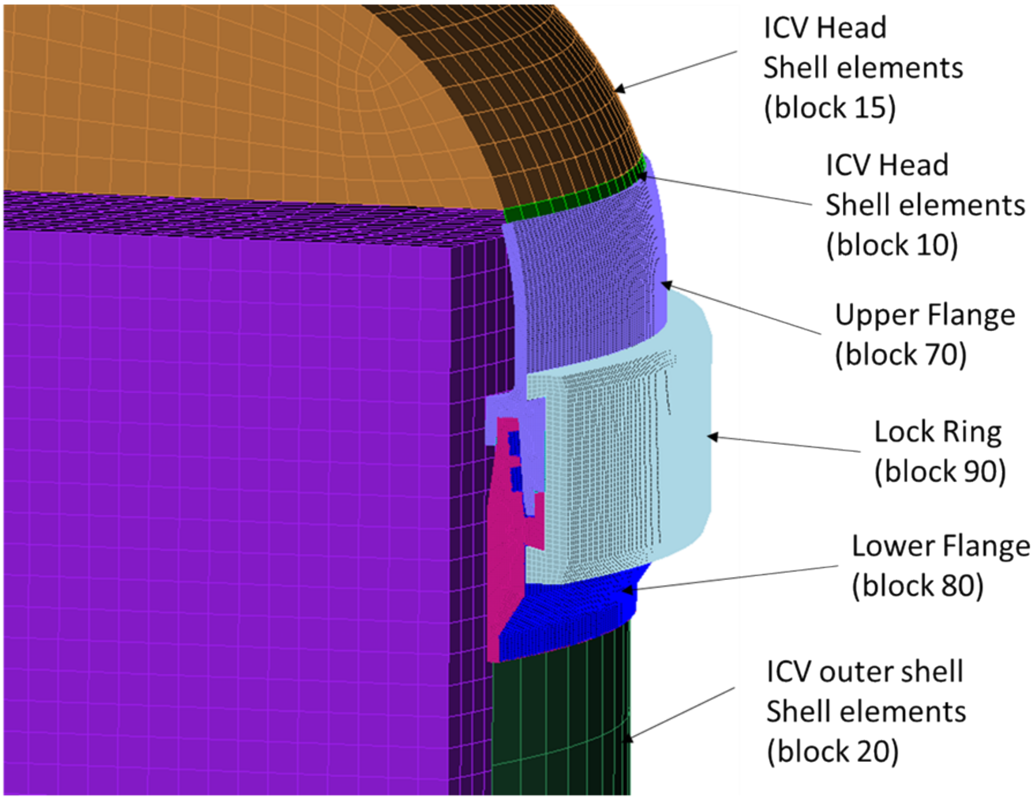

Figure 2. Detailed view of the ICV Flange

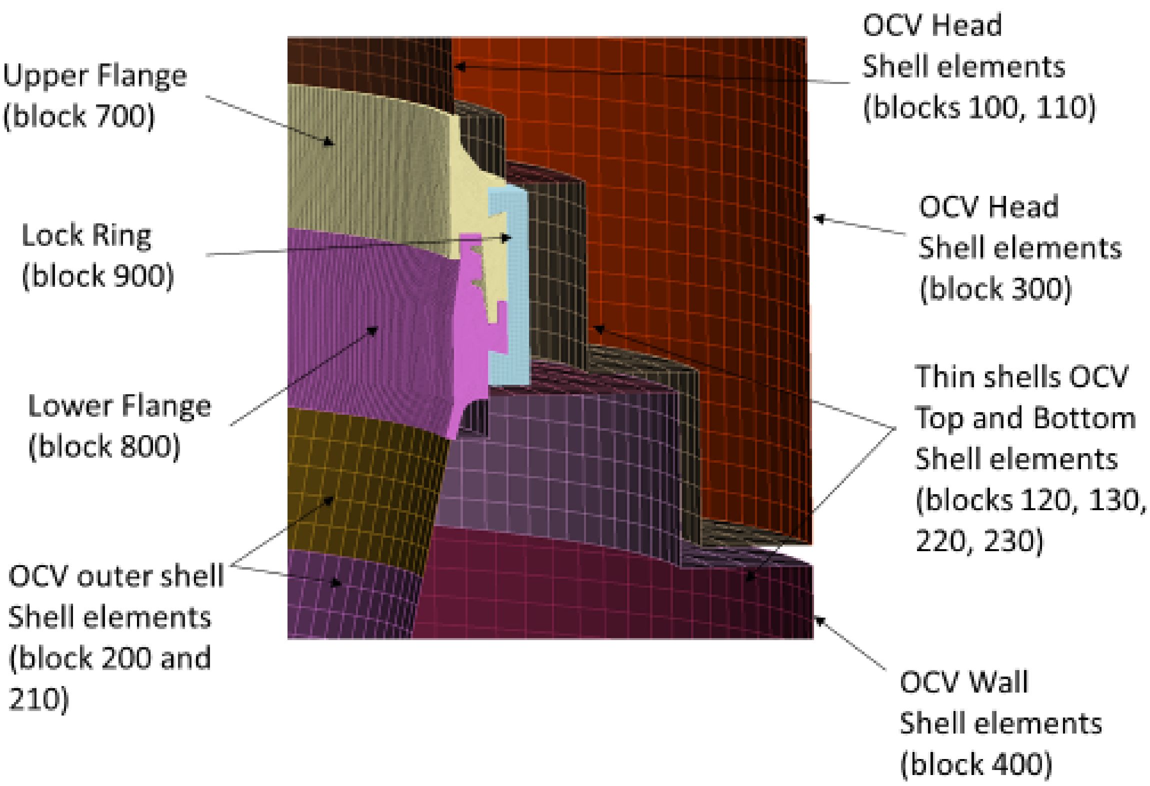

Figure 3. Detailed view of the OCA Flange

MATERIAL MODELS

The shells and flanges of the ICV and OCA are all made of 304 stainless steel. This material was modelled with a multi-linear Elastic-Plastic hardening model. Figure 4 shows the true-stress vs. true-strain curve used in the model. Material failure based on Appendix FF of the ASME Boiler and Pressure Vessel Code is assumed. The failure criterion used is represented by Equation 1 (ASME 2015).

$$[(TF)\left(\varepsilon_{eq}^{p}\right)]_{max} \leq [\varepsilon_{uniform} + 0.25(\varepsilon_{fracture} - \varepsilon_{uniform})] \quad \text{Eq. 1}$$

Where ε_{eq}^{p} is the equivalent plastic strain, $\varepsilon_{uniform}$ is the true strain at the onset of necking in a uniaxial tension test, $\varepsilon_{fracture}$ is the true strain at fracture, and triaxiality factor (TF) is defined as:

$$TF = \frac{(\sigma_1 + \sigma_2 + \sigma_3)}{\sqrt{\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]}}$$

Utilizing this definition of failure results in the maximum values for the product of plastic strain and triaxiality factor given in Table 1 for base material and weld material at room temperature and cold temperature.

Table 1. Maximum Allowable Values of $[TF\epsilon^p]_{max}$

Temperature (F)	Material	TF EQ max
-20	base	0.691
-20	weld	0.684
70	base	0.815
70	weld	0.664

The layer between the OCA outer shell and the OCA inner shell is filled with 8.25 lb/ft^3 polyurethane foam. This material acts as the impact limiter material for the package. It is modelled using the Low-Density Foam model (Neilson, M.K., Morgan, M.S. and Krieg, R.D., 1987). This model was based on decomposition of the foam response into two parts: (1) response of the polymer skeleton, and (2) response of the air inside the cells, which is completely volumetric. The parameters for this model were developed through testing and are based on the volume fraction of the material and the Young's modulus. The following equations taken from Neilson, M.K. et al. (1987) were used to derive the model parameters.

$$A = 3440\ \phi^{1.676}$$
$$B = 2780\ \phi^{1.645}$$
$$C = 2.11 - 31.1\ \phi$$
$$E = 454000\ \phi^{2.20}$$

Based on these equations and the material properties taken from the SAR (TRUPACT-II Safety Analysis Report, 2013) the foam material modelling parameters are presented in Table 2.

Table 2. Low-Density Foam Model Parameters

Parameter	Value
E	6,810 psi
ϕ	0.148
A	139.93
B	119.998

C	-2.4928

The foam material is very compliant and the high velocity impacts of the extra-regulatory analyses can generate large distortions in the foam elements. These highly distorted element can cause problems with the numerical stability of the model. Therefore, several criteria are applied to remove these distorted elements from the mesh. The following criteria are used to identify distorted elements during each simulation and elements that meet them are deleted from the model:

element inversion
nodal jacobian ratio <= 0.0
solid angle <= 0.0
timestep < 2.5E-08

The distortion criteria can remove a large number of elements from narrow regions of the impacted foam. This can result in less energy being absorbed by the foam and or a poor redistribution of the impacting load. This can cause higher, more localized loads to be transmitted to the ICV shell.

Two aluminum honeycomb spacer assemblies are used within the ICV, one inside each ICV torispherical head. The honeycomb has a density of 3.6 lb/ft^3. It is modeled using the orthotropic crush model. This is an empirically based model designed to model energy absorbing material. Three response regimes are assumed in the model: (1) orthotropic elastic, (2) crush, and (3) complete compaction.

The payload is modeled as one solid cylinder. The material is modeled as an Elastic-Plastic low density, low strength, concrete material. The density was calculated to get the mass of the volume equal to the maximum weight of the payload assembly. The material properties were chosen to provide a soft dense material for impact to represent partially filled drums.

MODEL VALIDATION RESULTS

To validate the finite element model, analyses were conducted of three of the free drop certification tests. The model results were compared to the test results documented in the TRUPACT-II Safety Analysis Report (SAR). Table 3 lists the post-test deformations of the test articles taken from Table 2.10.2-1 of the SAR for the three HAC tests along with the deformed dimension taken from the finite element analyses.

Table 3. Model Validation Results

Impact Orientation	Analysis Results	Test Results
30-mph Side Impact	36.9" wide flat at top (OCA lid) × ~3.75" deep	37" wide flat at top (OCA lid) × 35" wide flat at bottom (OCA body) × ~3-5/8" deep
30-mph CGOC impact	31.4" wide × 63.7" long flat at top (OCA lid) × ~10" deep	30" wide × 53" long flat at top (OCA lid) × ~3¾" deep
30-mph Top Impact	64" diameter flat at top (OCA lid) × ~5.3" deep	53" diameter flat at top (OCA lid) × ~3¾" deep

For the side impact orientation, the analysis shows good agreement with the test deformation and measurements. The width and depth of the impact region match the test article. For the end impact orientation, the model has a larger impact diameter than the impact diameter reported in the test (64.9 inches versus 53 inches). The depth of the impact region in the model is also larger than the depth recorded during the test (5.3 inches versus 3.74 inches). This indicates that the model foam material is slightly softer than the foam material in the test units. The deformation of the model in the center-of-gravity over corner (CGOC) orientation is larger than the deformation of the test unit. The minor diameter of the ellipse is slightly larger (31 inches versus 30 inches) than the test unit. The major diameter is larger by about 10 inches (63.7 inches versus 53 inches). There is significant difference between the crush depth of the model and the crush measured in the test. The depth of crush in the model is almost 10 inches while the reported depth in the SAR is 3.75 inches. Based upon the geometry of the package, for a crush minor diameter of 30 inches, the minimum crush depth should be closer to 8 inches, which suggests that the crush depth reported in the SAR may be under-reported. An 8-inch crush depth would reduce the difference between crush depth of the model and the test; resulting in better approximation and a model that is only slightly softer than the test unit.

For these analyses, having the foam material in the analysis be softer than the foam in the test units will provide larger deformations of not only the outer shell, but also the ICV, and it is therefore conservative.

EXTRA-REGULATORY IMPACTS

Four impact analyses were performed to determine the TRUPACT-II response to extra-regulatory impacts. Three analyses were performed in the top, side, and CGOC orientations at an impact velocity of 60-mph. The structural integrity of the ICV was used to determine whether the package remained leak tight. The limits developed for the ASME strain-based criteria were used as a failure criterion for the potential rupture of the ICV.

Top Impact 60-mph

The deformation of the TRUPACT-II from the 60-mph top impact is shown in the left-hand image of Figure 4 and the mapping of maximum product of stress triaxiality and plastic strain is shown in the right-hand image. In the shell elements of the ICV head, the peak value is 0.16, and in the flange, the peak value is 0.45. This latter value occurs in a single element at the plane of symmetry where the shell elements are attached to the solid elements of the flange, which is believed to be a modeling artifact. Other than in this location, the peak value in the flange is 0.025. These values are all well below the failure criteria, so it is concluded that the ICV survives the 60-mph top impact.

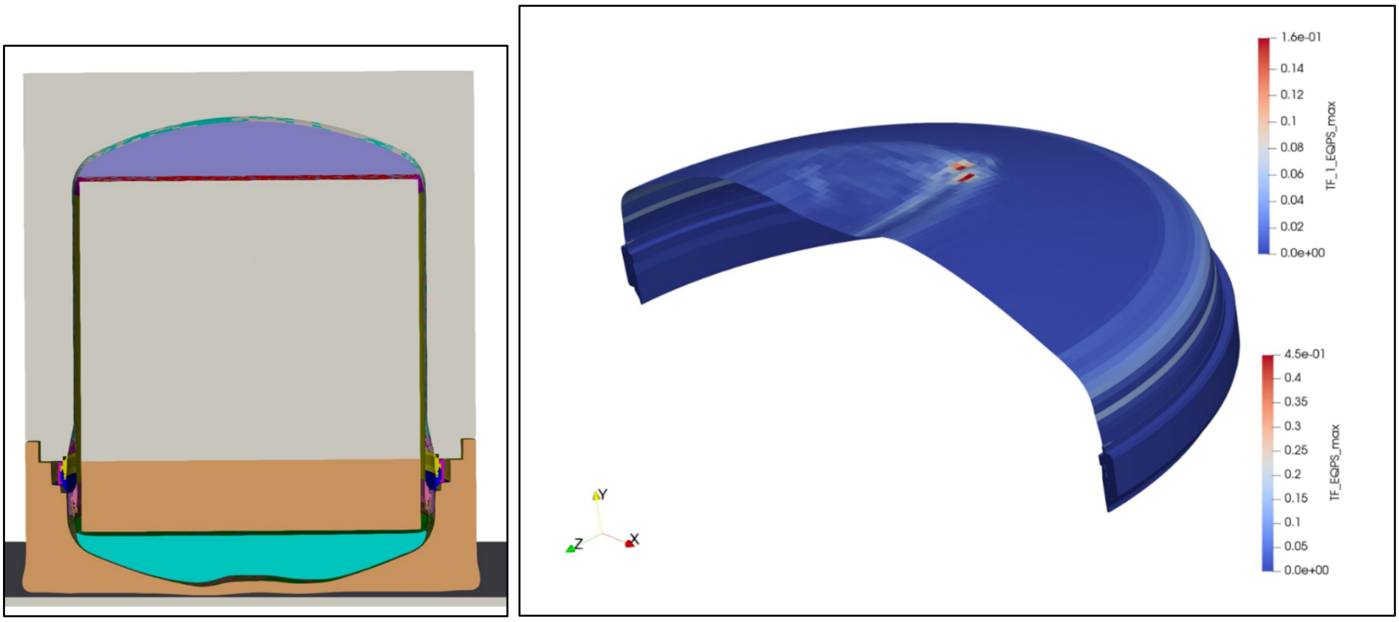

Figure 4. Deformations from the 60-mph end impact and resulting $[TF\epsilon^p]_{max}$ values

Side Impact 60-mph

The deformation of the TRUPACT-II from the 60-mph side impact is shown in Figure 5. The mapping of maximum product of stress triaxiality and plastic strain for the shell of the ICV is shown in the left-hand image of Figure 6 and for the flange in the right-hand image. In the shell, the peak value is 0.13, and in the flange, the peak value is 1.0. This latter value occurs in a single element at the plane of symmetry where the shell elements are attached to the solid elements of the flange, which is believed to be a modeling artifact. Other than in this location, the peak value in the flange is 0.40. These values are all well below the failure criteria, so it is concluded that the ICV also survives the 60-mph side impact.

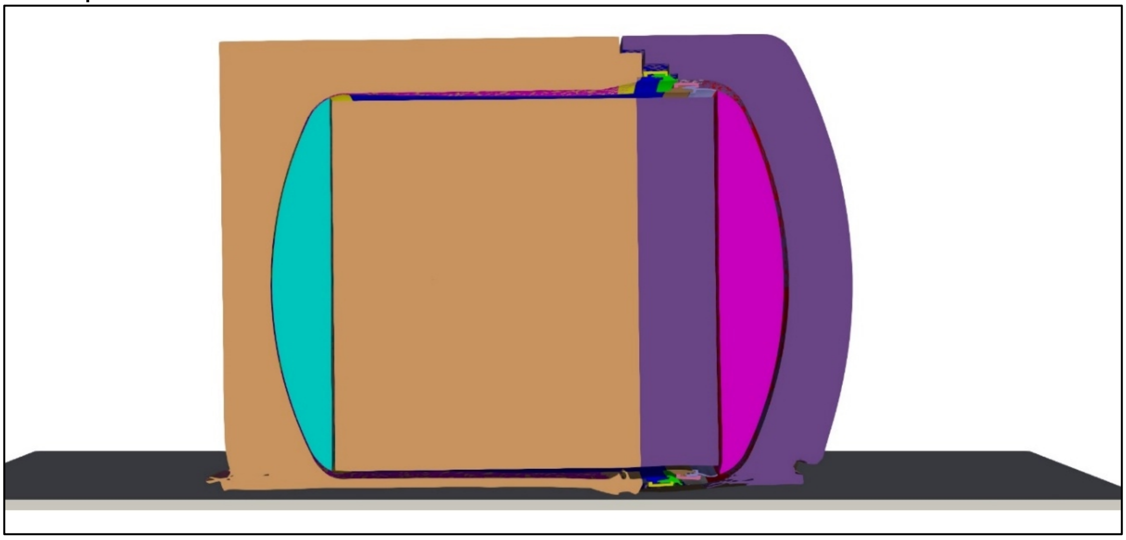

Figure 5. Deformations from the 60-mph side impact

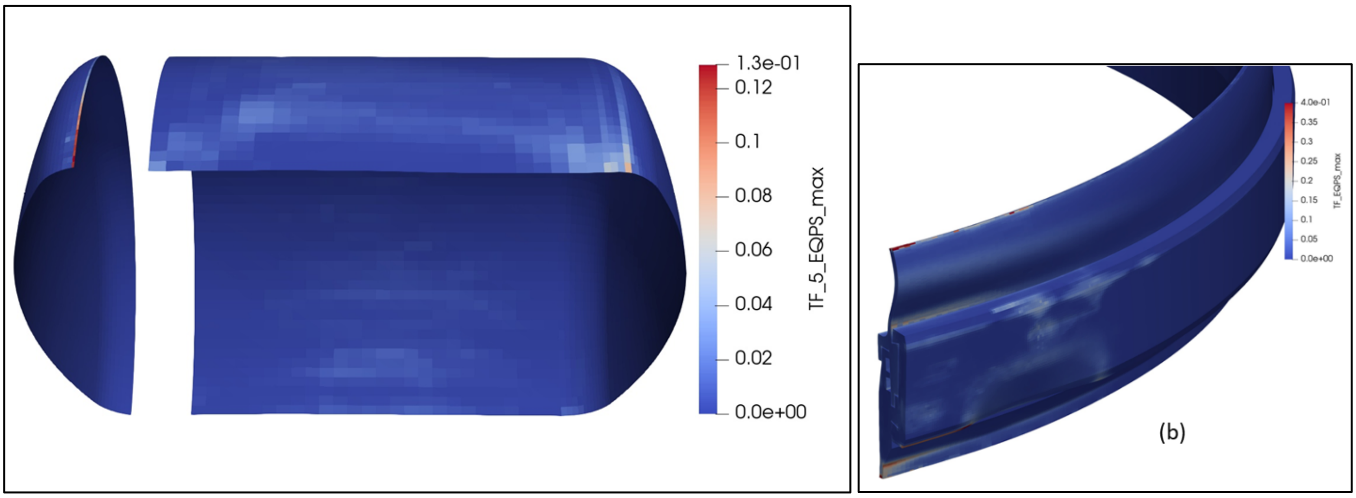

Figure 6. $[TF\epsilon^p]_{max}$ **values in the ICV shell and flange from the 60-mph side impact**

CGOC Impact 60-mph

The deformation of the TRUPACT-II from the 60-mph CGOC impact is shown in the left-hand image of Figure 7 and the resulting mapping of maximum product of stress triaxiality and plastic strain is shown in the right-hand image. In this case there are significant portions of both the shell and flange that have peak values greater than the 0.67 failure limit, so it is assumed that tearing will occur and the ICV will fail for a 60-mph corner impact. For this reason, an additional analysis was performed in this orientation with a 45 mph impact velocity.

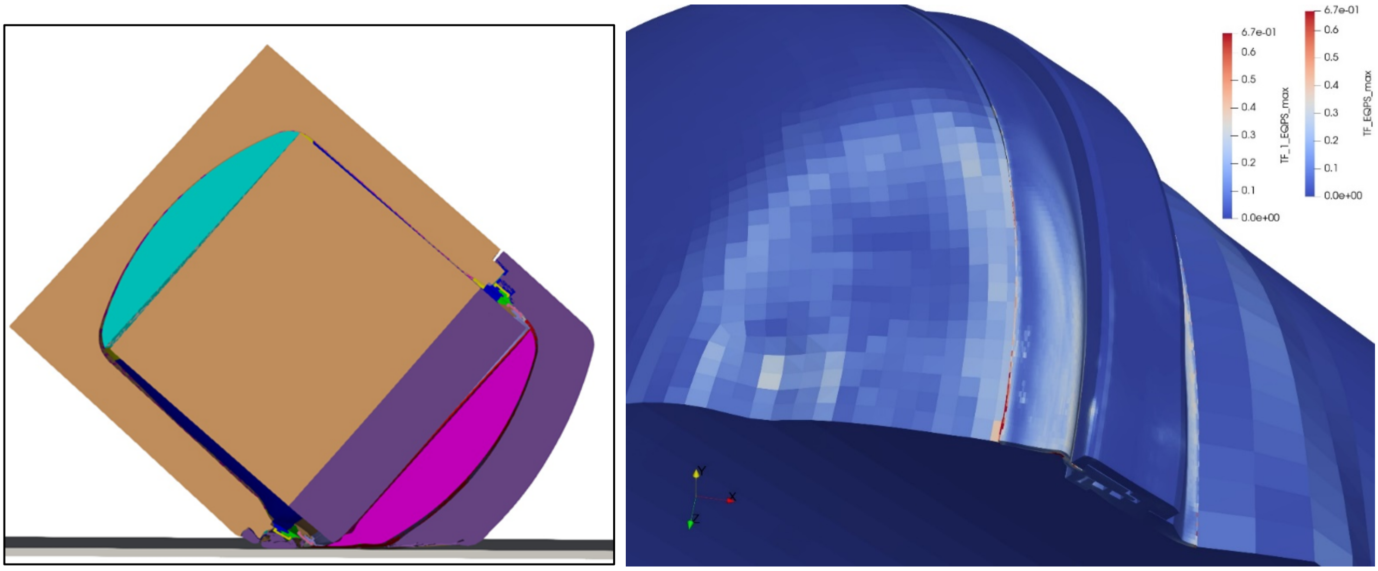

Figure 7. Deformations from the 60-mph CGOC impact and resulting $[TF\epsilon^p]_{max}$ values

<u>CGOC Impact 45-mph</u>

The deformation of the TRUPACT-II from the 45-mph CGOC impact is shown in the left-hand image of Figure 8 and the resulting mapping of maximum product of stress triaxiality and plastic strain is shown in the right-hand image. At this velocity the maximum value in the shell of the ICV is 0.19, and in the flange, it is 0.11. Both of these values are well below the failure limit, so it can be concluded that the ICV survives a 45-mph impact in the CGOC orientation. Additional analyses were not performed to determine the lowest impact velocity that would result in a failure of the ICV using the conservative criteria of ASME, but given the low values obtained in the 45-mph impact, it is expected that the failure velocity would be at least 50 mph.

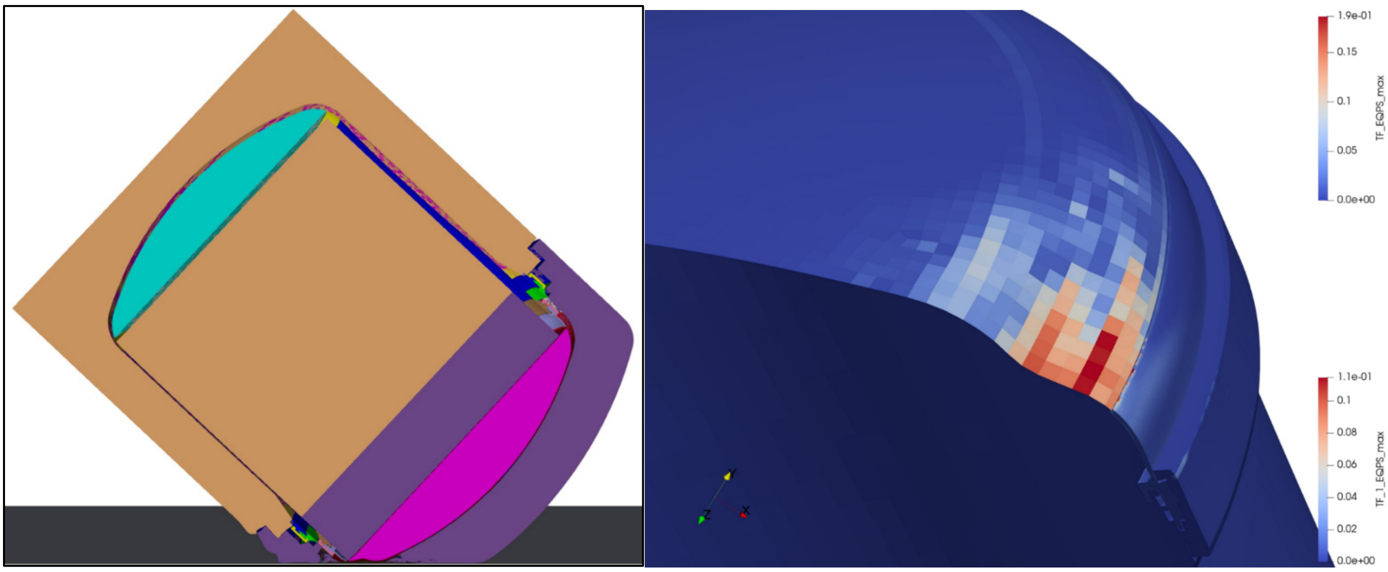

Figure 7. Deformations from the 45-mph CGOC impact and resulting $[TF\epsilon^p]_{max}$ values

CONCLUSIONS

Seven structural analyses were conducted of the TRUPACT-II package as part of the WIPP Transportation Assessment. The first three were to calibrate the model by comparing the model results to the certification free drop tests. These analyses showed good agreement with the deformation produced during the tests. Four additional analyses were performed to determine the package response to higher impact velocities. These analyses focused on maintaining the integrity of the ICV, using the ASME strain-based failure criteria. Three analyses were performed at an impact velocity of 60-mph in the top, side, and CGOC orientations. The top and side analyses show that the ICV would remain leak tight. In the CGOC orientation, the ASME strain-based criteria showed that a break in the ICV flange may occur. An additional analysis was conducted in the CGOC orientation at a velocity of 45-mph. At this velocity the ICV remained leak tight.

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