PAT-1 SAR Addendum Structural Analysis Videoconference with the NRC

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Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin company, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Primary Topics Outline

- **Overview of SAR Addendum analysis goals and PAT-1.**
- **Overview of overpack modeling.**
- **Overview of Tearing Parameter.**
  - **How developed? Theory. (vs. Johnson-Cook, etc.)**
  - **1D vs. 3D**
- **Overview of "Strain Locus".**
  - **How bounding envelope was generated.**
- **Component testing.**
  - **Velocities and/or strain rates bounded?**
- **Comparisons with EQPS.**
  - **Thru-thickness (T-Amp) comparisons of EQPS and TP.**

Secondary Topics Outline

- Overview of preprocessor.
- Overview of input file generation.
  - Basic feature of input file.
  - Syntax overview.
- Overview of postprocessor.
  - Opening output files.
  - Basic operations for results extraction.
- Sample air transport accident simulations.
  - Table 2-9, runs 1, 5, 7, 9, 12, 20
- Sample dynamic crush simulations.

SAR Addendum Analysis Goals

- **The PAT-1 package has been certified by the NRC (since 1978) for air transport of 2 kg powdered PuO_2.**
  - **SAR Addendum is to add solid metal to the contents list.**
  - **The only new requirement is dynamic crush (benign).**
- **SAR Addendum analyses demonstrate that solid metal contents do not affect the TB-1 containment boundary in normal and accident conditions.**
- **The integrity of a thin eutectic barrier is shown to be maintained using a component test-generated "strain locus" and an empirically-based analytical failure criterion called "Tearing Parameter".**
  - **Staying below critical Tearing Parameter avoids even the initiation of a ductile tear in the Ti-6Al-4V eutectic barrier.**

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Requirements and Acceptance Criteria

- **Overall Program-Defined Package Constraints:**
  - **PAT-1 already meets all regulatory criteria (except dynamic crush) for the same mass TB-1 contents (but oxide).**
  - **AQ-1 overpack to remain the same; same TB-1 provides containment throughout NCT, HAC, air transport environments.**
  - **Total contents mass within TB-1 (fissile and structure) not to exceed 4.6 lb; 25 watts heat generation.**
  - **Contents subcritical; radiation limits on container.**
  - **T-Ampoule is a eutectic barrier only (not for Pu containment during air transport accident conditions) and maintains integrity.**

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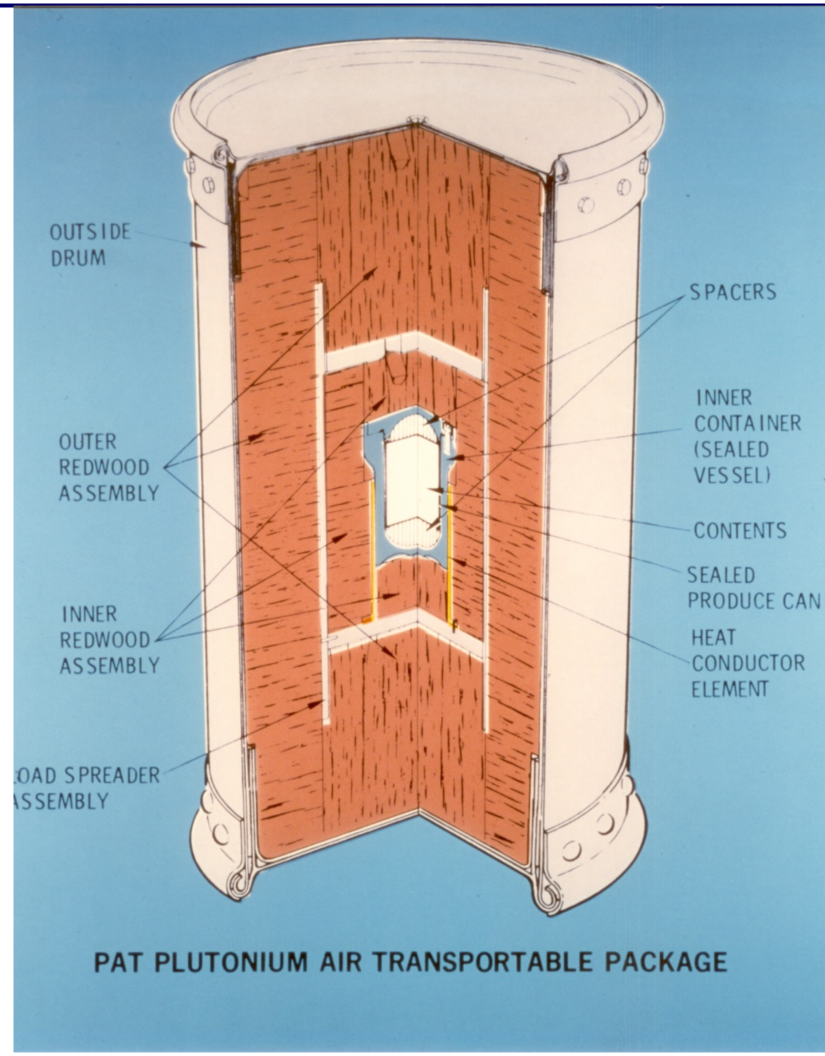
PAT-1 Air Transport Package (USA/0361/B(U)F-96)

- **Major Components**
  - **AQ-1 Protective overpack**
  - **TB-1 SS Containment Vessel**
  - **PC-1 SS Product Can**
- **Gross Weight: 500 lb (227 kg)**
- **Dimensions: 24 ½ in. (62.2 cm) dia. x 42 ½ in. (108 cm) height**



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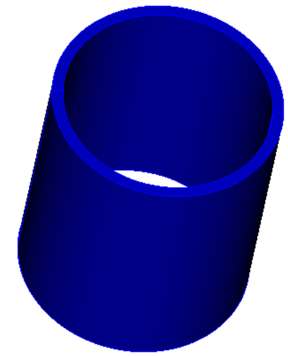
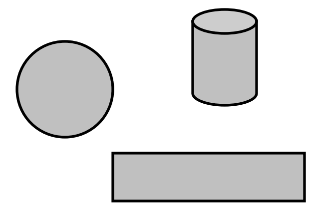
Materials to be Shipped

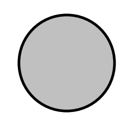
- **Electro-refined Pu bulk material**
  - **Machined hollow cylinder form**



- **Pu metal samples of varying age**
  - **Samples are typically in disc, strip, or cylinder form**



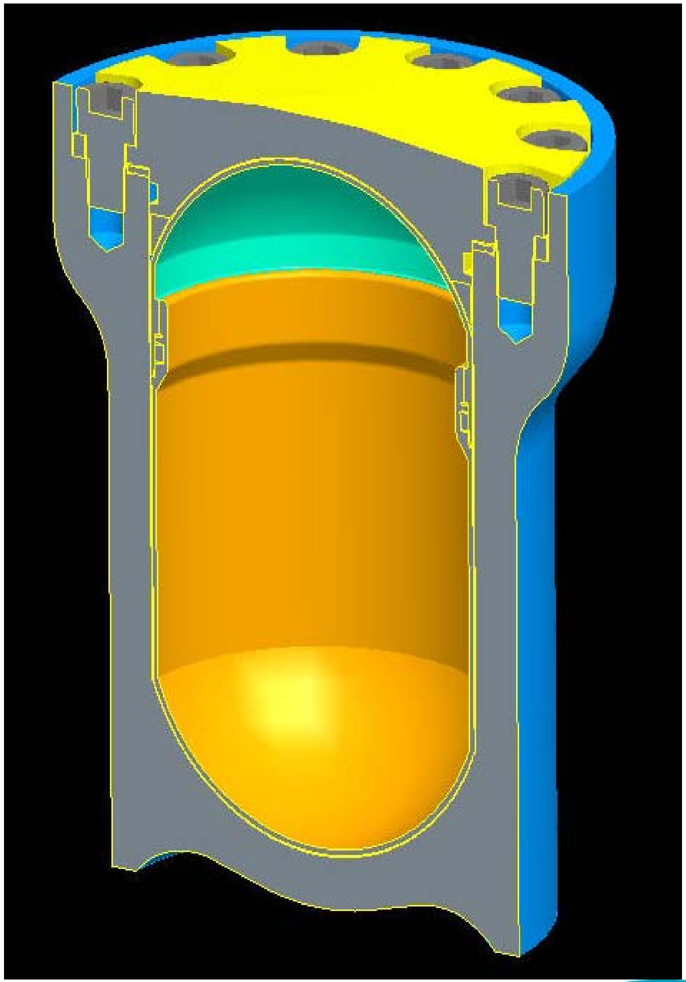
- **Pu-Be Composite samples**
  - **Samples are machined into disc (or other) forms from extracted samples**



TB-1 Containment Vessel
(Shown with T-Ampoule)

Attributes:

- PH13-8Mo stainless steel
- 12 fasteners
- Copper gasket
- 25 watts decay heat
- 4.6 lbs (2.1 kg) content weight
- 41.6 lbs (18.9 kg) maximum gross weight
- Maximum 1080˚F (582˚C) during air accident fire test
- TB-1 design unchanged for plutonium metals transport



Focus on T-Ampoule

Attributes:

- Eutectic prevention barrier
- Titanium alloy (Ti-6Al-4V)
- 2-piece construction
- Machined from solid bar stock
- No welding processes
- Threaded closure bore seal w/ elastomeric O-ring (for product quality)
- Minimum 0.060” wall thickness
- Contents include bulk Pu metal and sample containers supported by titanium structure
- Maximum gross weight of contents and T-Ampoule is 4.6 lbs (2.1 kg)

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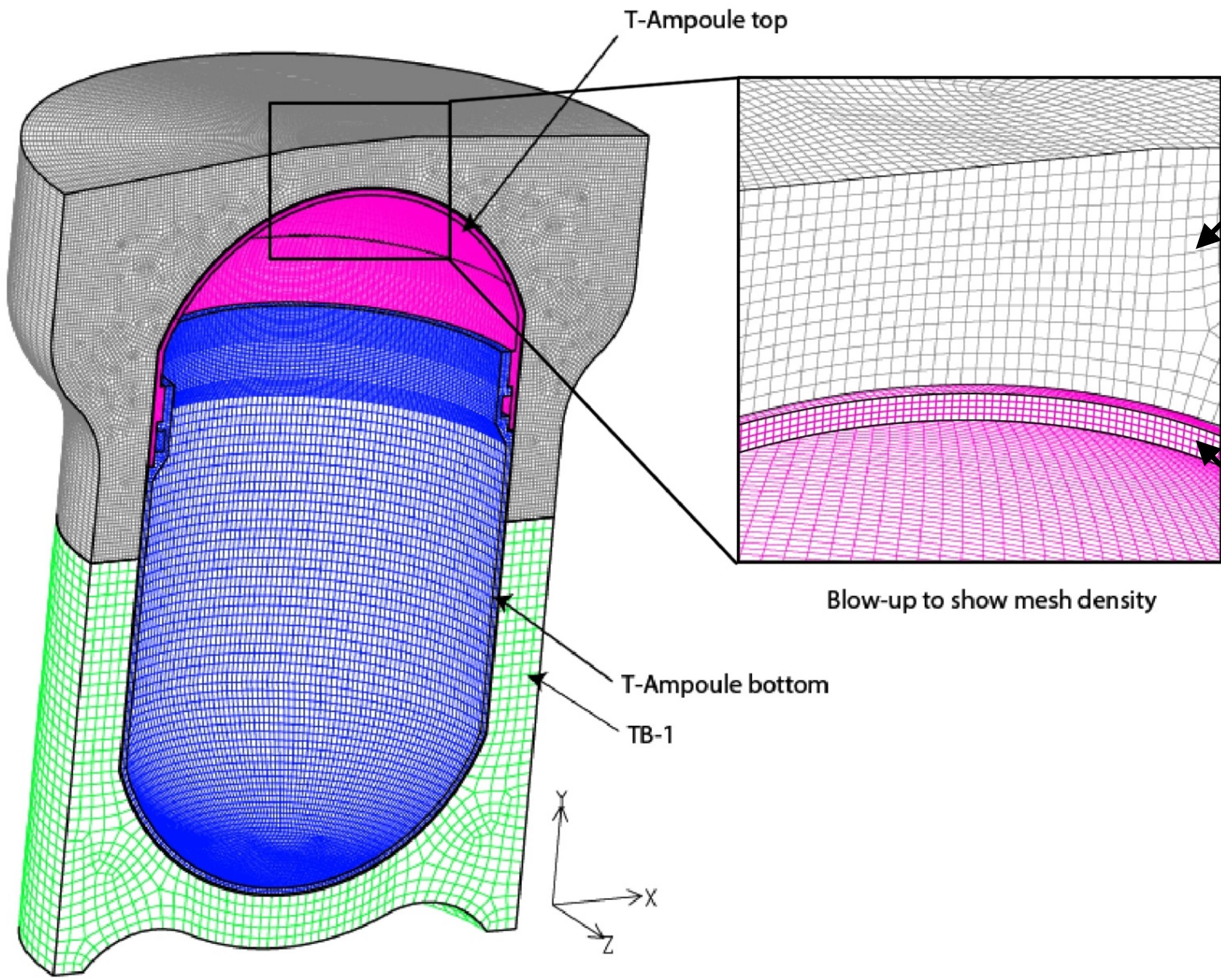
TB-1 and T-Ampoule PRONTO Model



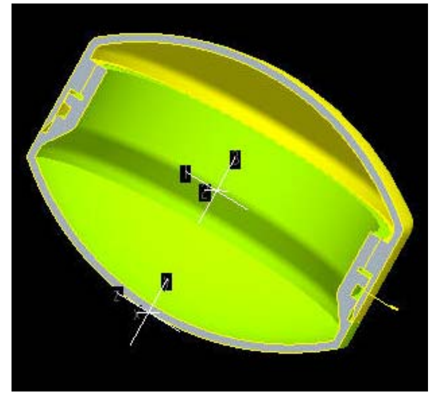
240,000 TB-1 elements

580,000 T-Ampoule elements

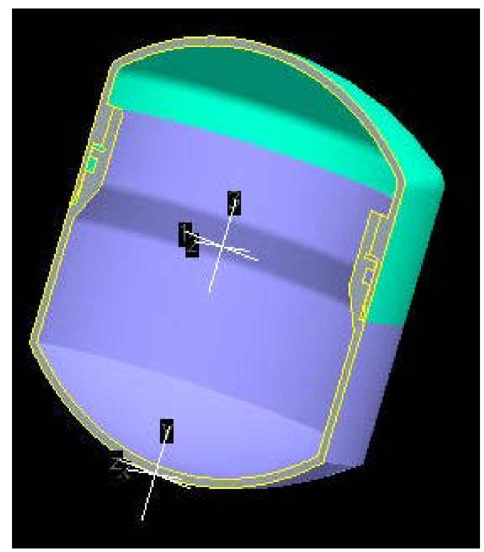
Sample Containers (SC)

Attributes:

- Titanium alloy (Ti-6Al-4V)
- 2-piece construction
- Machined from solid bar stock
- No welding processes
- Threaded closure w/ elastomeric O-ring (for product quality)
- Minimum 0.060" wall thickness
- Provides convenience container for single or multiple samples
- Samples placed in tantalum foil



SAMPLE CONTAINER SC-1



SAMPLE CONTAINER SC-2

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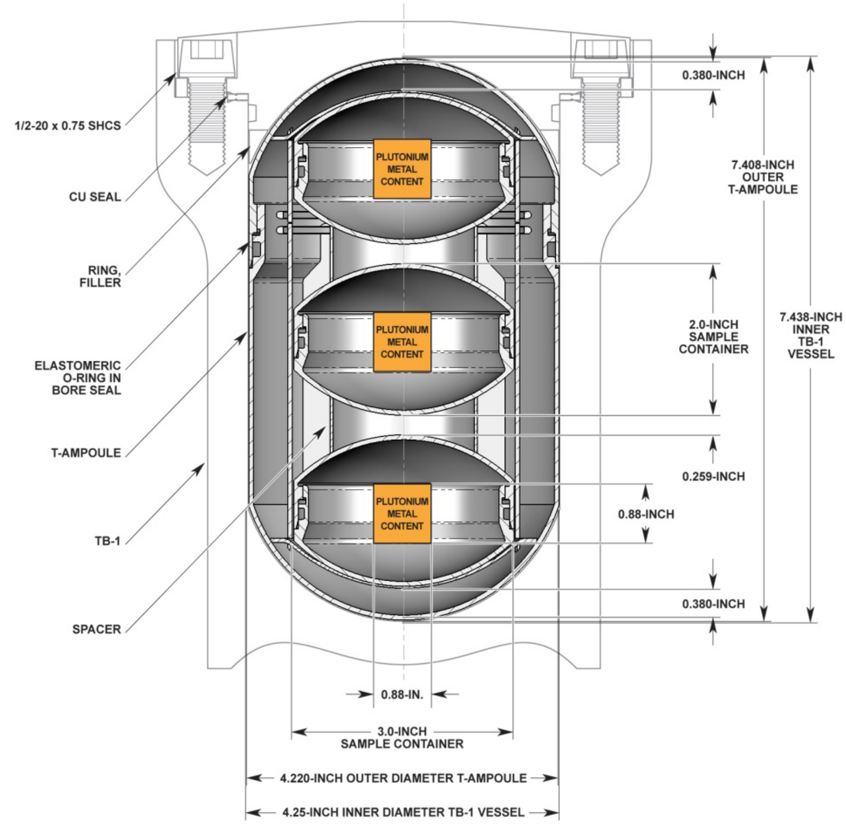
Sample Container Configuration

Attributes:

- **3 individual SC-1 per T-Ampoule**
  - **Pu Metal Allowances:**
    - **≤ 174 grams per SC-1**
    - **≤ 522 grams for 3 SC-1**
- **2 individual SC-2 per T-Ampoule**
  - **Pu metal allowances:**
    - **≤ 338 grams per SC-2**
    - **≤ 676 grams for 2 SC-2**
- **Titanium legs and bowl end supports serve as a position control component**



Three SC-1 Sample Containers in T-Ampoule

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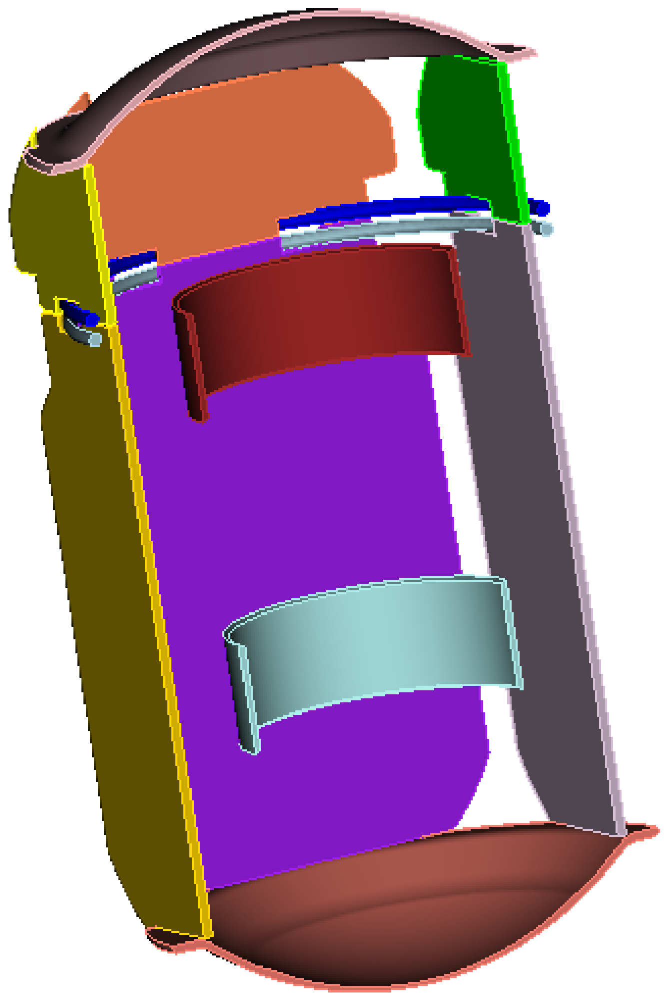
Sample Containers Cradle

Attributes:

- **Thin titanium "legs" and asymmetric edges can cause localized stress risers in contact with T-Ampoule**
- **Ti-6Al-4V construction (~0.060")**
- **No welding**



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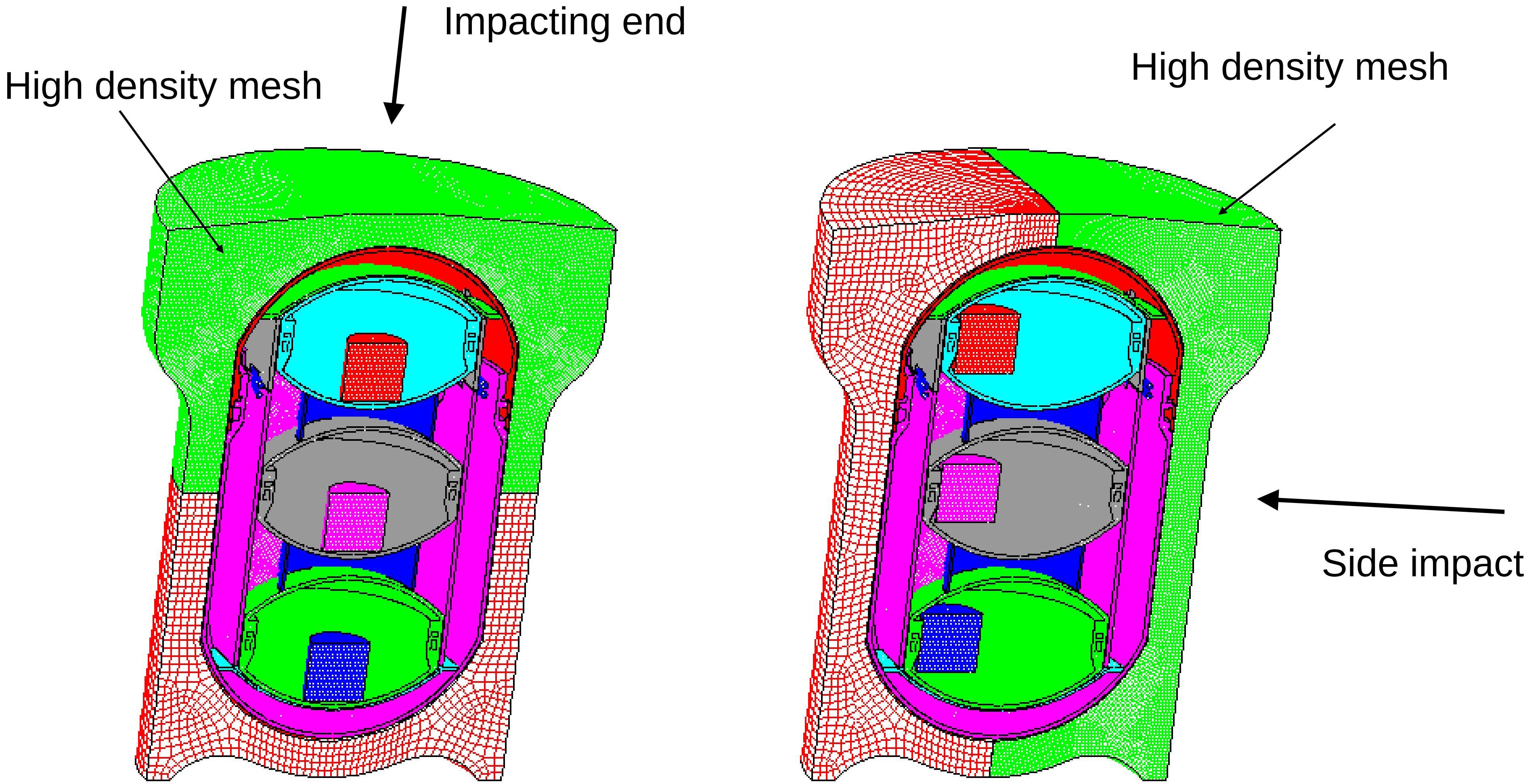
Three SC-1 Lumped Pu Contents Models



Assume worst-case locations of contents; no Ta foil

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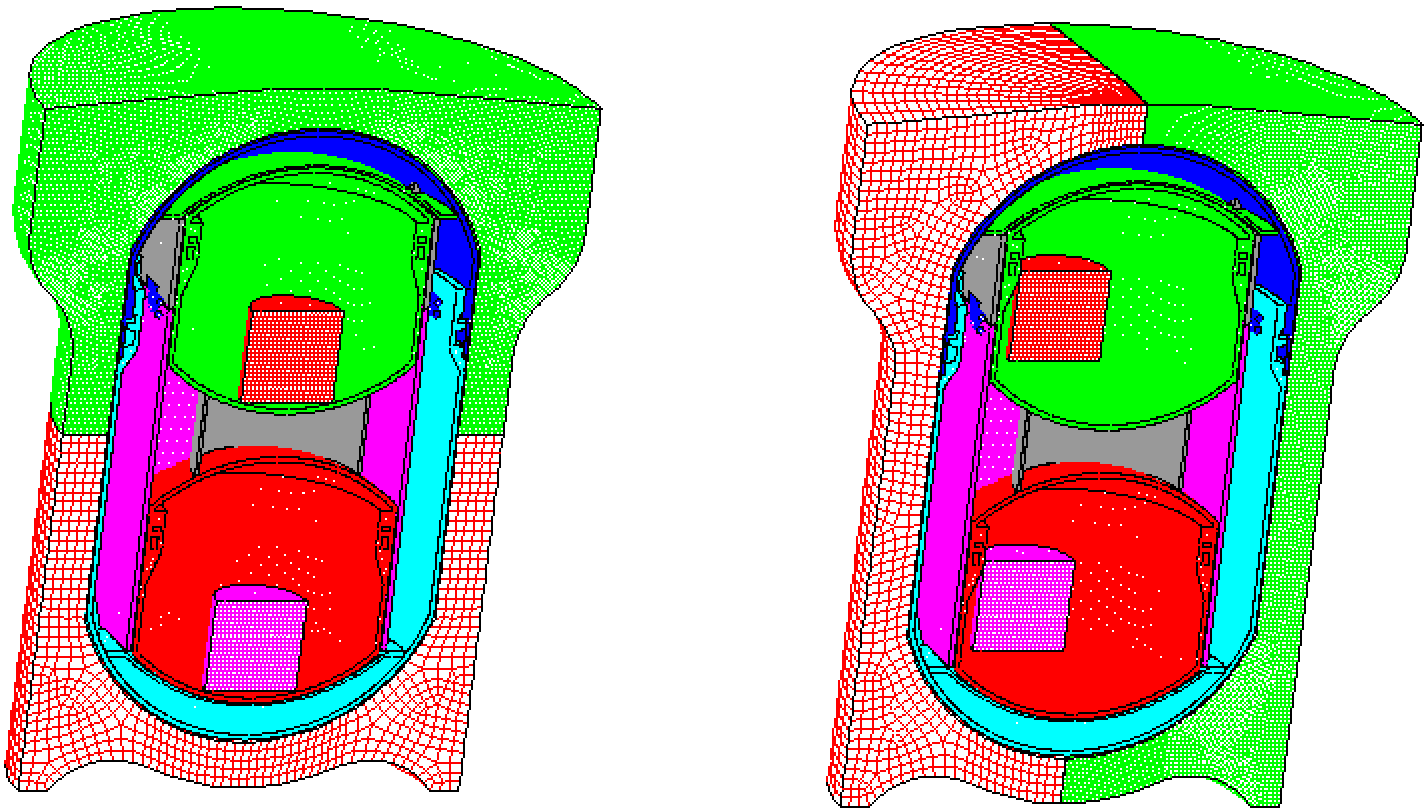
Two SC-2 Lumped Pu Contents Models



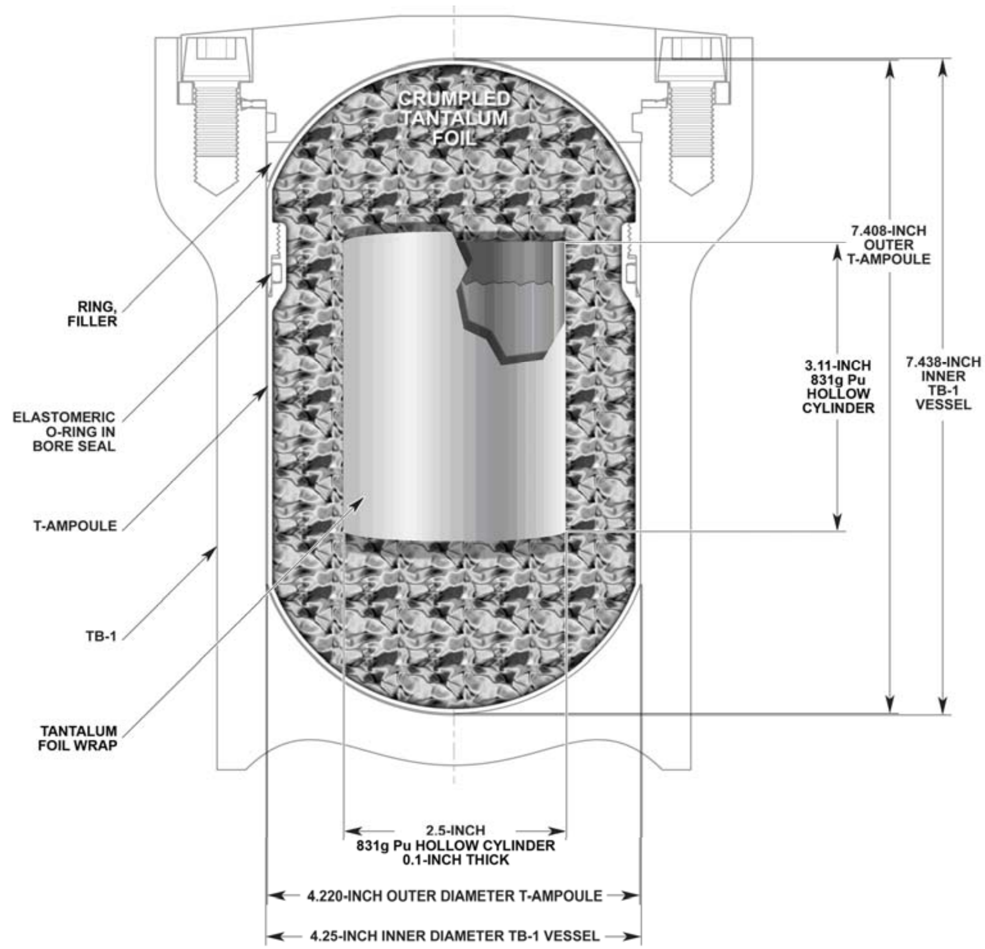
Note larger Pu cylinders with higher mass

Electro-Refined Plutonium Cylinder

Attributes:

- **Hollow Pu cylindrical shape allows softer deformable configuration to mitigate impact stresses**
- **Allowable Pu mass is 831 and 731 grams**
- **Pu metal cylinder wrapped in tantalum foil, no other supports are required.**

3 to 3.5 kg, 102 mm dia. x 13 mm wall x 51 mm length



831 gm Hollow Cylinder

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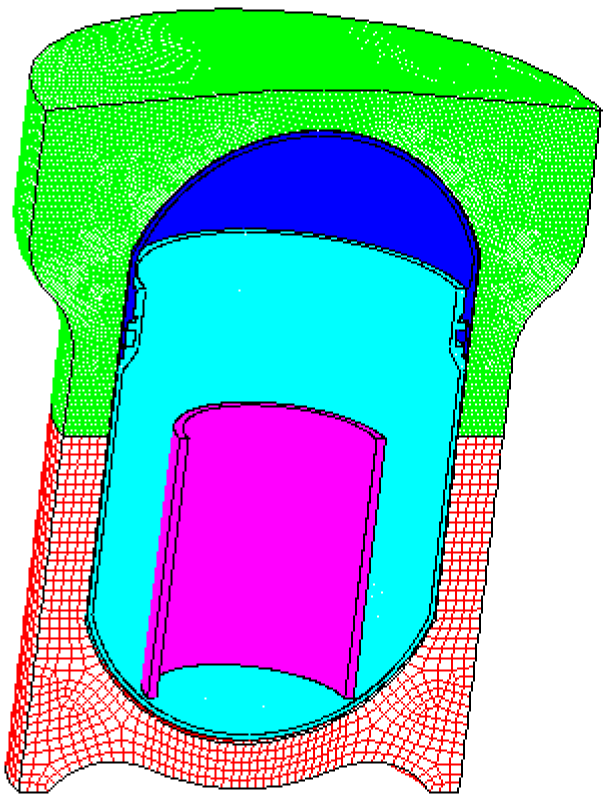
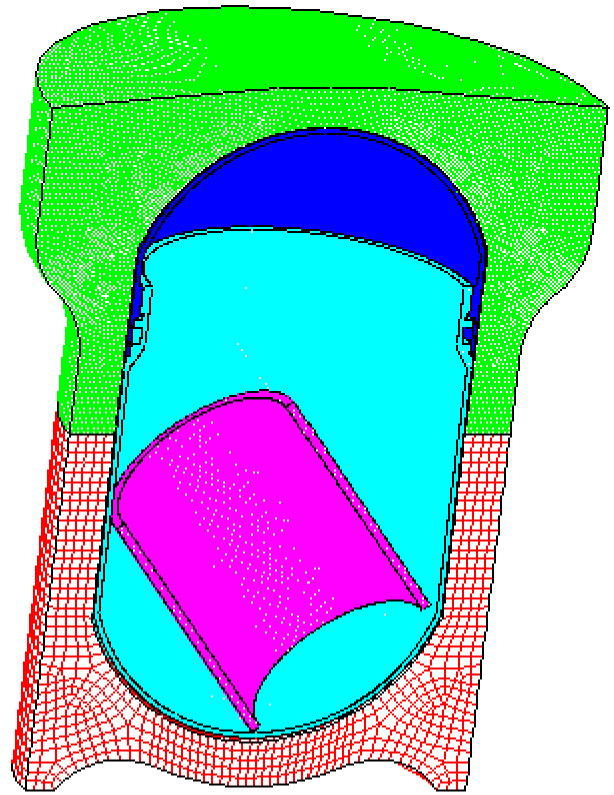
831 g ER Cylinder Models

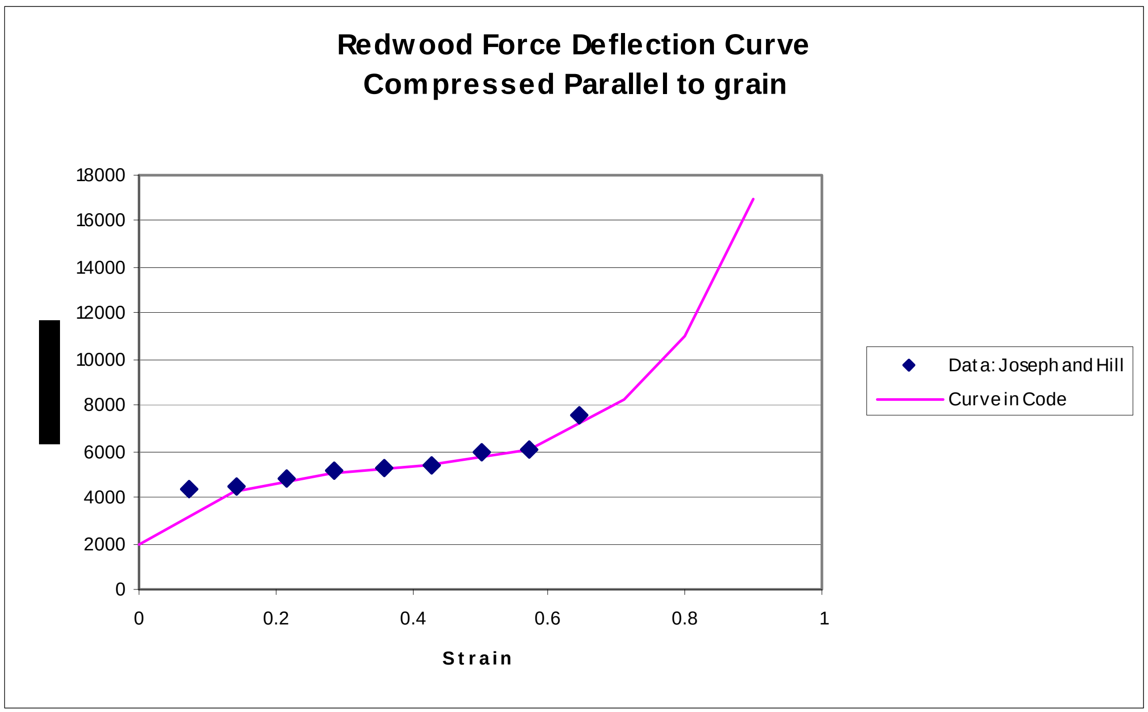




Assume worst-case locations of contents; no Ta foil

Previous Redwood Modeling

- **PRONTO orthotropic redwood constitutive model adapted from DYNA redwood model.**
- **Material properties originally tuned to match Hill and Johnson compression data (relatively constant stress until about 60% strain, where lockup begins):**



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Previous Redwood Modeling

- **Redwood model compared with more detailed Local Isotropic Global Orthotropic (LIGO) model.**

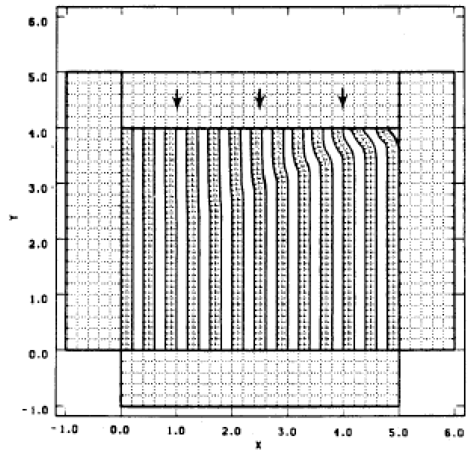

Figure 4.13. Deformed shape for loading parallel to the grain.

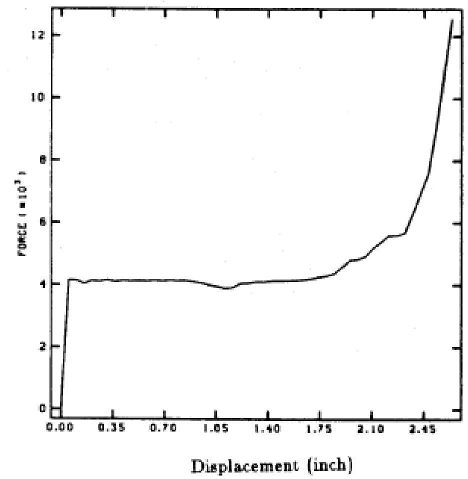

Figure 4.14. Compressive force versus crush, loading parallel to the grain.

Reference: Attaway, S.W., "A Local Isotropic Global Orthotropic Finite Element Technique for Modeling the Crush of Wood," SAND88-1449, 1988, SNL

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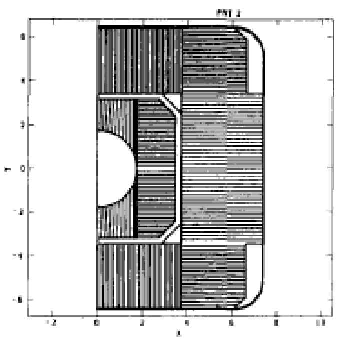
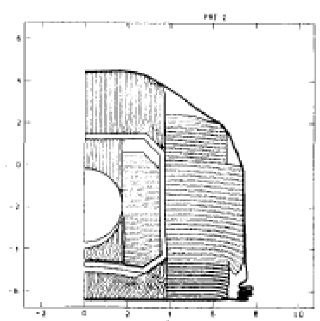
Previous Redwood Modeling

- **PRONTO wood crush model used to model PAT-2 air transport package, and validated against test results for end and side impacts.**



t = 0.0 ms



TIME 1.395E-3

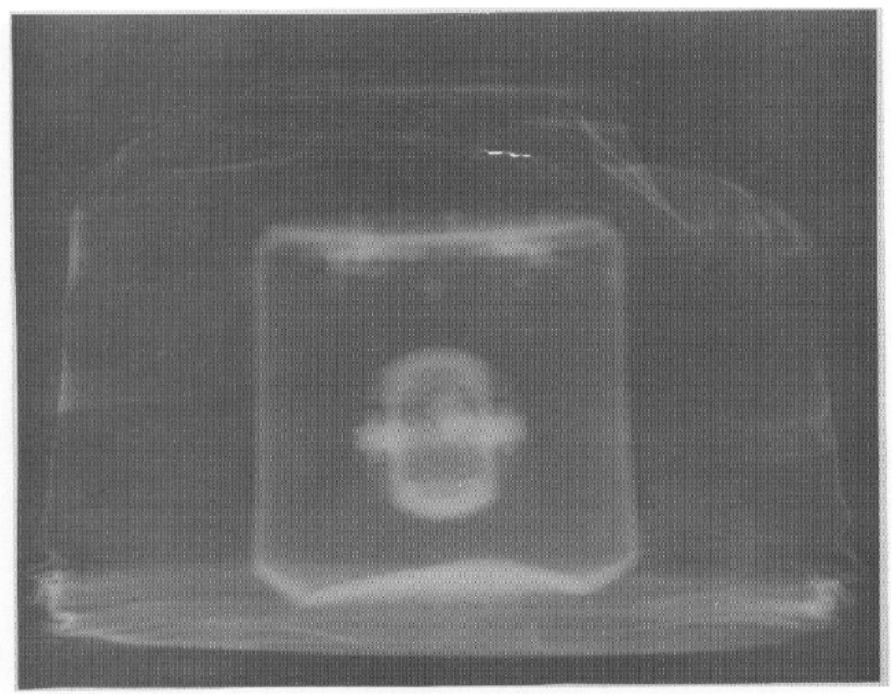
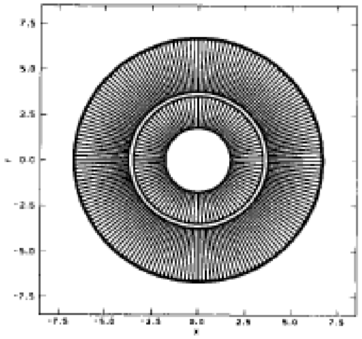
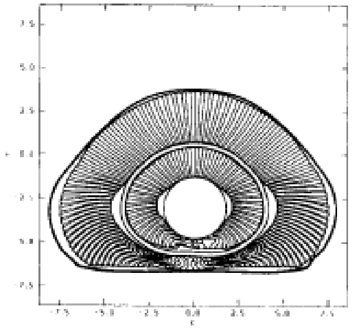


Figure 2.3. Radiograph of PAT 2 end-on impact at 438 ft/sec. The total package height after the impact was 11.5 inches. See the safety analysis report for PAT-2 [2] for a complete discription of this impact test.

Previous Redwood Modeling

- **PRONTO wood crush model used to model PAT-2 in side impacts.**


t = 0.0 ms


t = 2.0 ms

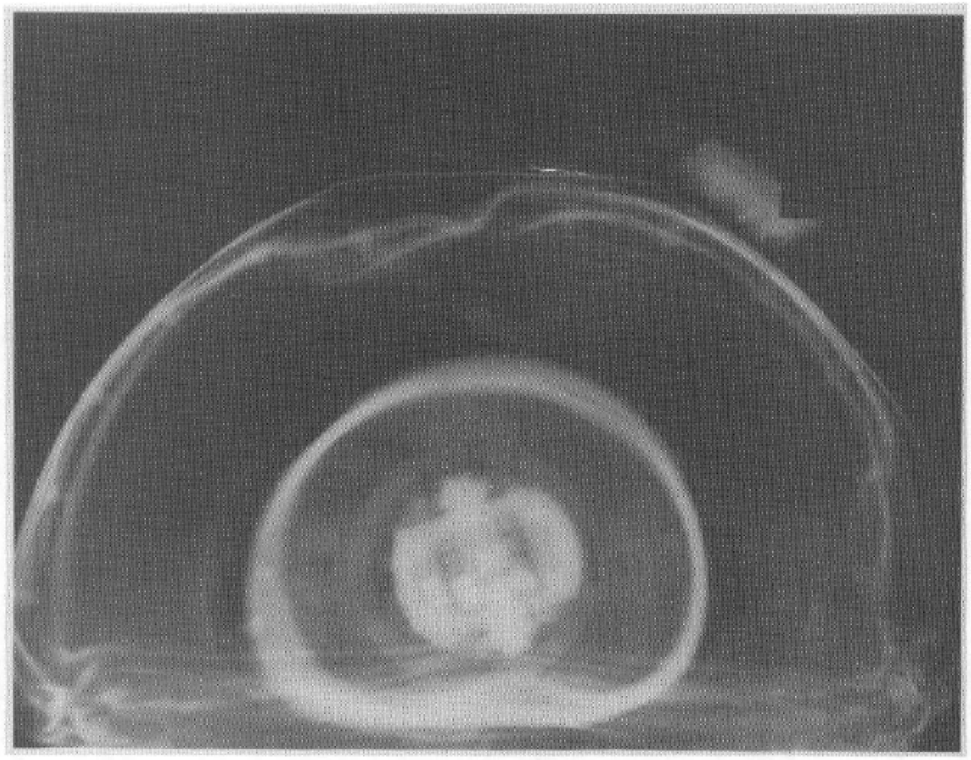


Figure 2.11. Radiograph of PAT 2 side-on impact at 433 ft/sec. The total package height after the impact was 11.25 inches. See the safety analysis report for PAT-2 [2] for a complete discription of this impact test.

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Previous Redwood Modeling

- Previous Reference: Attaway, S.W., "Structural Analyses of Plutonium Air Transport Packages," SAND89-474, 1989, SNL (Proprietary Information).

- Redwood model was also used to model very large proprietary Japanese air transport package, and compared with test results.

- Same redwood model used for PAT-1 analyses for SAR Addendum, and comparisons with 1970's certification tests were good.

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Current Redwood Modeling

- PAT-1 package: 8 circumferential blocks of grain-oriented redwood.
  - Model simplifies and uses 4 blocks, but oriented such that grain orientation aligned with impact; deformation results match tests
- Redwood orthotropic crush model properties listed in SAR Table 2-14.
- "Soft" PuO_2 powder simulated contents used to validate overall model against 445 ft/sec PAT-1 certification tests.
- Very similar overpack deformations (test vs. analysis) confirm that use of the previously-developed redwood model is likely producing similar loading on the TB-1 and its contents
  - A relatively short crush distance does not allow for multiple load path options
  - No yielding observed in tested or analyzed TB-1 provides additional confidence despite 11% KE "over-test"

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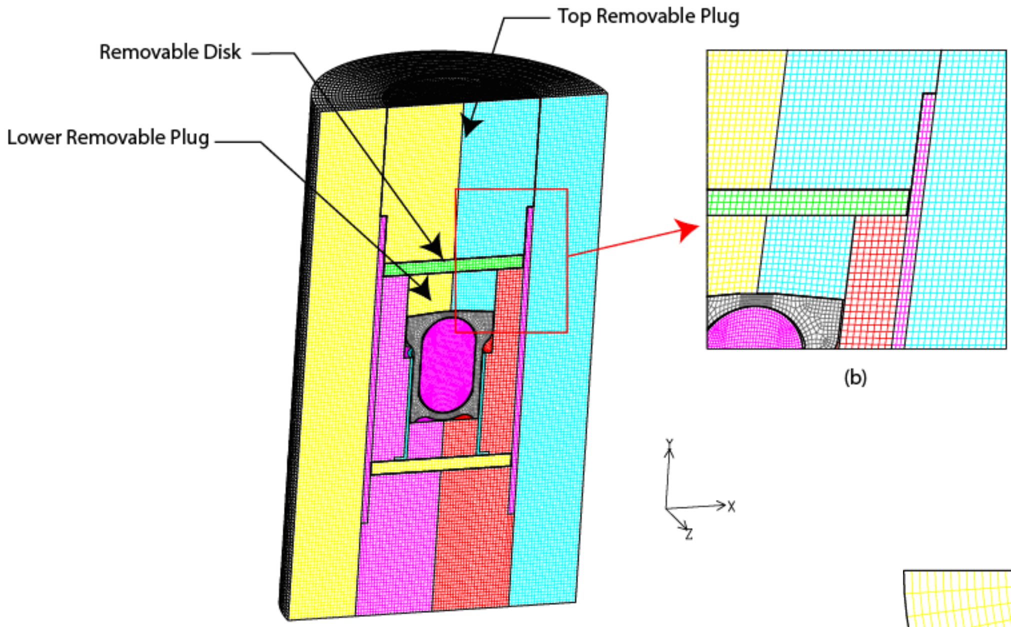
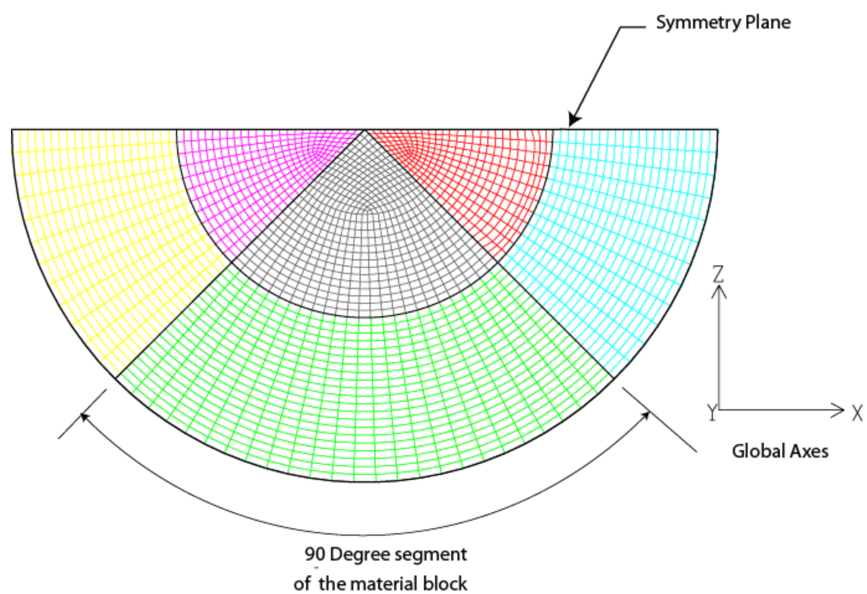
Current Redwood Modeling



(a) (b)



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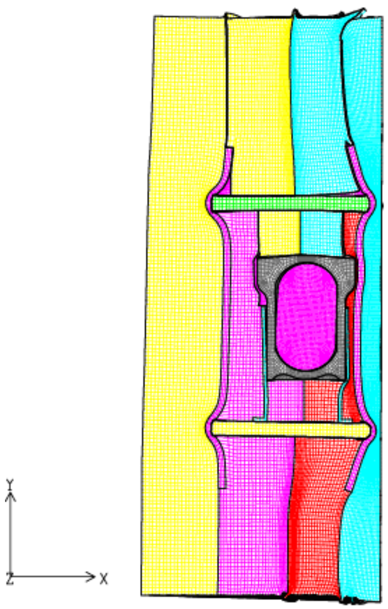
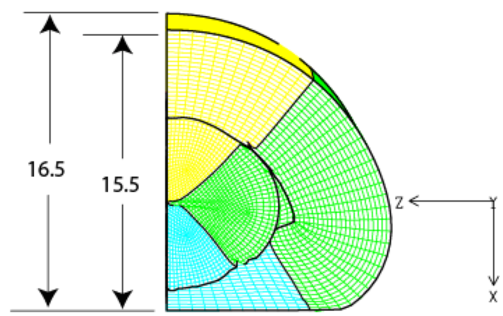
Redwood Model Validation: 445 ft/sec Side Impact

- **Overall deformation is very similar**



(a)



(b)

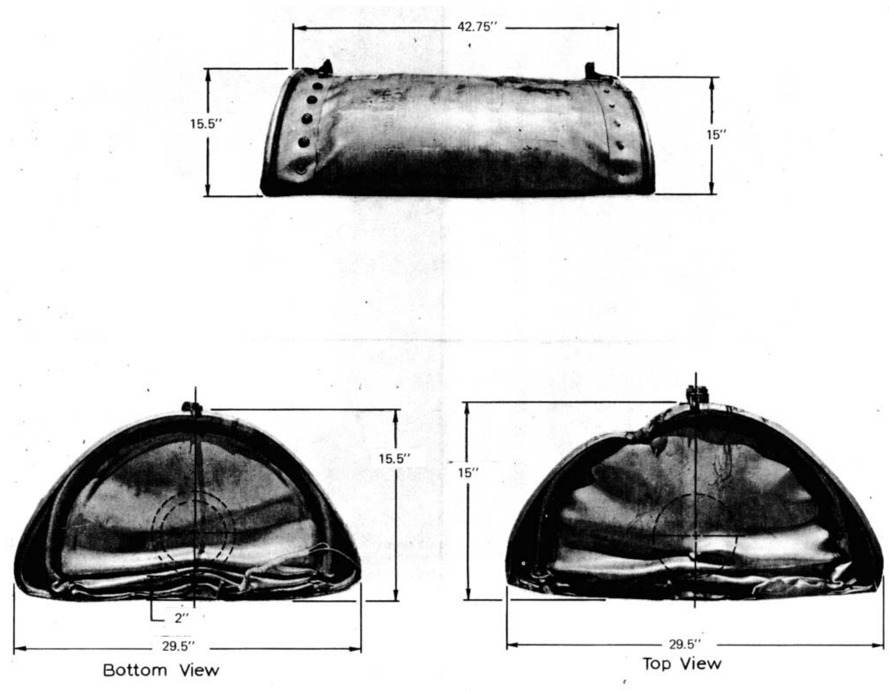


Figure 2.24 PAT-1 Dimensions Following 445-FPS Side Impact

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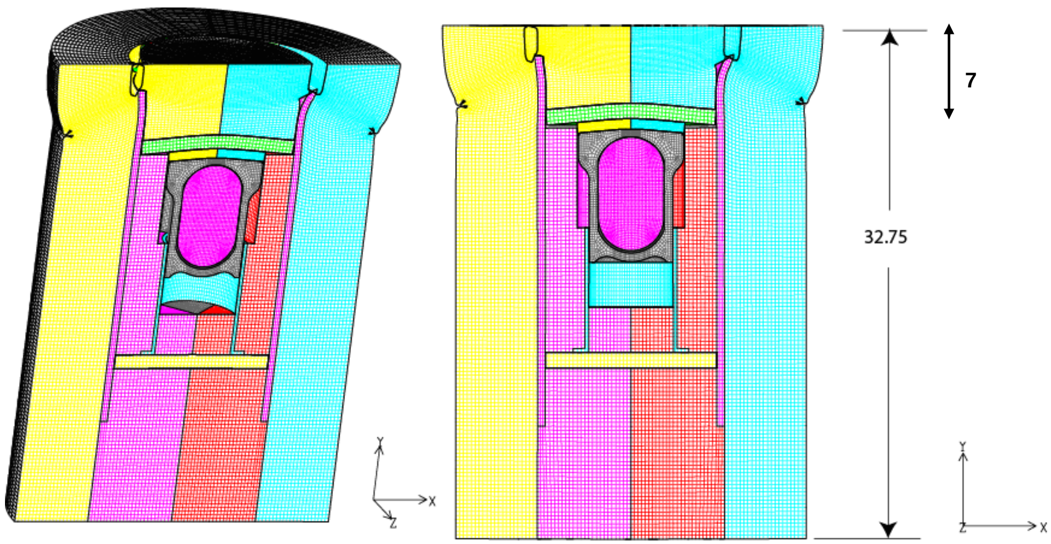
Redwood Model Validation: 445 ft/sec End Impact

- **Overall deformation is very similar**



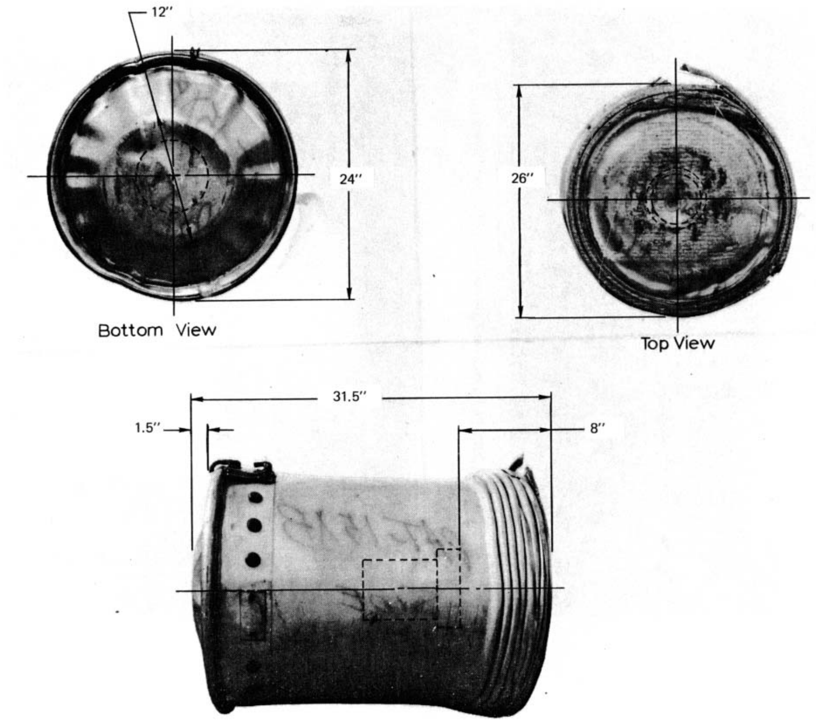
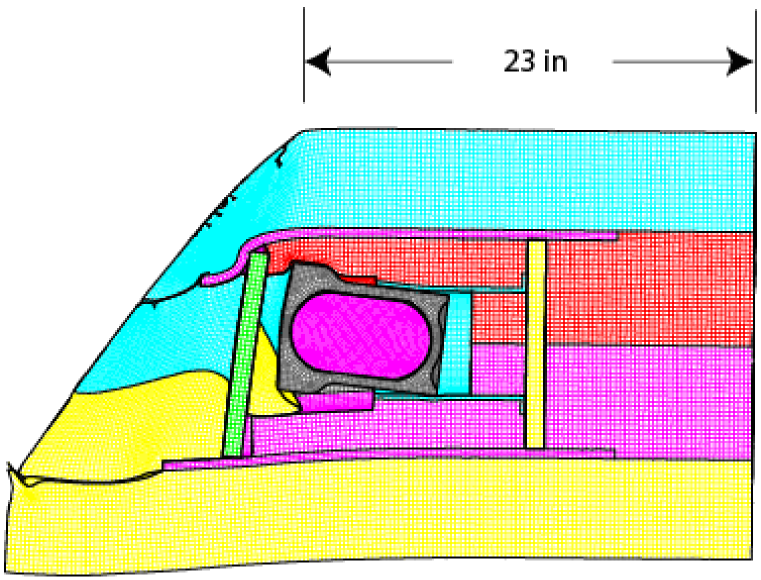


Figure 2.18 PAT-1 Dimensions Following 442-FPS Top End Impact

Redwood Model Validation: 445 ft/sec CGOC Impact

- Overall deformation is very similar



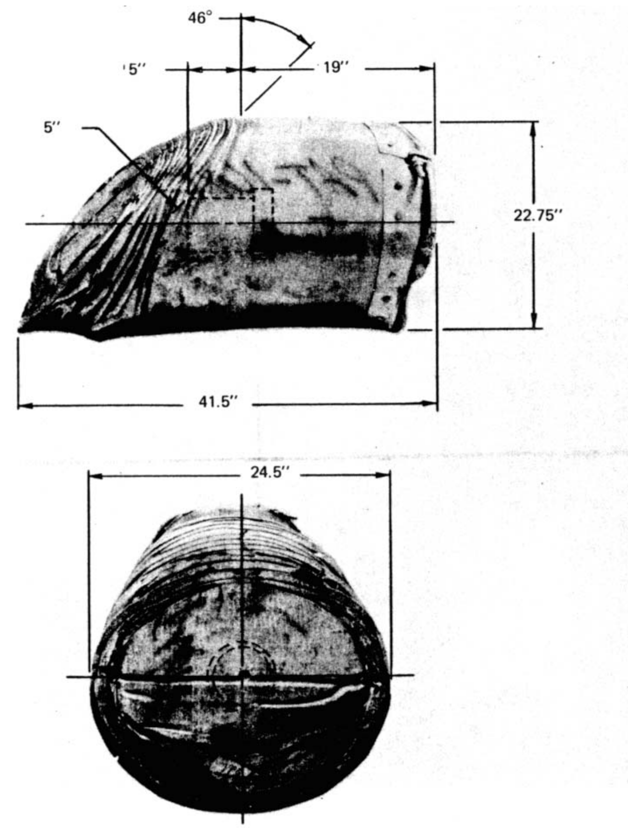


Figure 2.27 PAT-1 Dimensions Following 443-FPS Bottom Corner Impact

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FEA Model Conservatisms

- **Always assume contents in most damage-inducing location/orientation (velocity/sharpness).**
- **Ignore Ta foil slight energy absorber/load spreader.**
- **Pu, Be assumed infinitely plastic.**
- **Pu cylinders in sample containers are bounding.**
- **Be composite shape is bounding.**
- **ER cylinders assume strongest dimensions.**
- **Ductile crack propagation is not modeled in T-Amp; assume "failure" at ductile crack** *initiation.*

Acceptance Criteria

- **TB-1 containment vessel must**
  - **Meet the containment requirements of 10 CFR 71.64, special requirements for plutonium air shipments (<A_2/wk)**
    - **Shown through previous certification tests and current FEA demonstrating no plasticity in copper seal region**
  - **meet thru-wall ASME stress limits for NCT and HAC**
    - **NCT limits already accepted via previous certification tests**
    - **HAC dynamic crush is new requirement since original SAR; thru-thickness stress limits met via current FEAs**

- **T-Ampoule eutectic barrier maintains integrity.**

Methodology for Demonstrating That T-Ampoule Integrity Maintained

- **The integrity of the 0.060-inch-thick Ti-6Al-4V T-Ampoule eutectic barrier is shown to be maintained via:**
  - **Using a component test-generated "strain locus" (in stress triaxiality vs. equivalent plastic strain space) and an empirically-based analytical failure criterion called "Tearing Parameter".**
  - **Staying below critical Tearing Parameter avoids even the initiation of a ductile tear in the Ti-6Al-4V eutectic barrier.**

Tearing Parameter Failure Criterion

- **Over the last 40+ years, improvements to failure criteria have been made. The most successful criterion matching test data (including notched) very well is Tearing Parameter:**

$$TP = \int_0^{\bar{\varepsilon}_{pf}} \left\langle \frac{2\sigma_1}{3(\sigma_1 - \sigma_m)} \right\rangle^4 d\bar{\varepsilon}_p$$

- **This ductile Tearing Parameter has been successfully used for many years at Sandia to simulate ductile failure.**
  - **References: Bridgman, 1964; Brozzo, et al., 1972; Johnson & Cook, 1985; Wellman, et al., 1993; Dawson, et. al., 1998; Bao & Weirzbicki, 2003; Wellman, 2007.**

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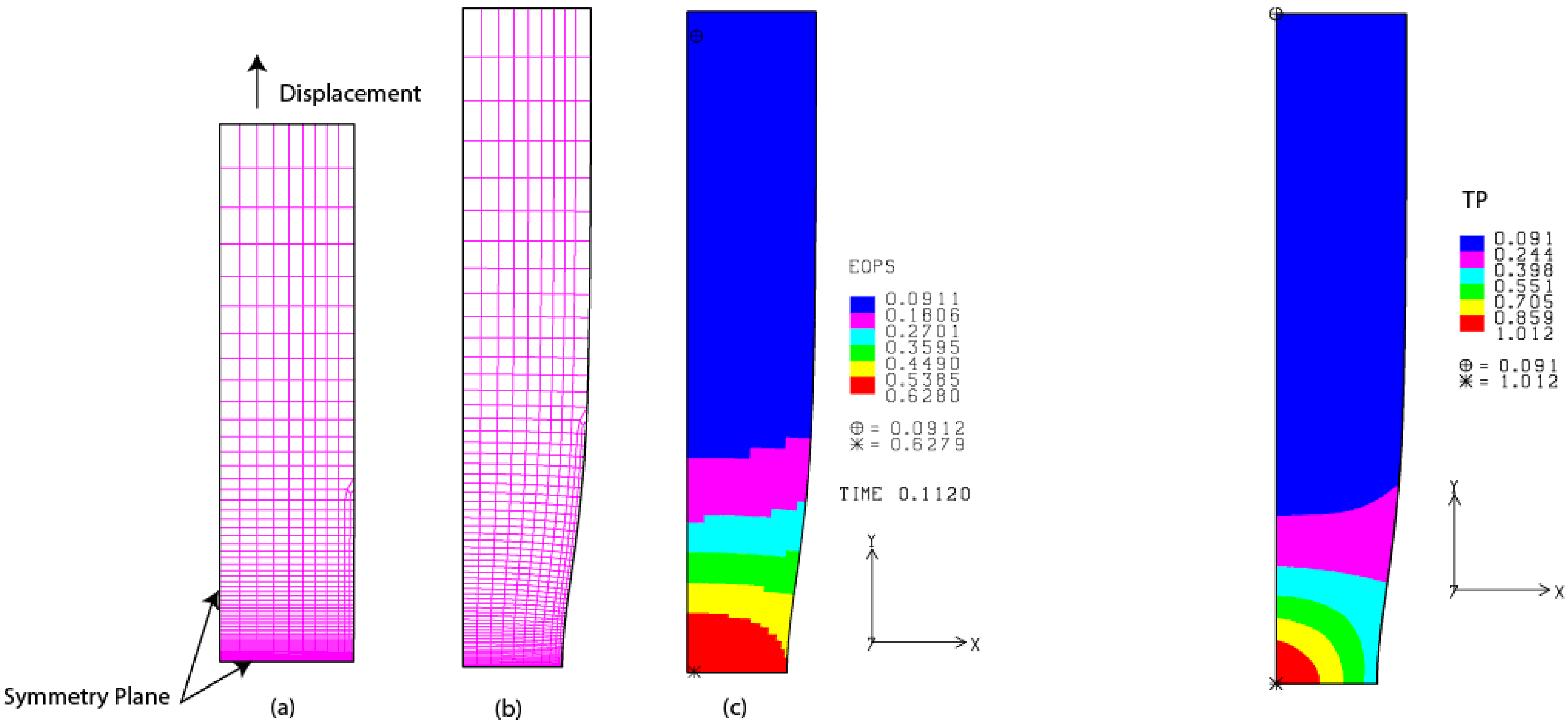
Critical Tearing Parameter

- **The critical value of TP is determined from the analysis of a tensile test to failure, for the Ti-6Al-4V T-Ampoule material.**
- **TP is evaluated using the computed stress state, with the EQPS at failure used as the upper integration limit.**
- **TP_{crit} = 1.012 for Ti-6Al-4V based on tensile tests.**
- **TP can be computed for elements in the T-Ampoule and compared to the critical value of 1.012.**

Analysis of Ti-6Al-4V Tensile Test



Uniaxial tension test produces 3-D stress and strain fields due to necking

Tearing Parameter Origins

- **Tearing Parameter is a minor variation on a 1972 failure indicator by Brozzo, DeLuca, & Rendina who built upon sheet forming work by Bridgman much earlier, who observed that ductility decreased with increasing positive (tensile) hydrostatic or mean stress and increased greatly with decreasing negative (compressive) hydrostatic stress.**

$$I = \int_0^{\bar{\varepsilon}_{pf}} \frac{2\sigma_{\max}}{3(\sigma_{\max} - \sigma_m)} d\bar{\varepsilon}_p \qquad TP = \int_0^{\bar{\varepsilon}_{pf}} \left\langle \frac{2\sigma_1}{3(\sigma_1 - \sigma_m)} \right\rangle^4 d\bar{\varepsilon}_p$$

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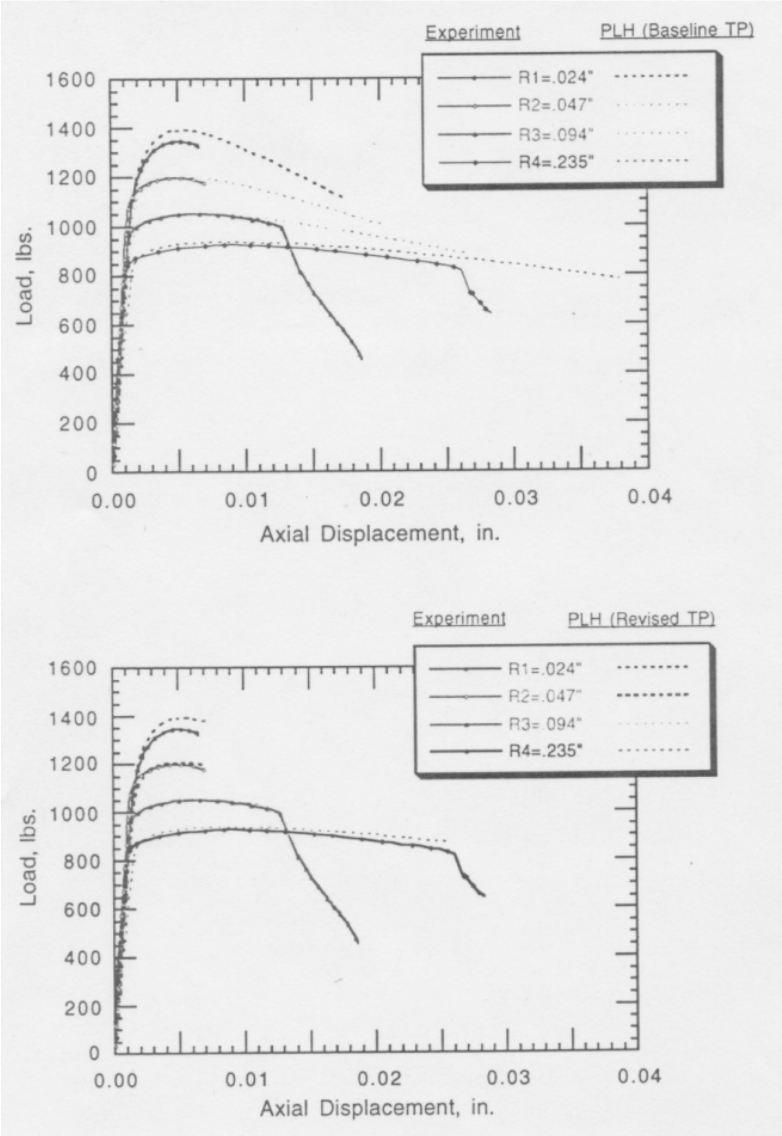
Improved Fit for Notched Tensile Specimens (Brozzo TP vs. Sandia TP)



Note the improved experiment vs. Power Law Hardening (analysis) results when using the revised TP. The failure point is captured more accurately.

Ductile Fracture Prediction Models

- **"A Comparison of Models for Ductile Fracture Prediction in Forging Processes," Zheng, et al. 2007, Computer Methods in Material Science:**
  - **Generally it is accepted that ductile damage criteria should take into account:**
    - **The deformation path, because the current stress/strain state is not enough to characterize the damage state**
    - **The hydrostatic or mean stress, σ_m, because ductility grows rapidly as σ_m decreases**
    - **An adequate ratio of stresses, namely the triaxiality stress ratio, σ_m / σ_{eq}, in which σ_{eq} is the equivalent or Mises stress, so that the general state of plasticity and fracture may be better described**
  - **Brozzo's original TP model is listed as working well in compression (Sandia's TP model also works well in tension and notched tension with the 4th power and Heaviside function, but is not widely published due to its primary application in weapons modeling)**

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Johnson-Cook Model (not used here)

- **Tensile equivalent flow stress:**

$$\sigma = [A + B(\varepsilon_p)^n][1 + C \ln \dot{\varepsilon}_p{}^*][1 - T^{*m}]$$

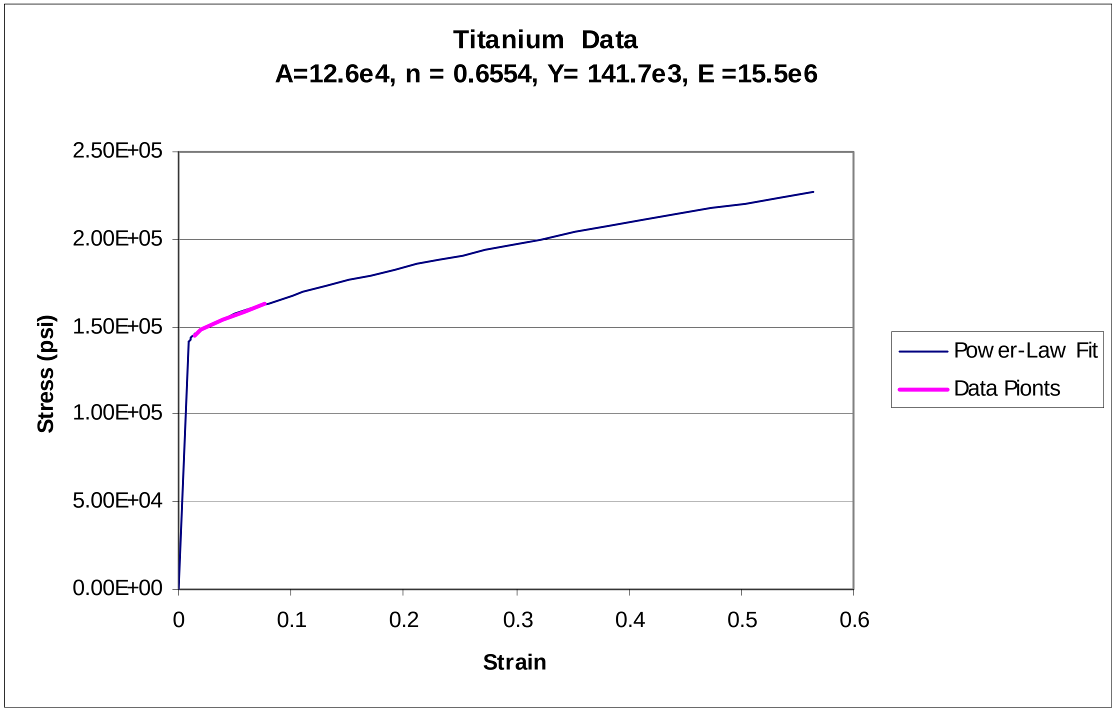
- **Fracture model:**

$$\varepsilon_f = [D_1 + D_2 \exp^{D_3 \sigma^*}][1 + D_4 \ln \dot{\varepsilon}_p{}^*][1 + D5T^*]$$

Ti Model Used

- **Power law hardening constitutive model used in SAR Addendum for Ti-6Al-4V (TP for failure):**

$$\sigma = \sigma_y + A\left(\varepsilon_p\right)^n \qquad TP = \int_0^{\bar{\varepsilon}_{pf}} \left\langle \frac{2\sigma_1}{3(\sigma_1 - \sigma_m)} \right\rangle^4 d\bar{\varepsilon}_p$$



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"Failure" Criteria: EQPS vs. TP

- **Equivalent Plastic Strain is a scalar "effective" plastic strain, much like von Mises stress is an "effective" stress (involving multiple components).**
- **It is common practice in non-linear FEA to compare EQPS values to "failure" levels of EQPS, which are most typically generated from uniaxial tension tests to failure.**

TP Comparisons with EQPS

- **The material property "elongation" is length-dependent due to localization at necking (instability), so "reduction in area" is more accurate.**

- **"Strain to failure" in uniaxial test is related to reduction in area:**
  - $\varepsilon_f = \ln A_o/A_f$
  - $\varepsilon_f = \ln 1/(1-q)$, **where q is "reduction in area"**

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TP Comparisons with EQPS (cont'd)

- **ASME Code lists minimum "elongation" for Grade 5 Ti-6Al-4V at 10%; "reduction in area" at 25%.**
  - **ε_f = ln 1/(1-q) = 29% for Ti-6-4 (ASME Code minimum mat'l)**

- **SAR Addendum lists minimum "elongation" for T-Ampoule Grade 5 Ti-6Al-4V at 10%; "reduction in area" at 20%.**
  - **ε_f = ln 1/(1-q) = 22% for Ti-6-4 (SAR minimum mat'l props)**

- **MatWeb lists "elongation" for Grade 5 Ti-6Al-4V at 14%; "reduction in area" at 36%.**
  - **ε_f = ln 1/(1-q) = 45% for Ti-6-4 (MatWeb mat'l data)**
  - **Our analyses showed EQPS >22-45%, but only at negative stress triaxialities where ductile fracture would not be initiated.**

TP Comparisons with EQPS (cont'd)

- **Unfortunately, EQPS is not a good indicator of fracture initiation, because it does NOT account for the stress state:**
  - **High stress triaxialities lead to fracture at reduced plastic strains.**
  - **Stress triaxialities below -1/3 lead to NO fracture at any plastic strain level.**
  - **Average stress triaxiality can be defined by:**

$$\left(\frac{\sigma_m}{\bar{\sigma}}\right)_{av} = \frac{1}{\varepsilon_f}\int_0^{\bar{\varepsilon}_f} \frac{\sigma_m(\bar{\varepsilon})}{\bar{\sigma}(\bar{\varepsilon})} d\varepsilon$$

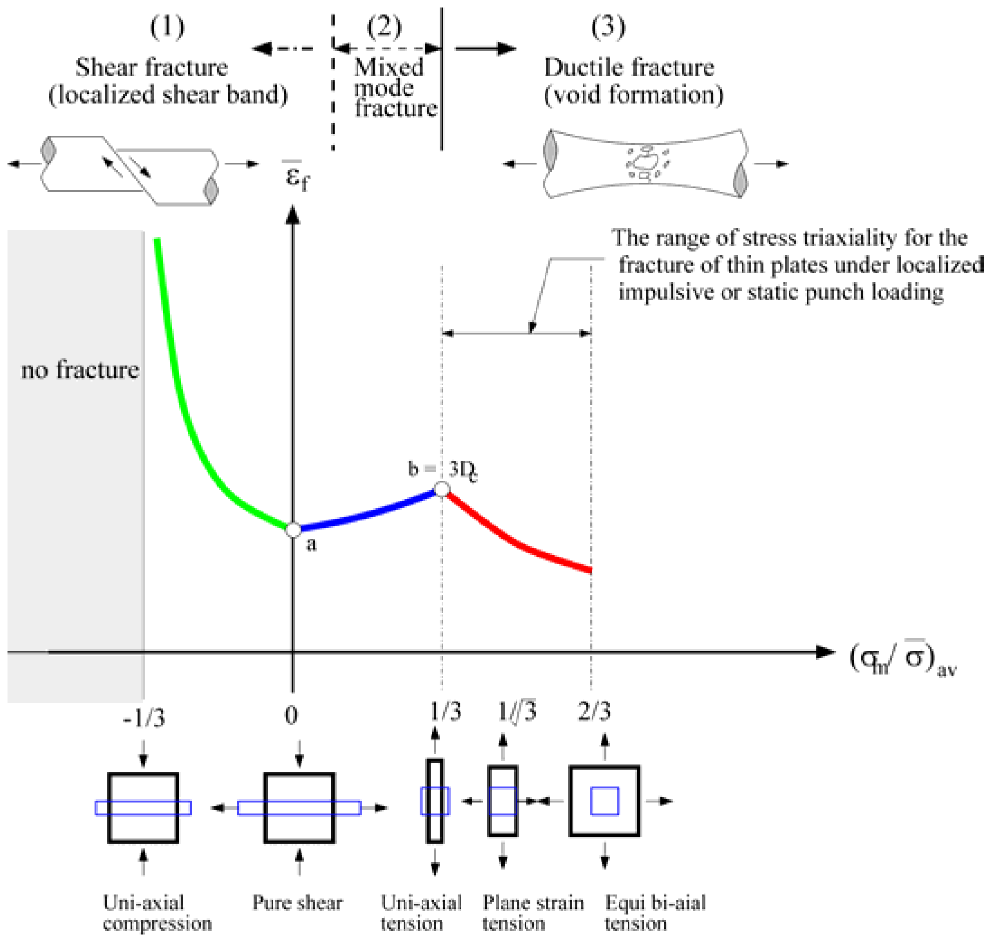
where $\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3$

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

Note that this stress triaxiality is 1/3 of ASME TF

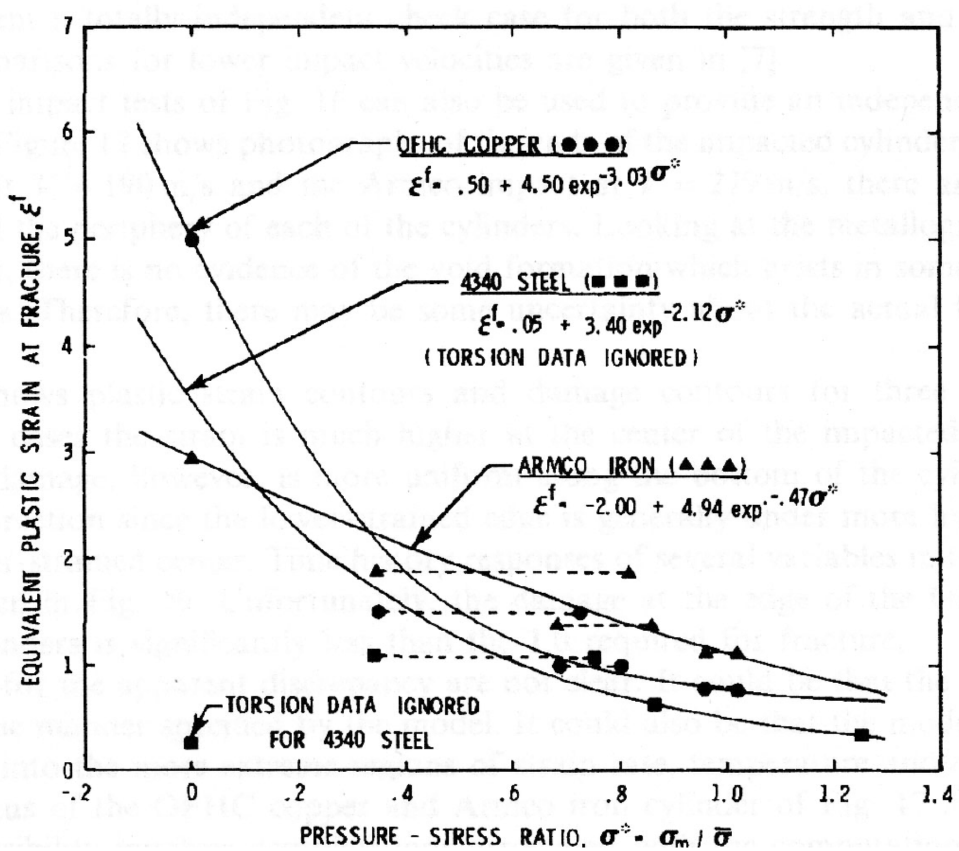
TP Comparisons with EQPS (cont'd)

- **Bao & Wierzbicki data for aluminum:**



TP Comparisons with EQPS (cont'd)

- **Johnson and Cook data for copper, steel, iron:**



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TP Comparisons with EQPS (cont'd)

- Tearing Parameter is a much more accurate indicator of ductile fracture initiation since it takes into account the stress state, and more rapidly accumulates "damage" in effectively high positive stress triaxialities.
- Conversely, when the maximum principal stress is negative (corresponding to negative stress triaxiality), TP does not accumulate value or damage.

$$TP = \int_0^{\bar{\varepsilon}_{pf}} \left\langle \frac{2\sigma_1}{3(\sigma_1 - \sigma_m)} \right\rangle^4 d\bar{\varepsilon}_p$$

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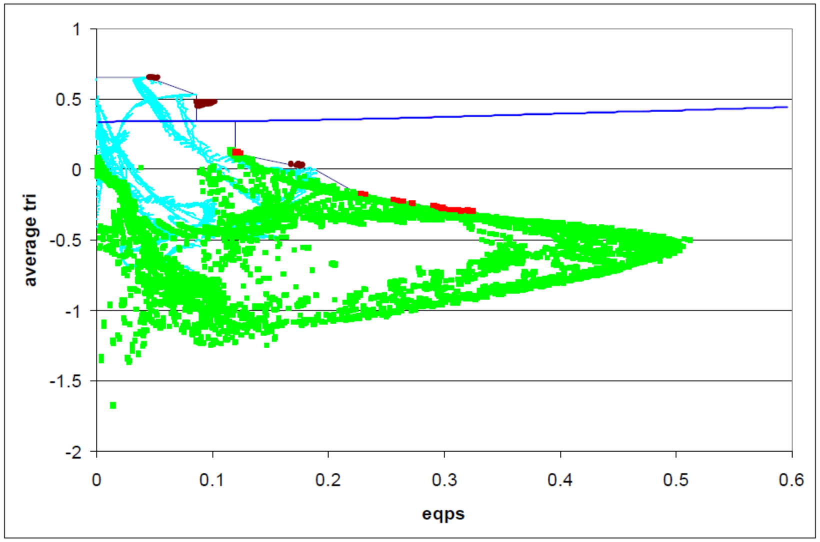
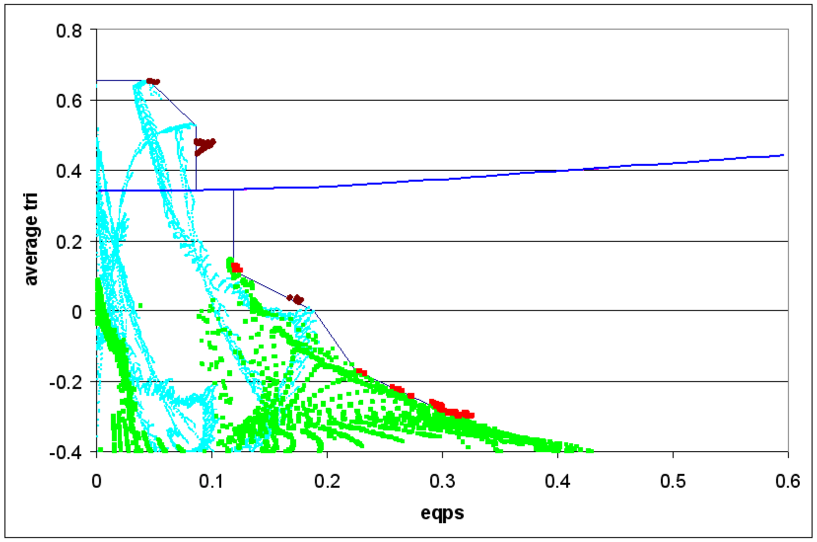
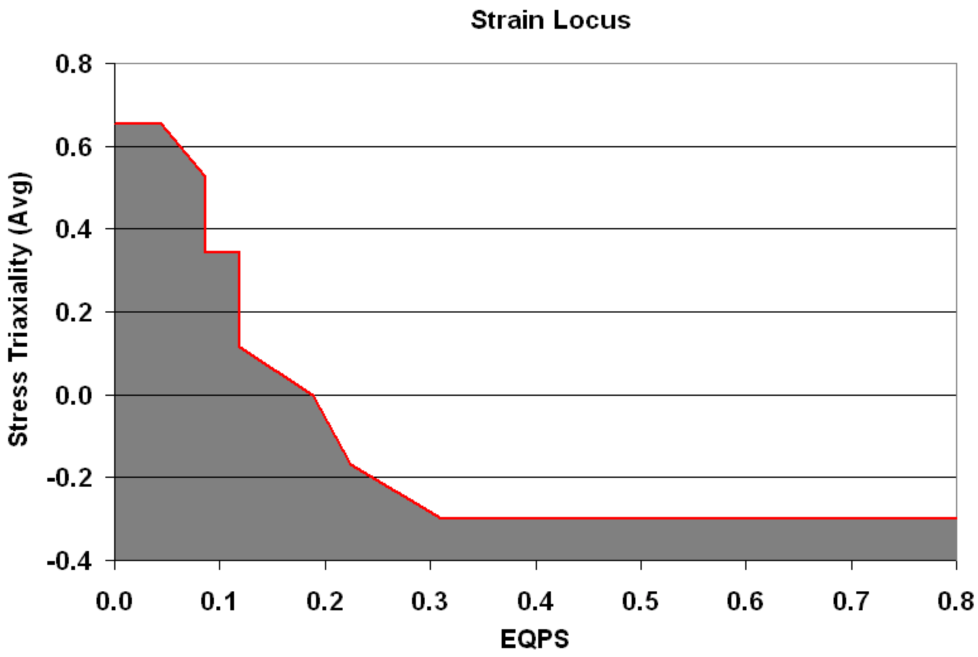
Purpose of Strain Locus

- **Bao & Wierzbicki developed an empirical "failure" envelope in the EQPS vs. stress triaxiality space for 2024 aluminum (work for the auto and aluminum manufacturing industries).**
- **SNL, after consulting with NRC, believed that developing an "acceptable" locus of stress triaxiality vs. EQPS points experimentally for Ti-6Al-4V would provide additional confidence to the NRC that structural integrity of the T-Ampoule would be maintained in accident conditions.**

Strain Locus







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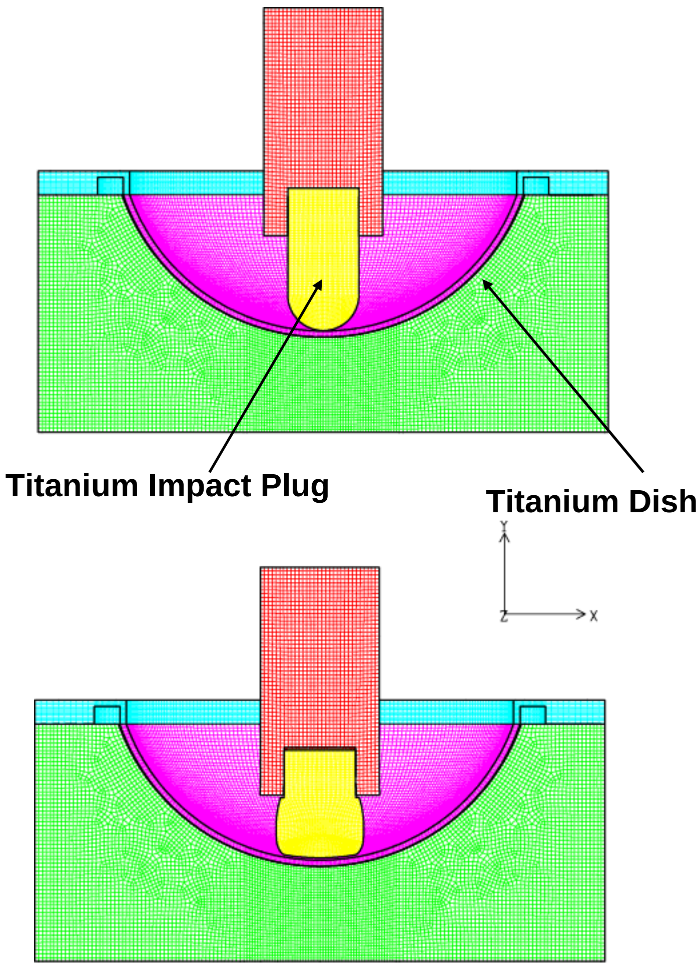
“Acceptable” Strain Locus

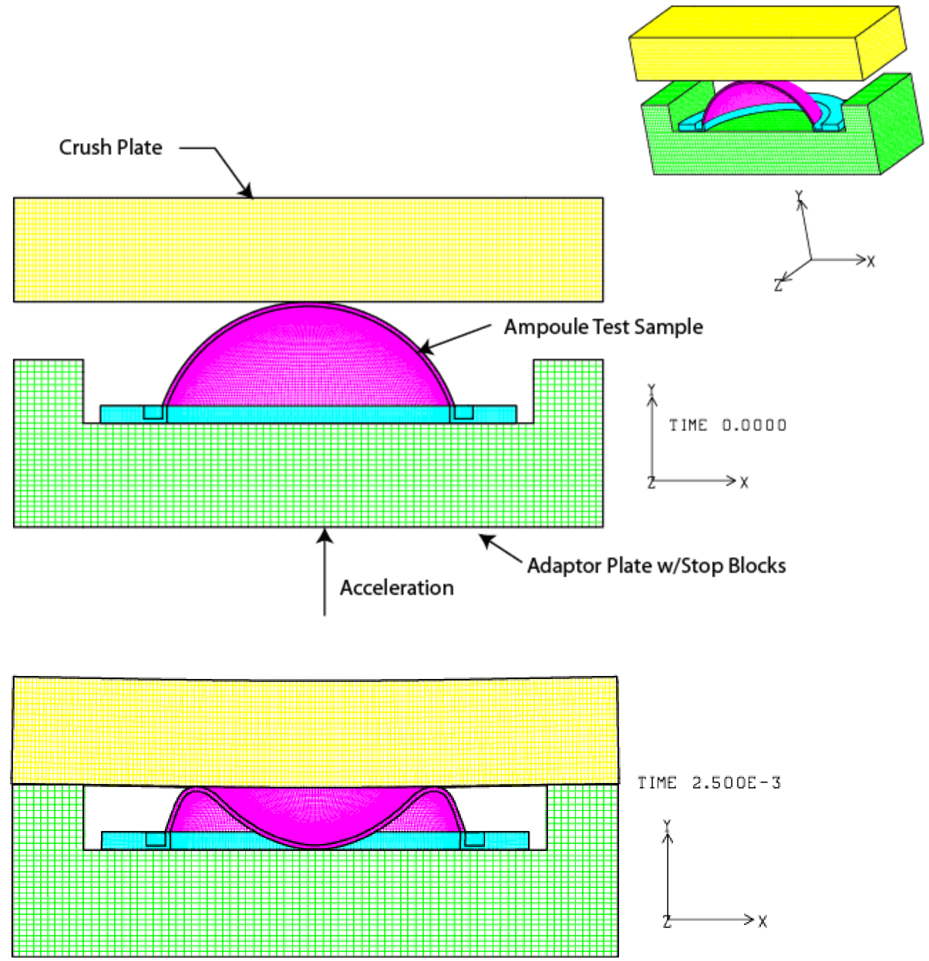
- **Velocity limitations with the test apparatus led to a relatively few elements exceeding the tested strain locus, but this did NOT mean failure or ductile tearing occurred in the eutectic barrier.**
- **In order to provide additional confidence to the NRC that the eutectic barrier had no initiation of ductile tearing, a true failure criterion was also used.**
- **Of the two most common failure criteria for ductile materials (Johnson-Cook, and Tearing Parameter), TP was chosen because of Sandia’s previous success using it to match test-to-failure data in varying 3-D stress states.**

Component Testing and Strain Rates

- **A hemispherical section of the 0.060-inch-thick Ti-6Al-4V T-Ampoule, backed by a hemispherical section of the PH13-8-Mo TB-1 containment vessel lid were fabricated as targets for brass, tungsten and Ti impactors, simulating Pu contents.**
- **Horizontal actuator impact tests at 200 ft/sec were performed to generate a locus of stress triaxiality vs EQPS (from analyses of the tests).**
- **No failure (tearing of T-Ampoule) was observed in any tests, whose strain rates enveloped those occurring in the air transport tests.**

Component Testing to Generate Stress Triaxiality vs. EQPS Locus





Component Tests: Real Time 200 ft/sec Ti Impactor

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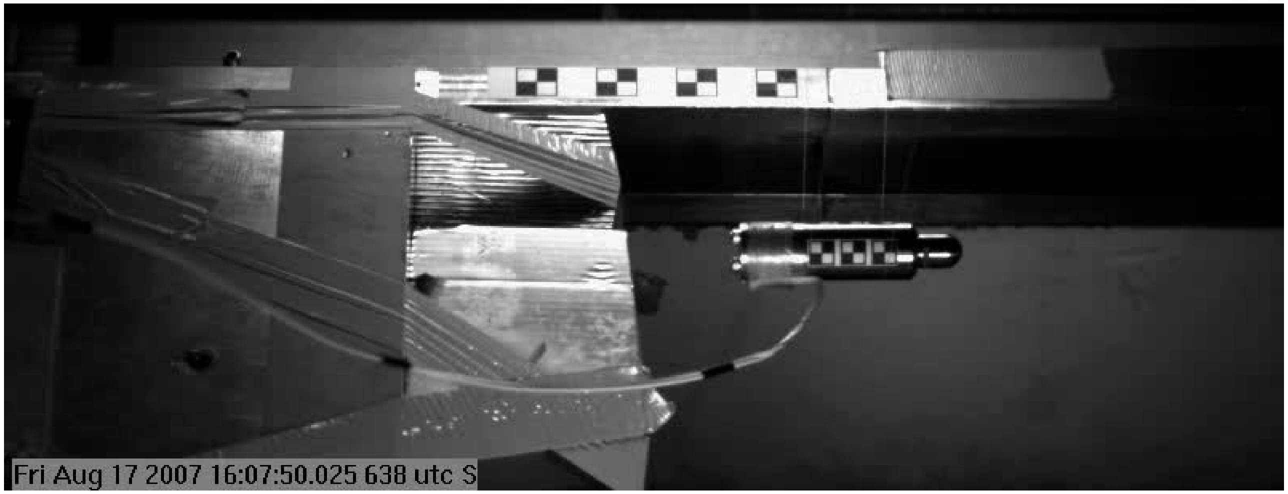
Component Tests:
Slow Motion 200 ft/sec Ti Impactor



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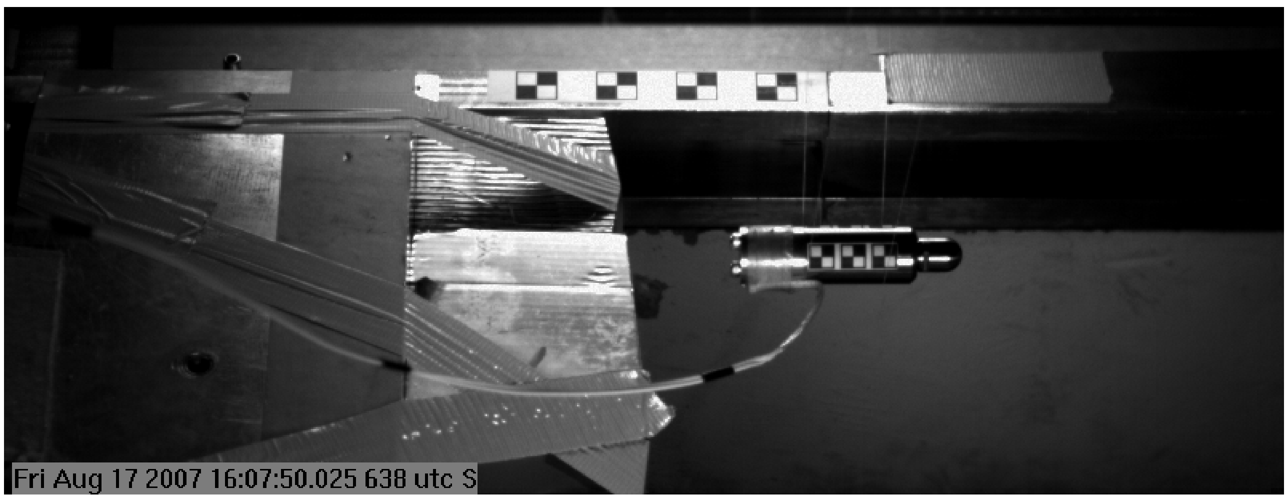
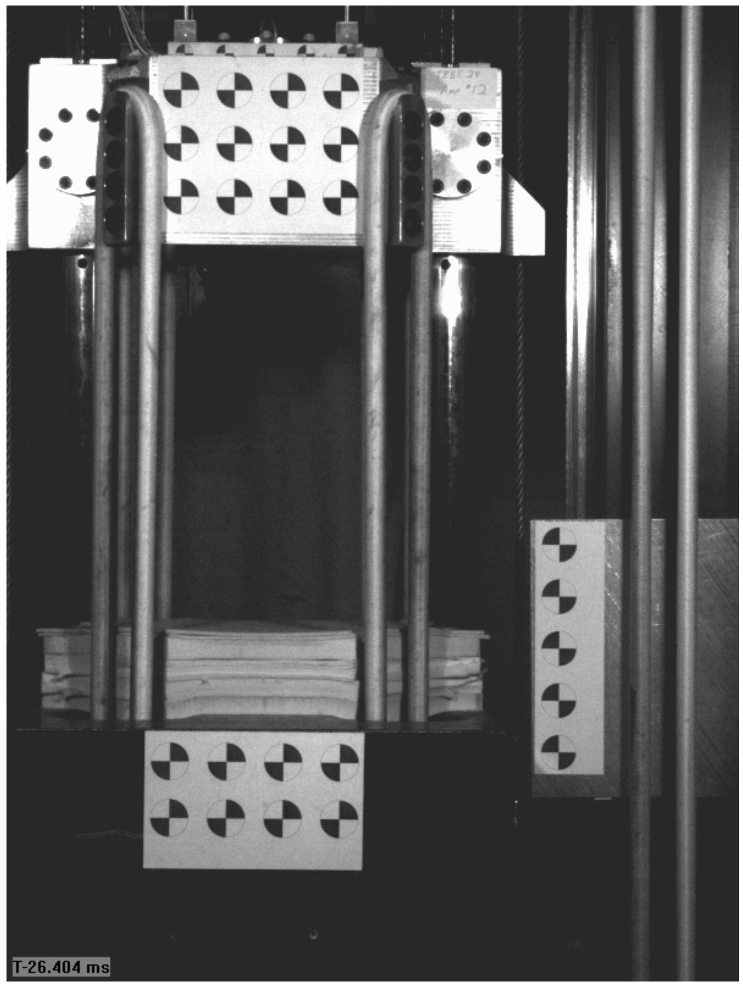
Component Tests:
Slower Motion 200 ft/sec Ti Impactor



Component Tests: Slow Motion Drop Table (Bowl Inversion)



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Strain Rate Comparisons for Component Tests and Air Transport Impacts

Run	Max Strain Rate	Min Strain Rate
Impact Test (dish)	1.19E+05	-1.18E+05
Impact Test (plug)	5.40E+04	-4.11E+04
Drop Table	1.78E+03	-2.73E+03
HSRun2	7.42E+04	-6.30E+04
HSRun3	1.71E+04	-2.99E+04
HSRun4	4.72E+04	-9.04E+04
HSRun5	1.21E+04	-1.70E+04
HSRun7	5.92E+04	-8.07E+04
HSRun8	2.20E+04	-2.47E+04
HSRun9	4.26E+04	-9.18E+04
HSRun10	4.14E+04	-5.15E+04
HSRun12	3.66E+04	-2.05E+04
HSRun13	4.98E+04	-4.06E+04
HSRun17	3.92E+04	-3.63E+04
HSRun18	8.94E+04	-1.08E+05
HSRun22	3.15E+04	-2.75E+04
HSRun23	1.84E+04	-2.14E+04
HSRun26	9.75E+04	-7.59E+04
HSRun27	4.06E+04	-5.30E+04

NOTE: All strain rates in the air transport impacts were bounded by the strain rates observed in the impact test and drop table test.

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Strain Rate Sensitivity of Ti-6Al-4V

- Very little data exists on failure testing of Ti-6Al-4V at higher strain rates.
- At lower strain rates, the yield stress hardens slightly, but ductility is unaffected (graph from Aerospace Structural Metals Handbook).

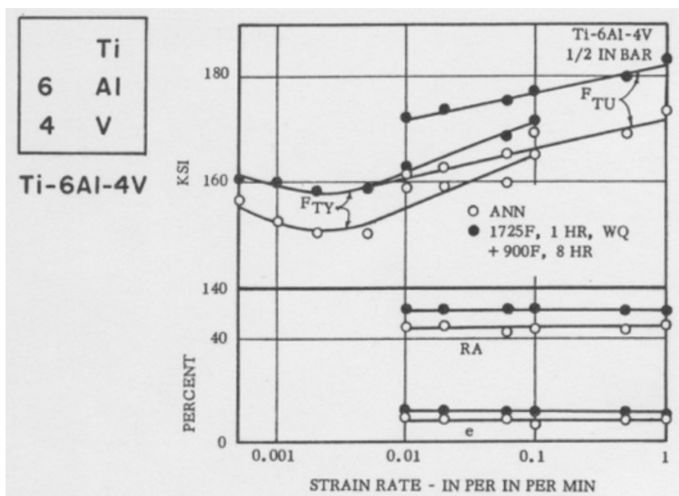

FIG. 3.0219 EFFECT OF STRAIN RATE ON TENSILE PROPERTIES OF ANNEALED AND AGED BAR (13, p. 9)

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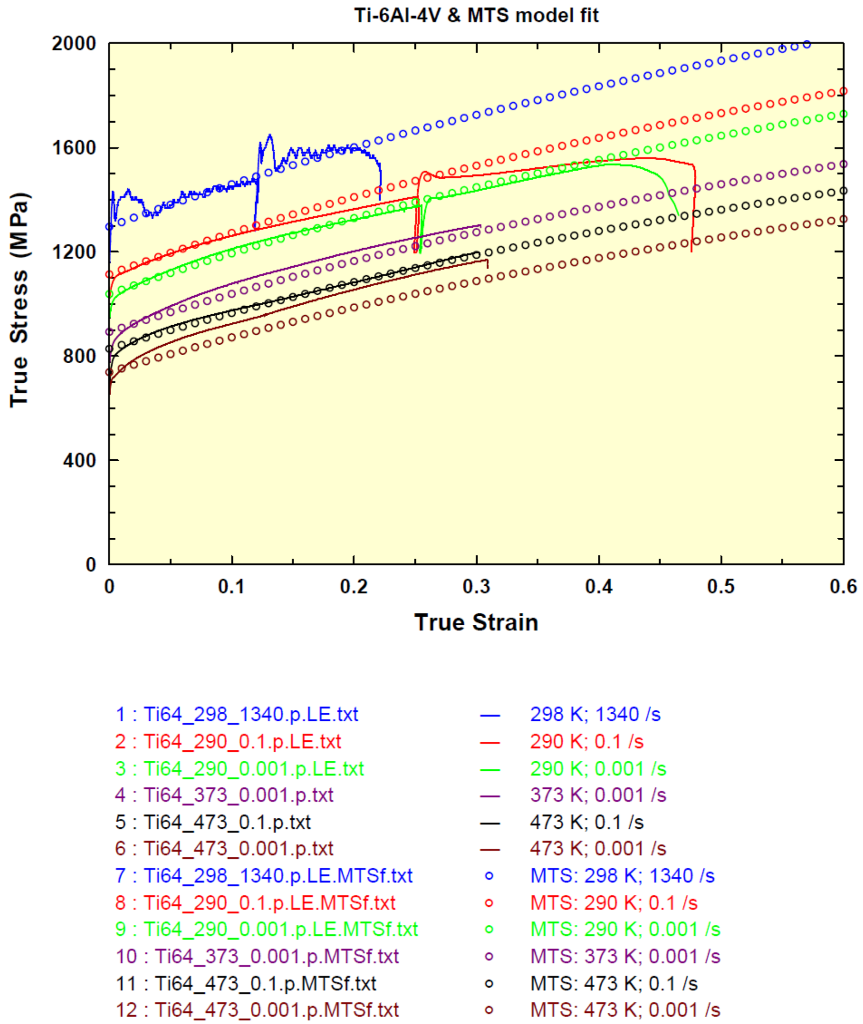
Strain Rate Sensitivity of Ti-6Al-4V

- At higher strain rates ductility decreases slightly (solid lines are test data used in a LANL model).



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Strain Rate Sensitivity of Ti-6Al-4V

- **Although the relative impact velocities in air transport accidents (between Pu contents and Ti T-Ampoule wall) are higher (180-404 ft/sec), the 200 ft/sec component tests generated slightly higher strain rates since the Ti impactor had a higher "stiffness" than the Pu (σ_y=140,000 psi vs. 9,200-36,000 psi for δ/α Pu).**
- **Since component tests exceeded strain rates analyzed in air transport accidents, and since no failure occurred in component tests, any small strain rate sensitivity in the T-Ampoule should not affect the structural integrity analyses performed in the SAR Addendum.**

Max EQPS and TP Comparisons for Component Tests and Air Transport Impacts

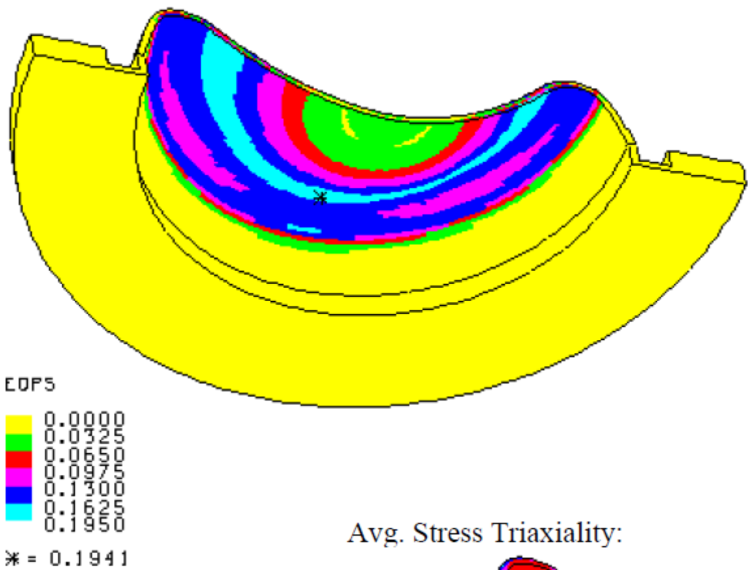
EQPS/TP Maxes:

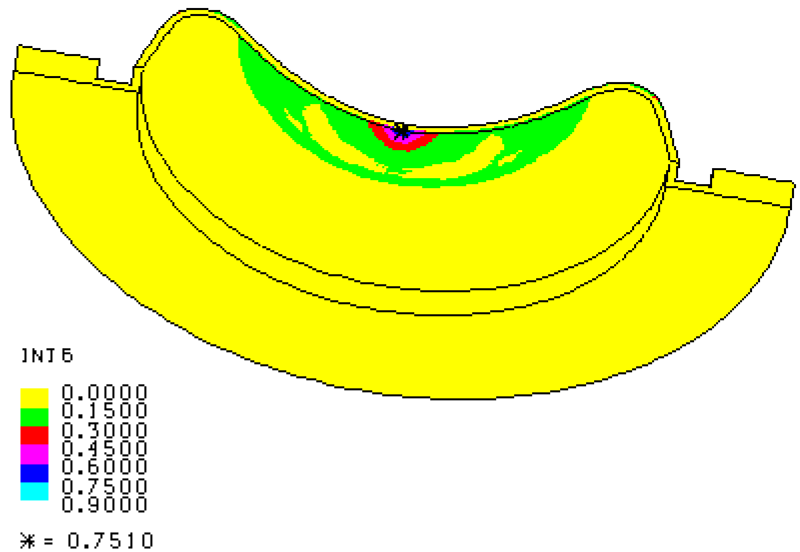
Run	EQPS in TAMP	TP in TAMP
Impact Test (dish)	0.175	0.0132
Impact Test (plug)	**0.5125**	0.1084
Drop Table	0.194	**0.7510**
HSRun1	0.0789	0.0528
HSRun2	0.1867	0.2115
HSRun3	0.1307	0.6177
HSRun4	0.0609	0.2896
HSRun5	0.0254	0.2389
HSRun6	0.1098	0.1507
HSRun7	0.0462	0.2831
HSRun8	0.1268	0.3967
HSRun9	0.0630	0.4896
HSRun10	0.0328	0.2842
HSRun11	0.0188	0.0319
HSRun12	0.6133	0.2417
HSRun13	0.7105	0.1958
HSRun14	0.1575	0.0935
HSRun15	0.0252	0.3061
HSRun16	0.1427	0.0132
HSRun17	0.6056	0.4788
HSRun18	0.8996	0.5137
HSRun19	0.0777	0.0953
HSRun20	0.0348	0.054
HSRun21	0.0867	0.0155
HSRun22	0.1779	0.2075
HSRun23	0.3487	0.497
HSRun24	0.0559	0.0597
HSRun25	0.0186	0.1197
HSRun26	0.9692	0.4888
HSRun27	0.8687	0.4673

NOTE: All TP values in the air transport impacts AND component tests were below the critical TP value of 1.012 (thus no ductile tearing would even initiate).

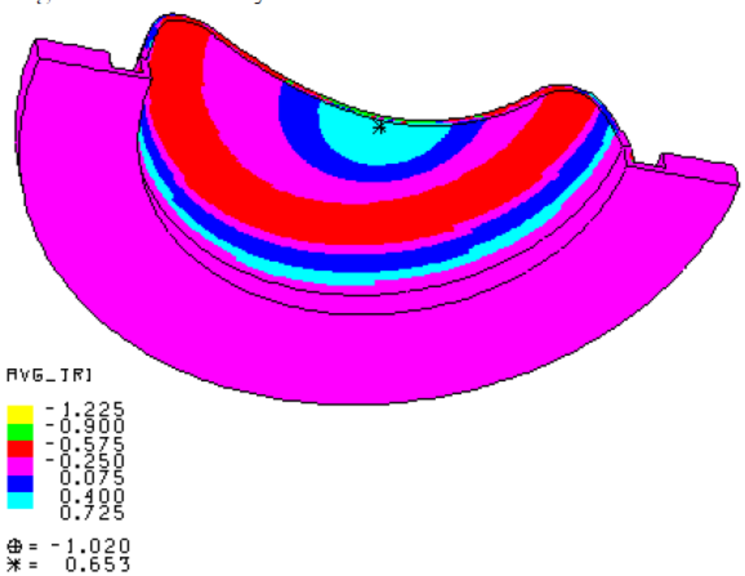
Compare EQPS, TP, Stress Triaxiality: Analysis of Drop Table Component Test

EQPS:





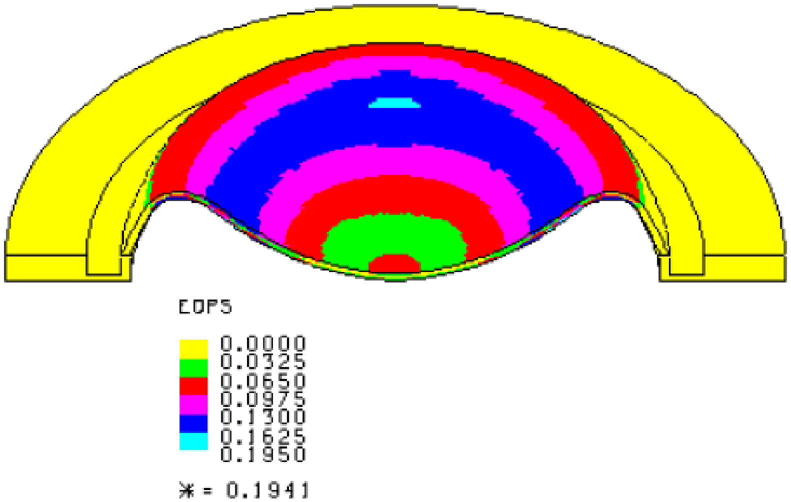
Avg. Stress Triaxiality:



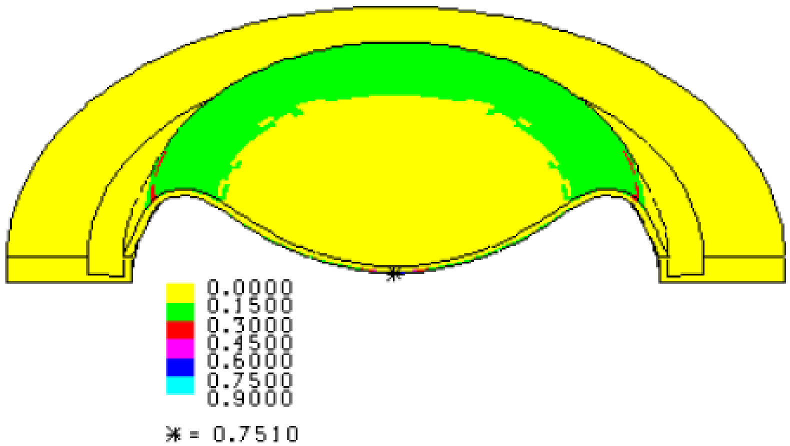
EQPS is low; it does not
Indicate region of interest
(high TP due to positive stress tri)

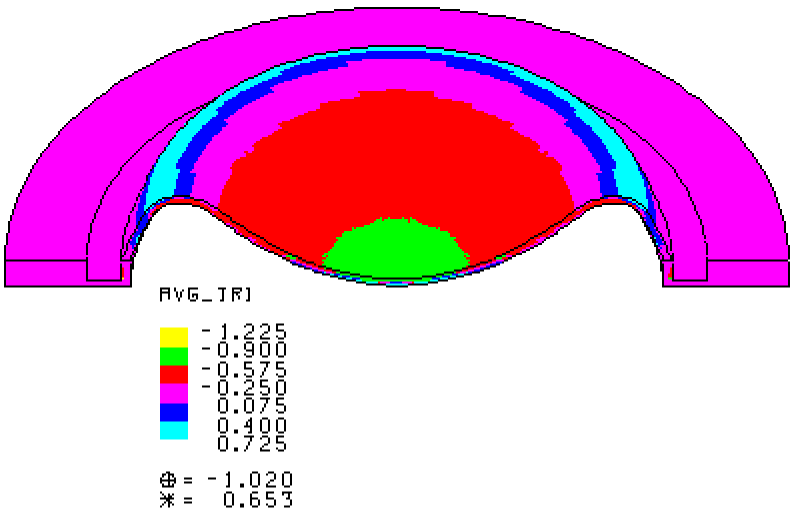
Compare EQPS, TP, Stress Triaxiality: Analysis of Drop Table Component Test

EQPS:

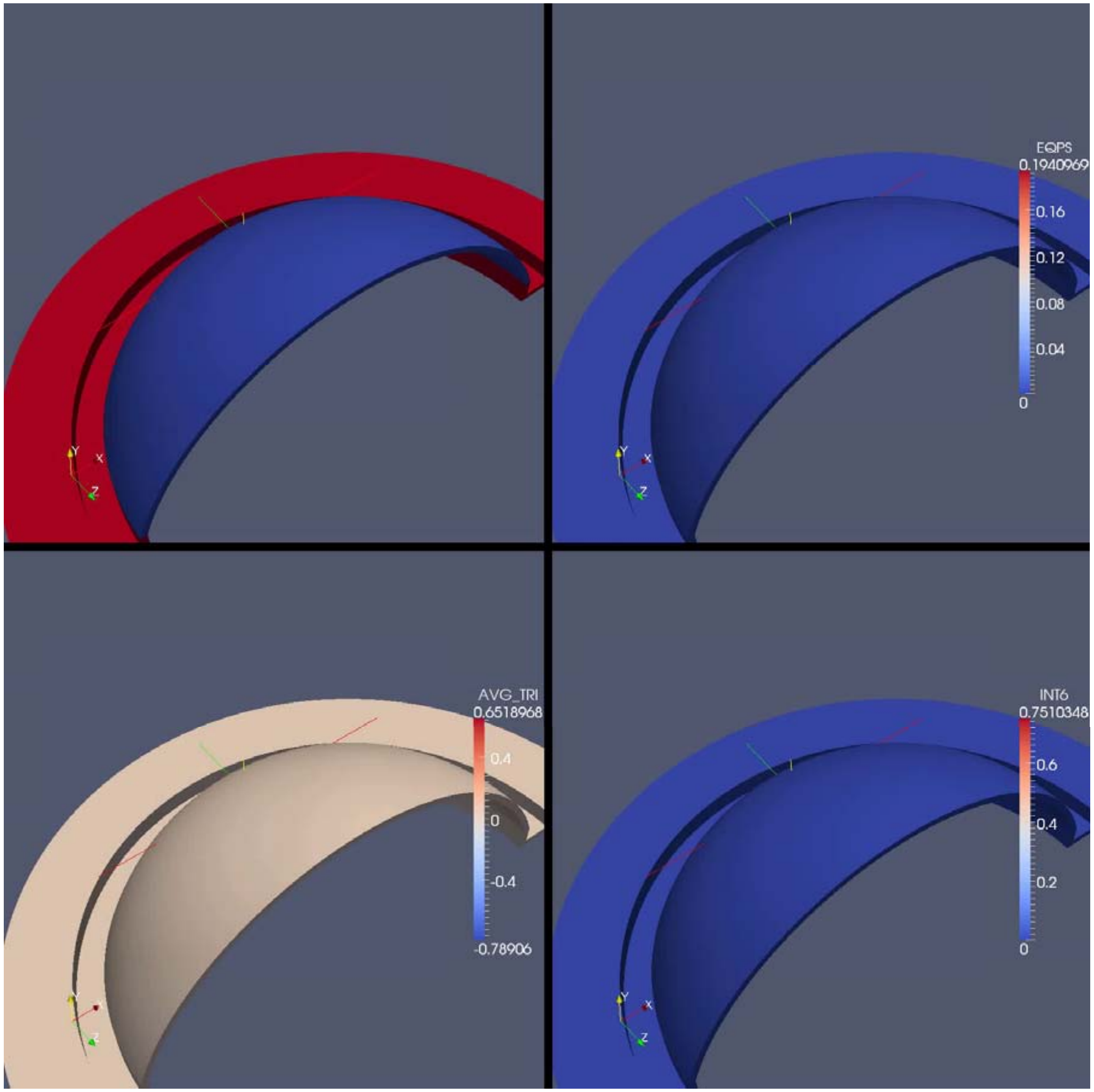


Tearing Parameter:



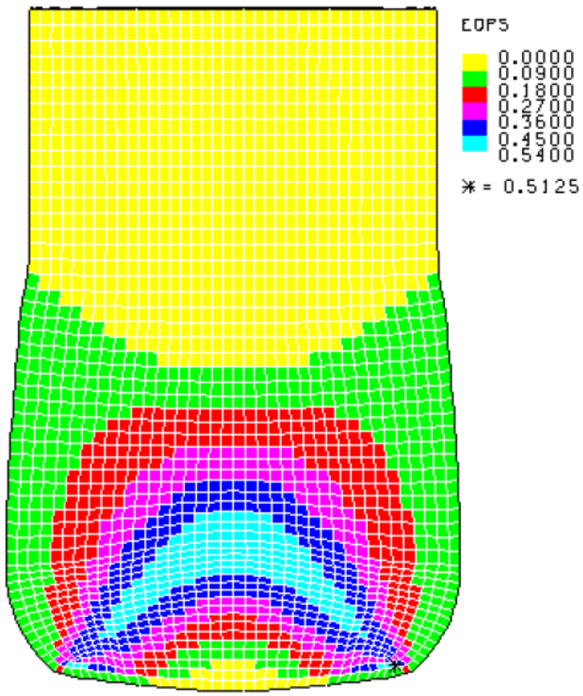


Compare EQPS, TP, Stress Triaxiality: Analysis of Drop Table Component Test

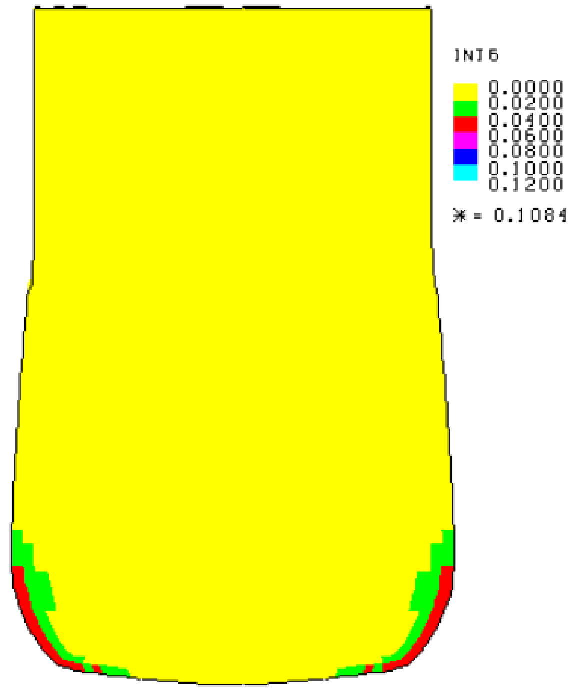


Compare EQPS, TP, Stress Triaxiality: Analysis of Ti Impactor Component Test

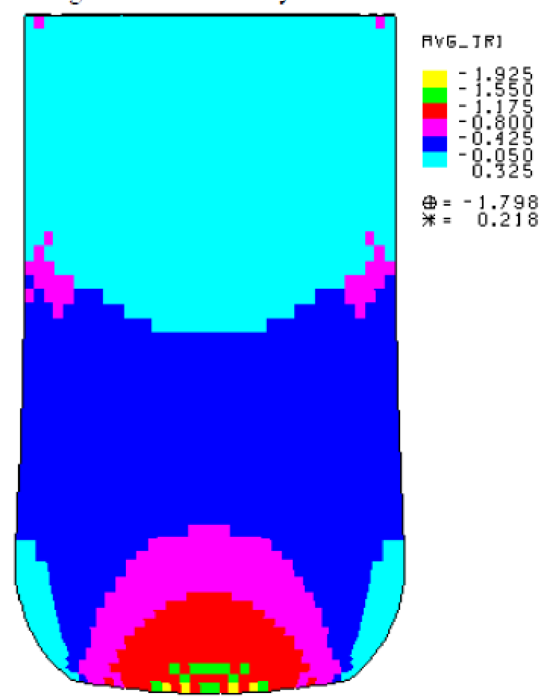
EQPS:



Tearing Parameter:



Average Stress Triaxiality:



Even at “high” EQPS, TP is low due to highly negative stress tri

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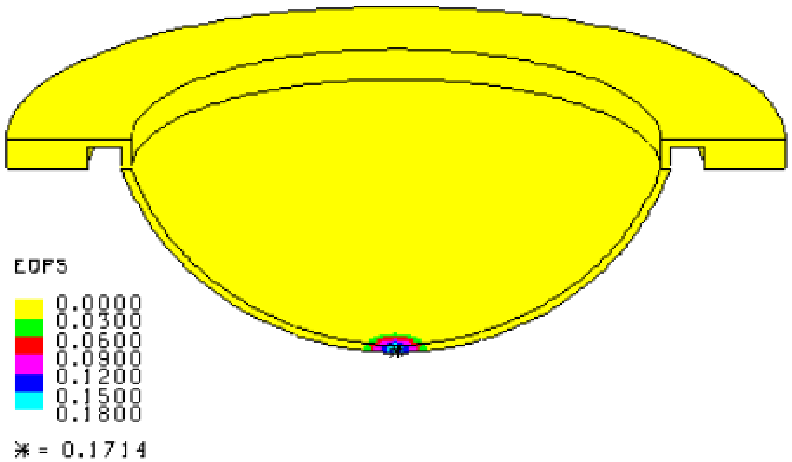
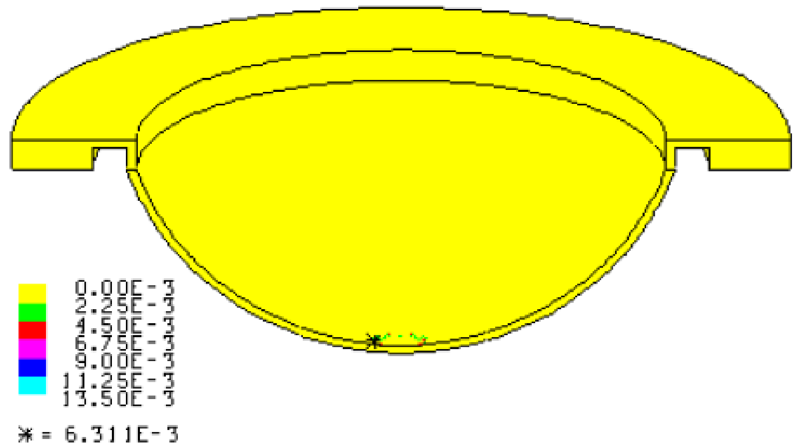
Compare EQPS, TP, Stress Triaxiality: Analysis of Ti Impactor Component Test

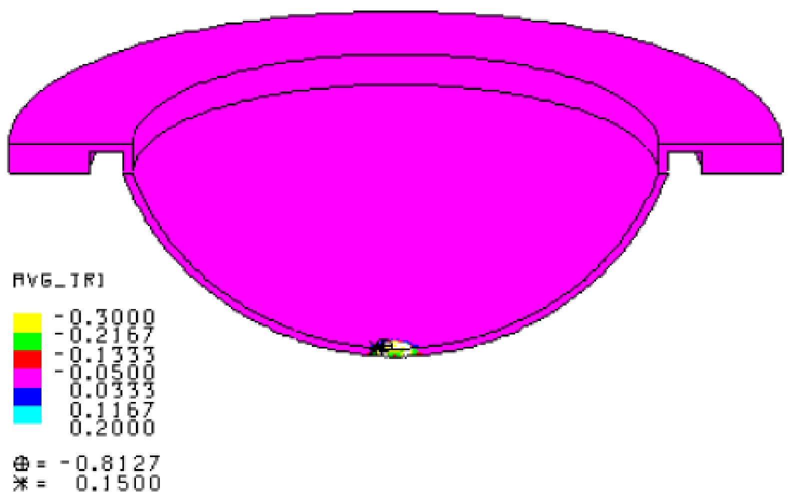
EQPS:



Tearing Parameter:



Average Stress Triaxiality:



Even at moderate EQPS, TP is low due to negative stress tri

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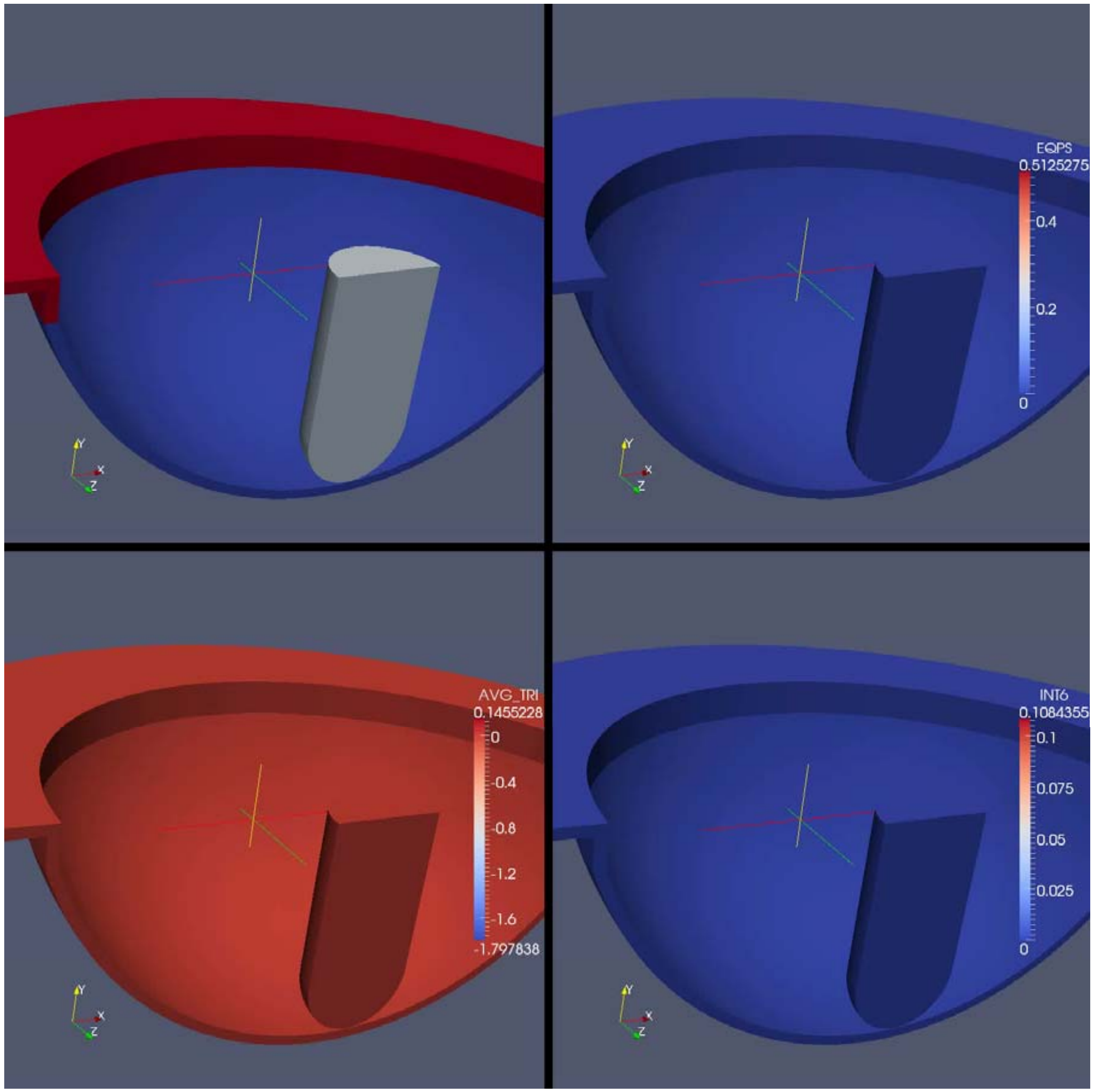
Compare EQPS, TP, Stress Triaxiality: Analysis of Ti Impactor Component Test



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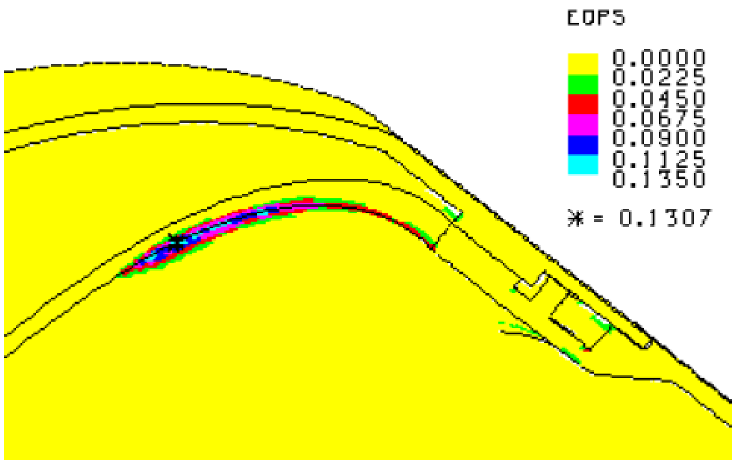
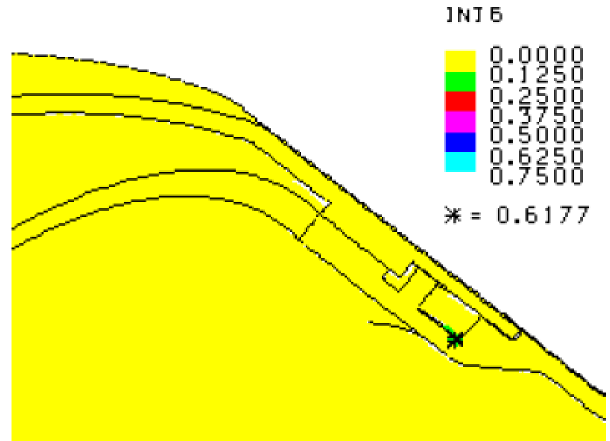
Compare EQPS, TP, Stress Triaxiality: Analysis of Aircraft Impact (831 g ER cyl, CGOC)

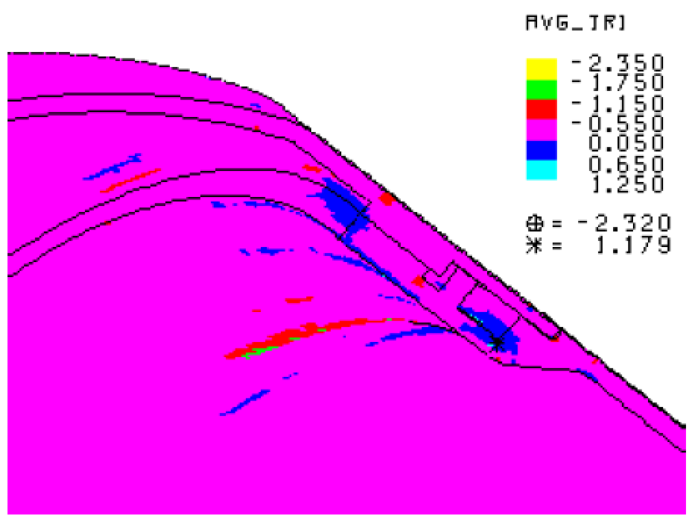
EQPS:



Tearing Parameter:



Average Stress Triaxiality:

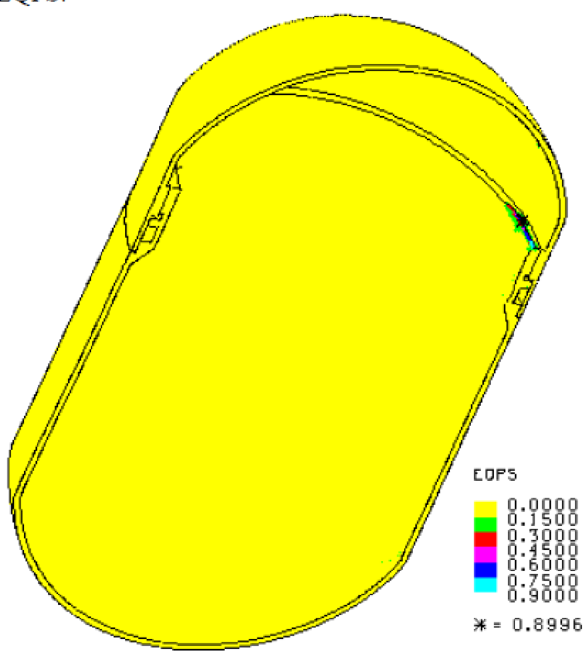


HSRun3

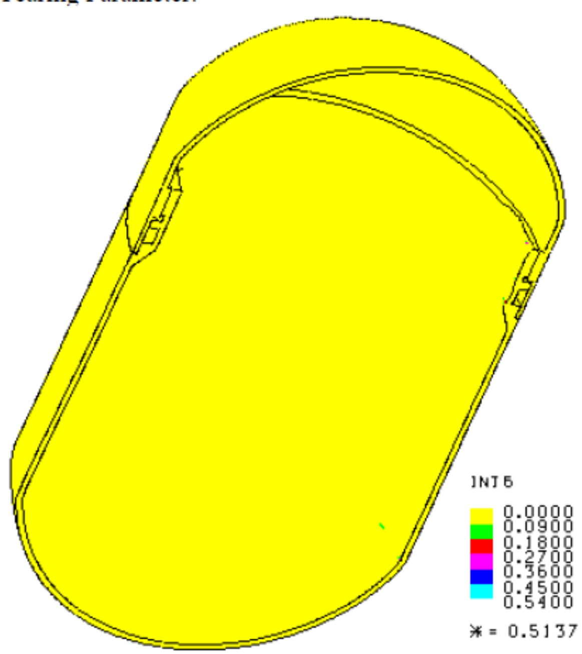
TP is larger where stress tri is positive

Compare EQPS, TP, Stress Triaxiality: Analysis of Aircraft Impact (2 amp, 45 deg, side impact)

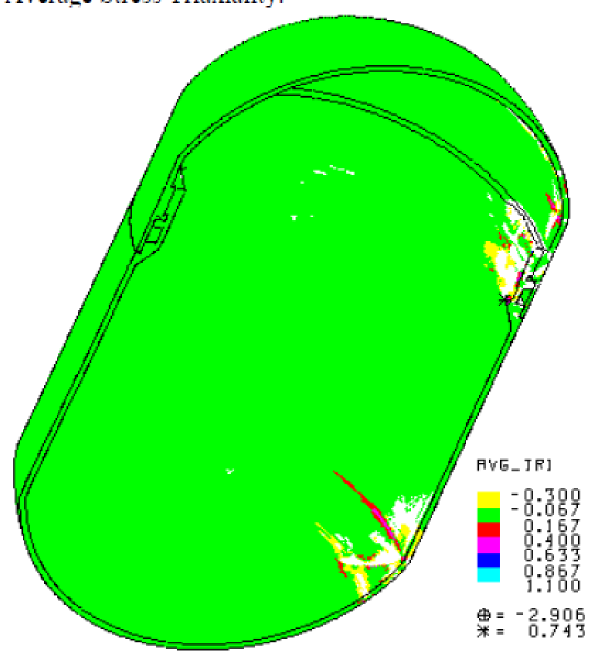
EQPS:



Tearing Parameter:



Average Stress Triaxiality:

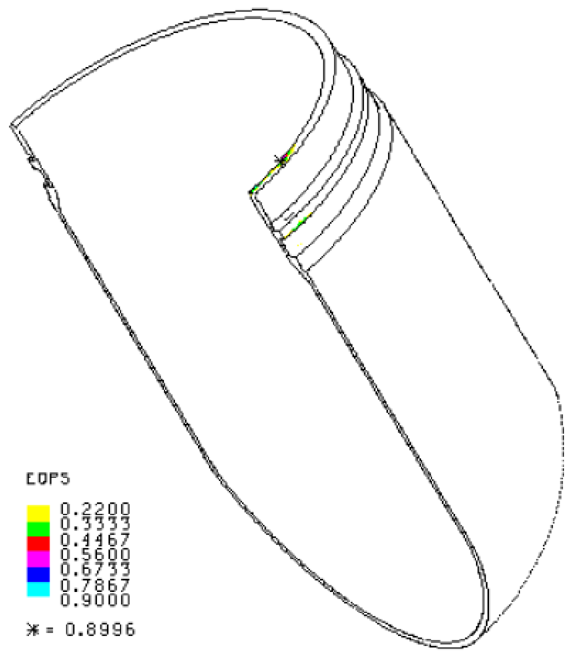


Although high EQPS, TP is moderate due to negative stress tri

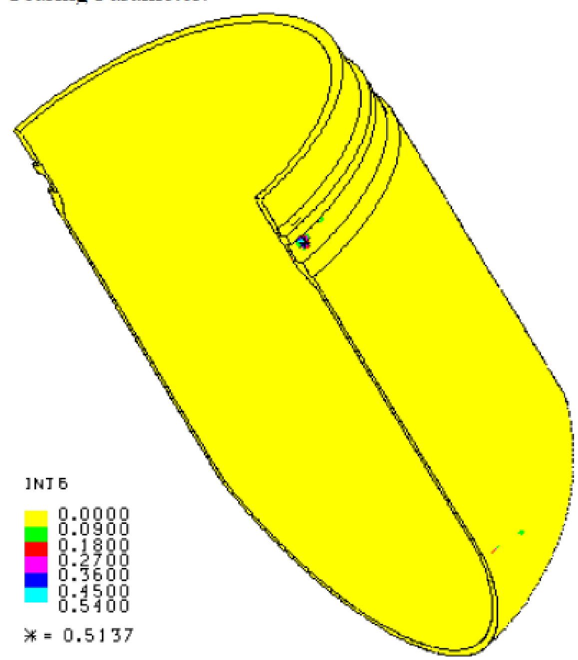
HSRun18

Compare EQPS, TP, Stress Triaxiality: Analysis of Aircraft Impact (2 amp, 45 deg, side impact)

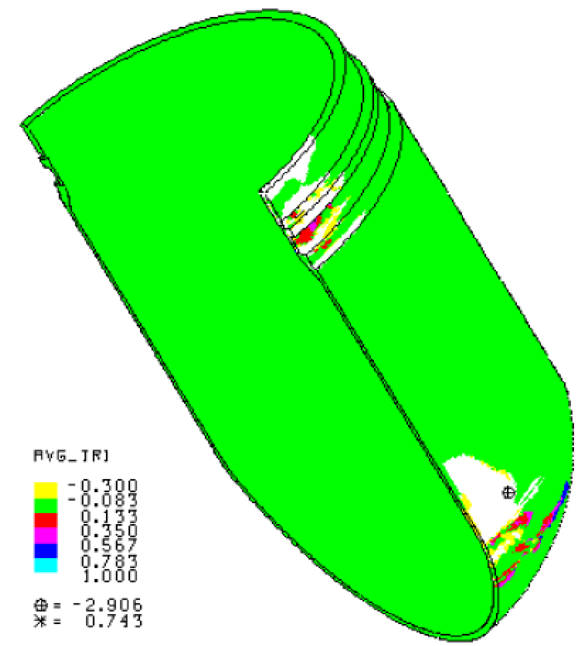
EQPS:



Tearing Parameter:



Average Stress Triaxiality:



Same case as previous slide, but different color scale for clarity

HSRun18

EQPS vs. Stress-Tri vs. TP in Ti-6Al-4V T-Ampoule

- **EQPS values appear to exceed "strain-to-failure" levels based on minimum reduction in area, but in all cases this occurs where stress triaxialities are below -0.3 where no failure would occur.**
- **The Critical Tearing Parameter was never exceeded in any regulatory aircraft impact case (various contents, orientations), thus structural integrity of the eutectic barrier T-Ampoule is maintained.**

Secondary Topics

- **Overview of preprocessor.**
- **Overview of input file generation.**
  - **Basic feature of input file.**
  - **Syntax overview.**
- **Overview of postprocessor.**
  - **Opening output files.**
  - **Basic operations for results extraction.**
- **Sample air transport accident simulations.**
  - **Table 2-9, runs 2, 3, 6, 9, 10, 11, 15, 18, 23.**
- **Sample dynamic crush simulations.**
  - **Table 2-8, run 2.**

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Preprocessor

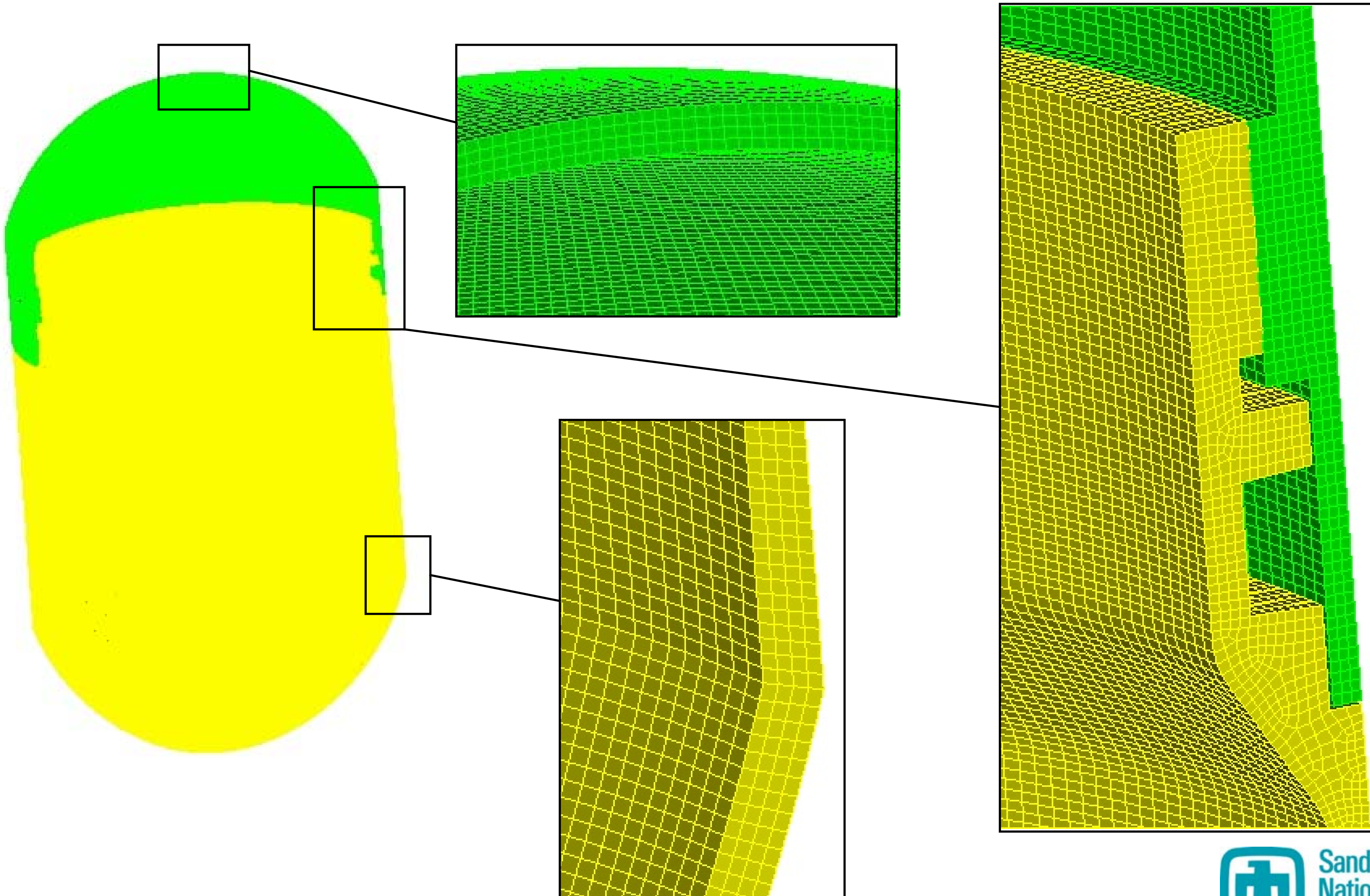
- **Cubit (Mesh Generation of Complicated Individual Parts)**
- **Sierra Suite (To Make Simple Parts and Combine All Parts)**
  - **Makefile**
  - **GJOIN**
  - **GREPOS**

```
4ft3au.g
fullSideLiliLS.g
revolve z 90
offset y -4.200008
end
add
HACplate.g
offset x -0.4375 y -38.88019 z 0
end
finish
HAC3auFull.g
```

```
HAC2auFull.g
revcen 0 -3.683853 0
revolve z 29.37754
delete material 5001
end
finish
HAC2aCGOCFulla.g
```

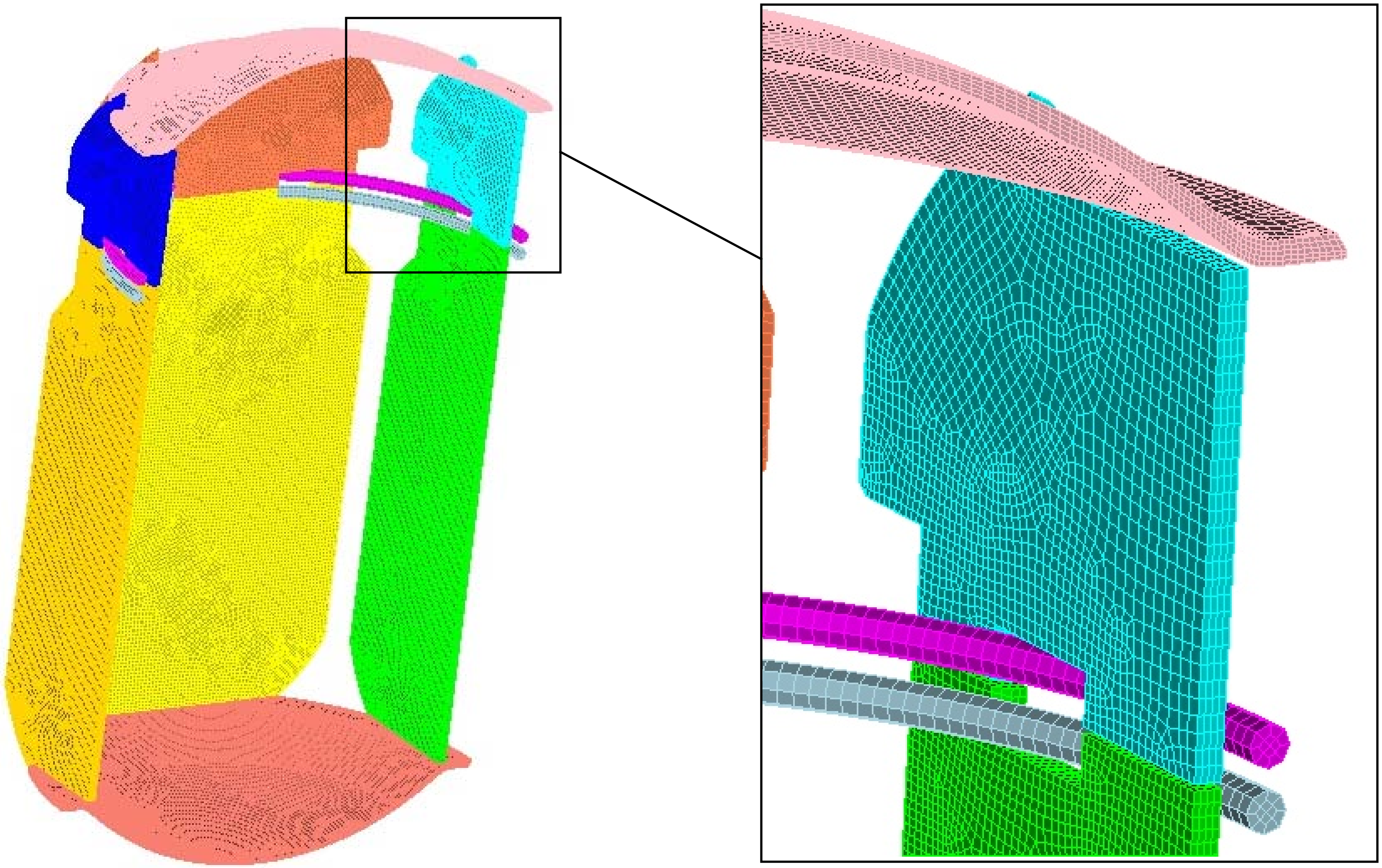
```
HAC3auFull.g:     4ft3au.g fullSideLiliLS.g HACplate.g HAC3auFull.gjn
                  gjoin2 < HAC3auFull.gjn

HAC2aCGOCFulla.g: HAC2auFull.g HAC2aCGOCFulla.grp
                  grepos -aprepro HAC2auFull.g HAC2aCGOCFulla.g < HAC2aCGOCFulla.grp
```

Preprocessor Continued (T-Ampoule Mesh)



Slide # 72

Preprocessor Continued (Support Structure Mesh)



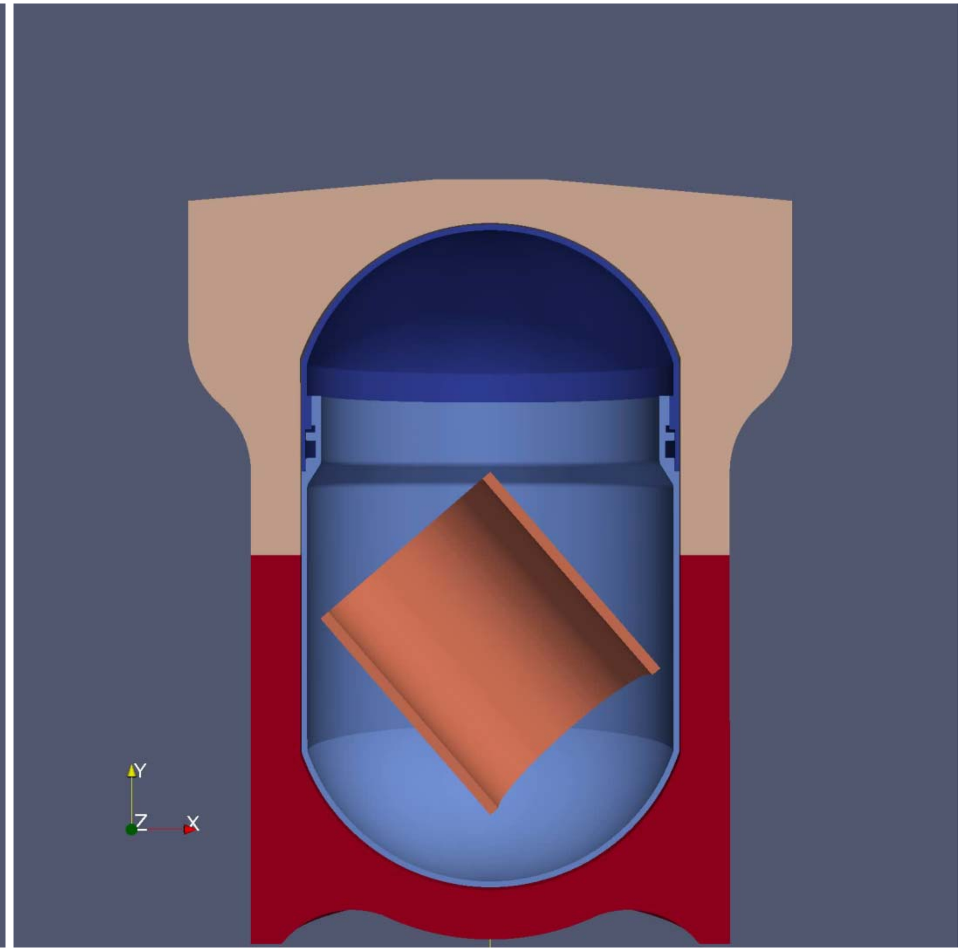
Input File

- **Walk Through Truncated Input File**
  - **Basic Features of Input File**
  - **Syntax**

Post Processor

- Blot
  - Tplot (Kinetic Energy, Specific Element Time History Information)
  - Contour Plots (EQPS, VonMises, Overall Displacements)
- Run PERL Script (To Determine Elements Exceeding Strain Locus and Their Corresponding Tearing Parameter)
  - Excel (To Generate Average Stress Triaxiality vs. EQPS and TP versus EQPS)
  - Blot (Examination of Individual Elements Exceeding Locus)
- Paraview (For Videos)

Representative Sample of Air Transport Accident Cases



HSRun2

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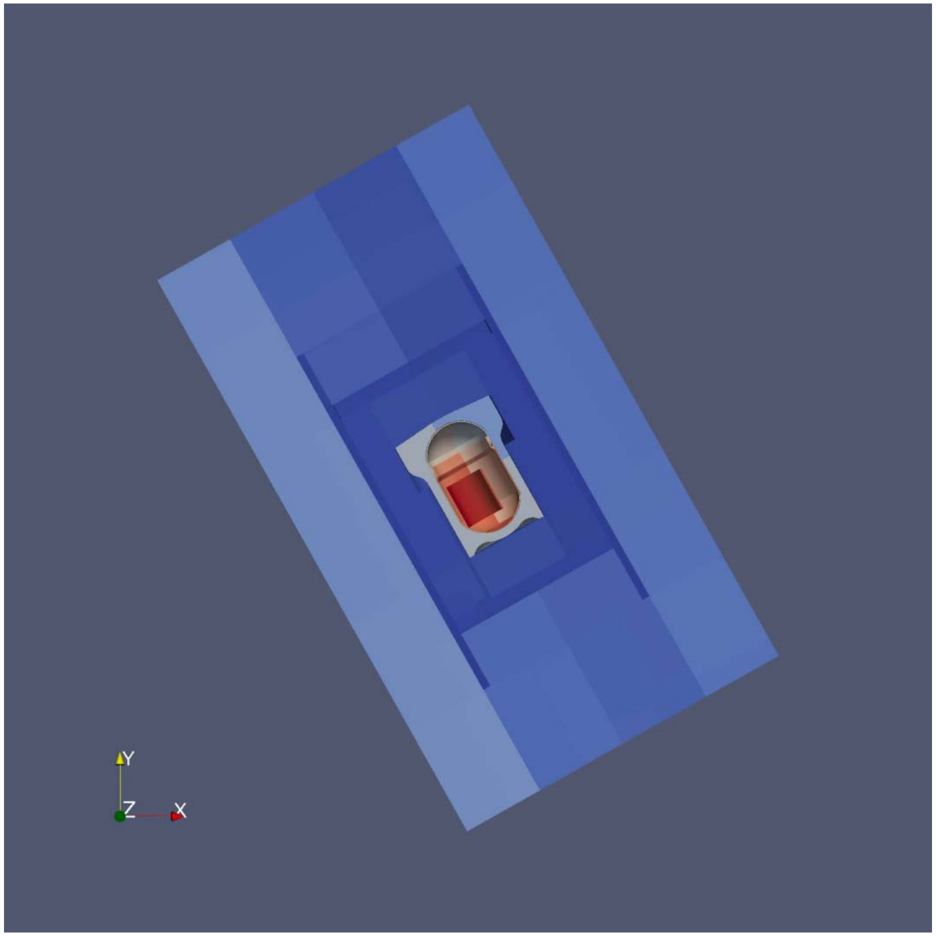
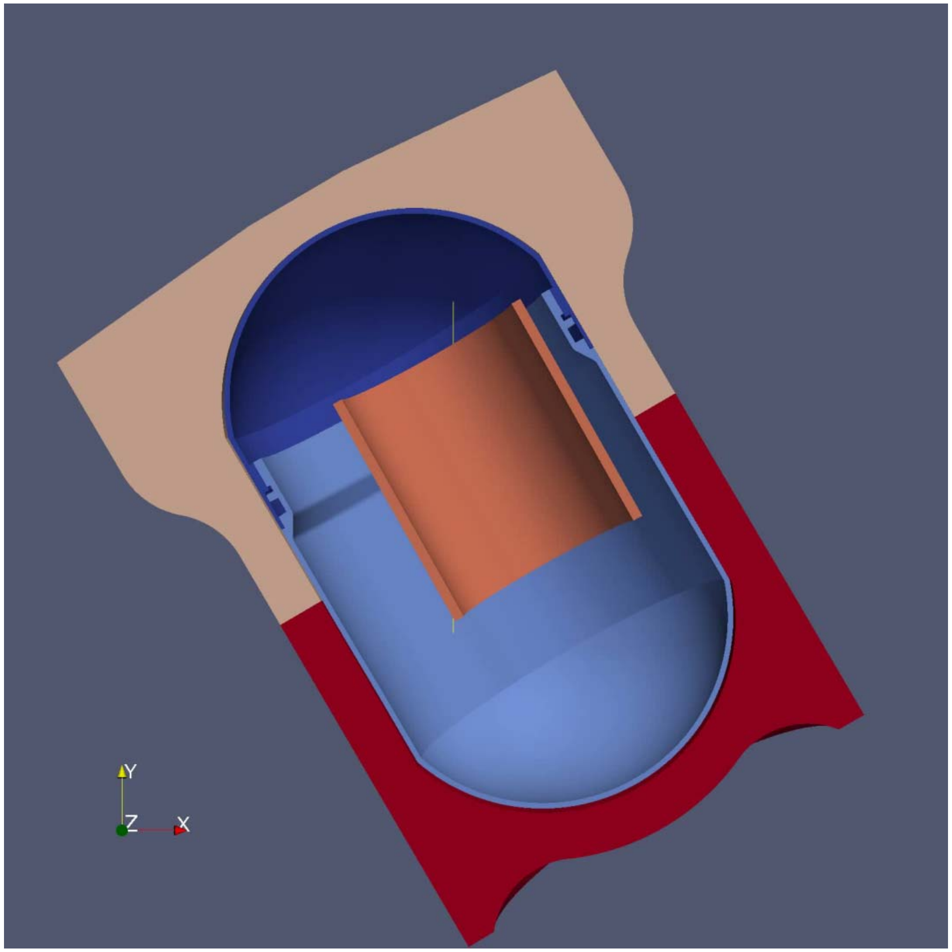
Representative Sample of Air Transport Accident Cases





HSRun3

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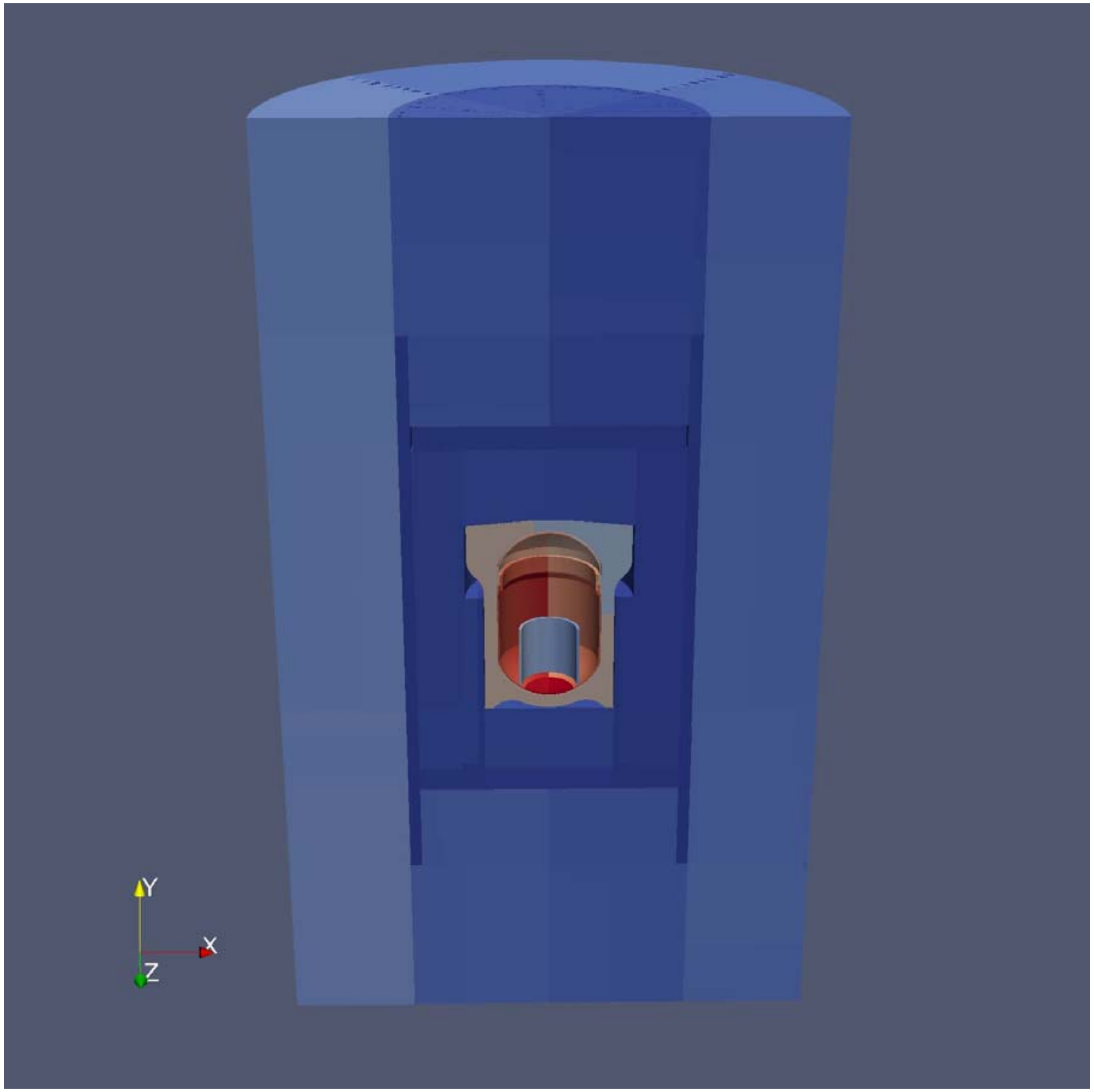
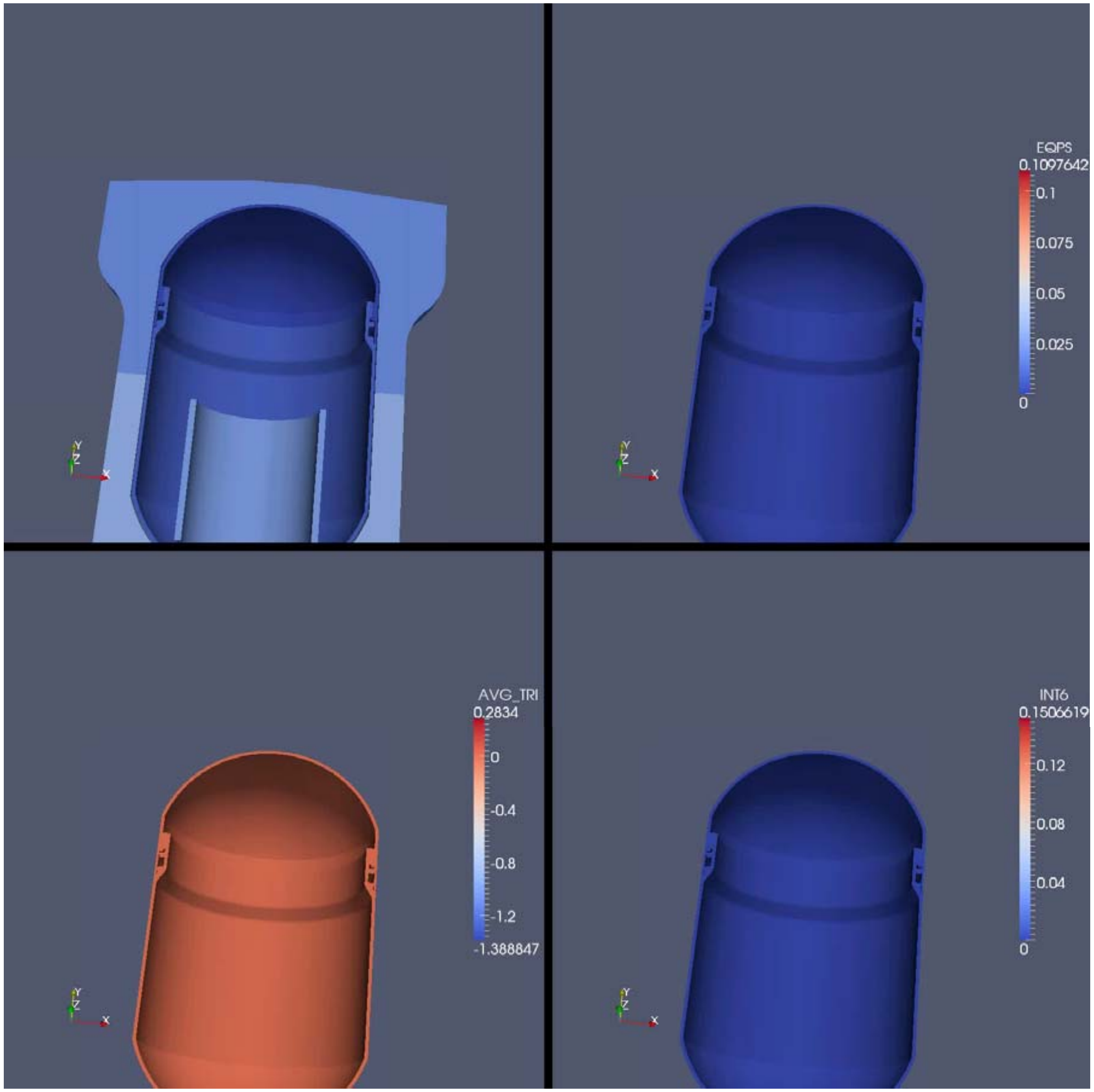
Representative Sample of Air Transport Accident Cases

HSRun6



Representative Sample of Air Transport Accident Cases

HSRun6



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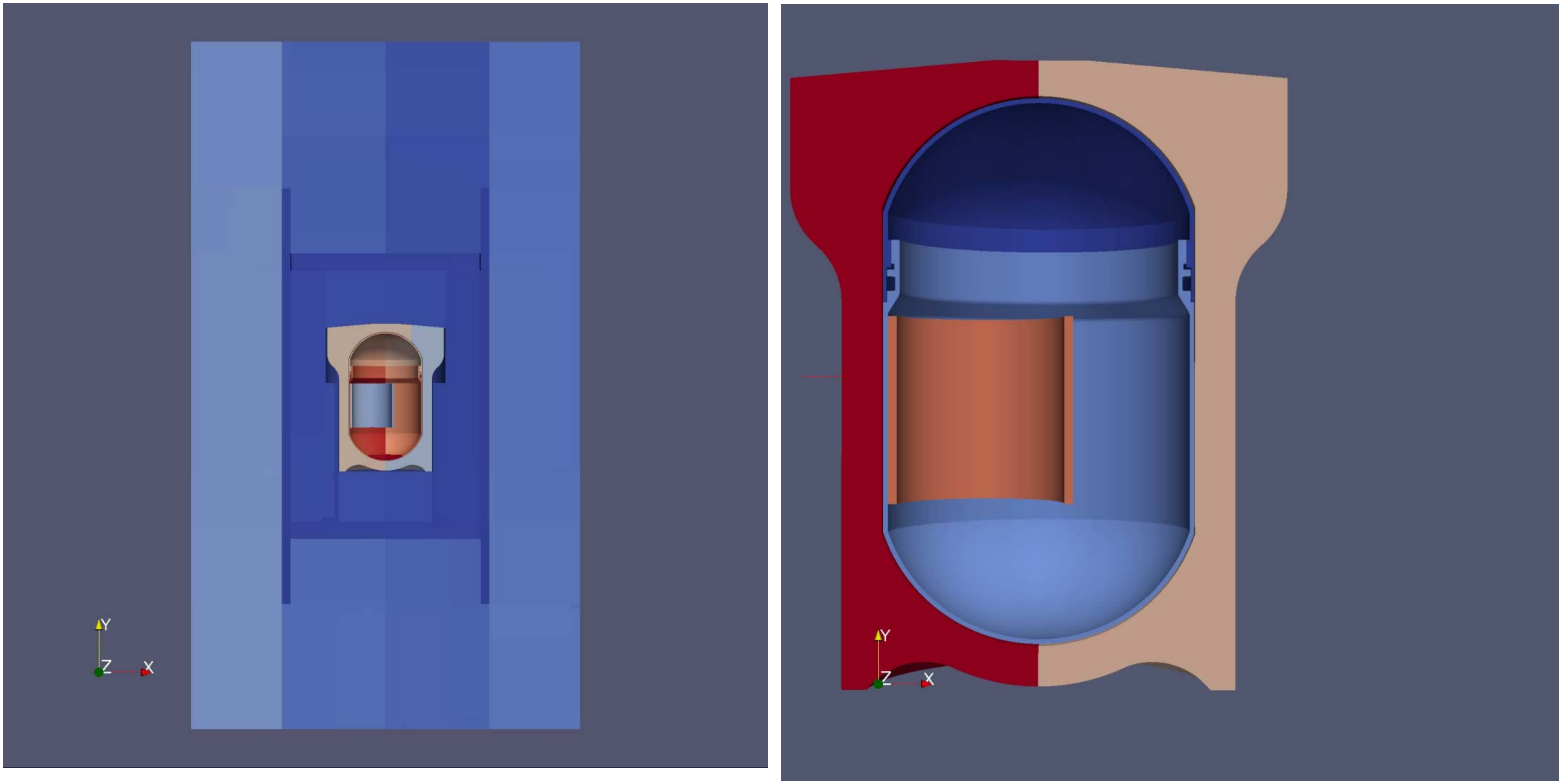
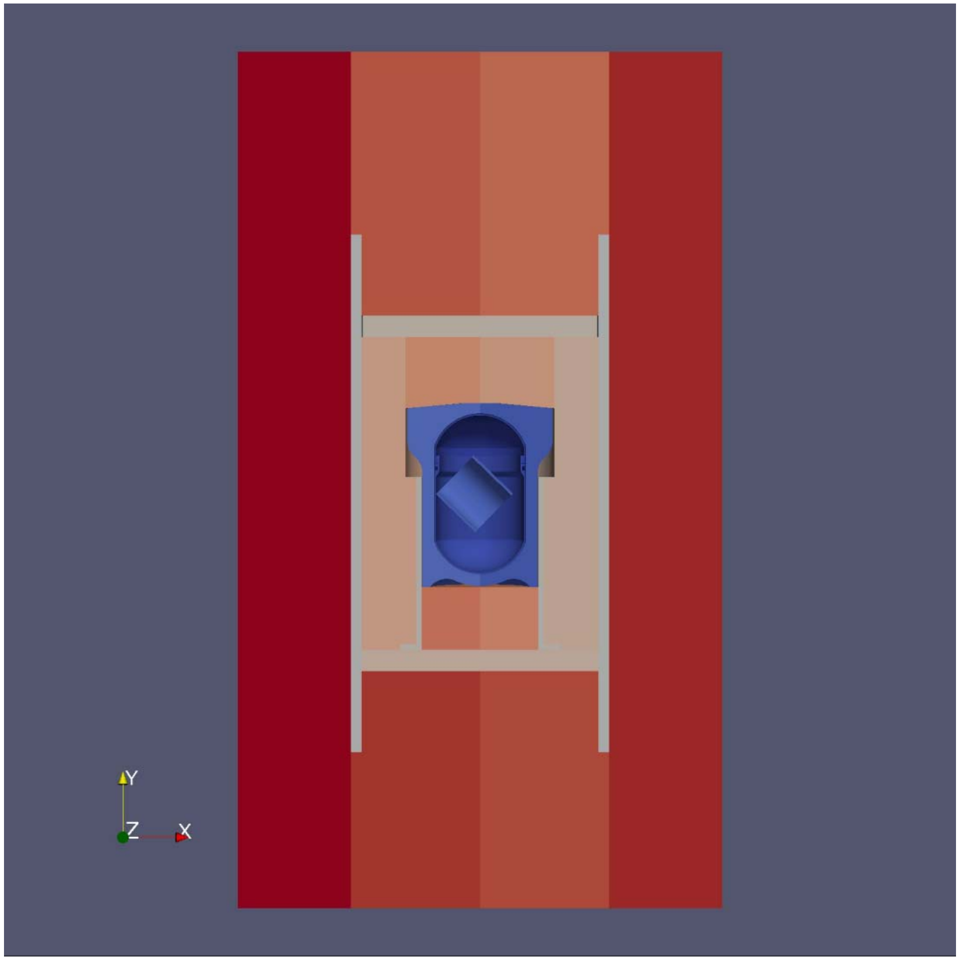
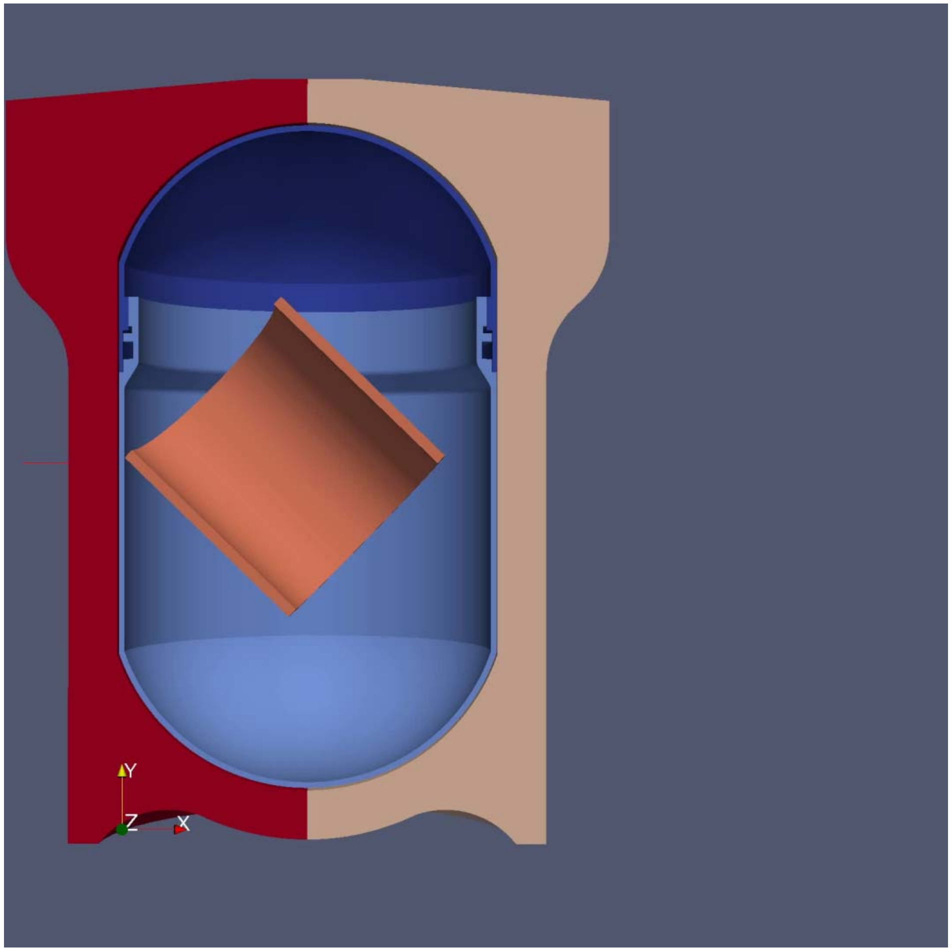
Representative Sample of Air Transport Accident Cases



HSRun9

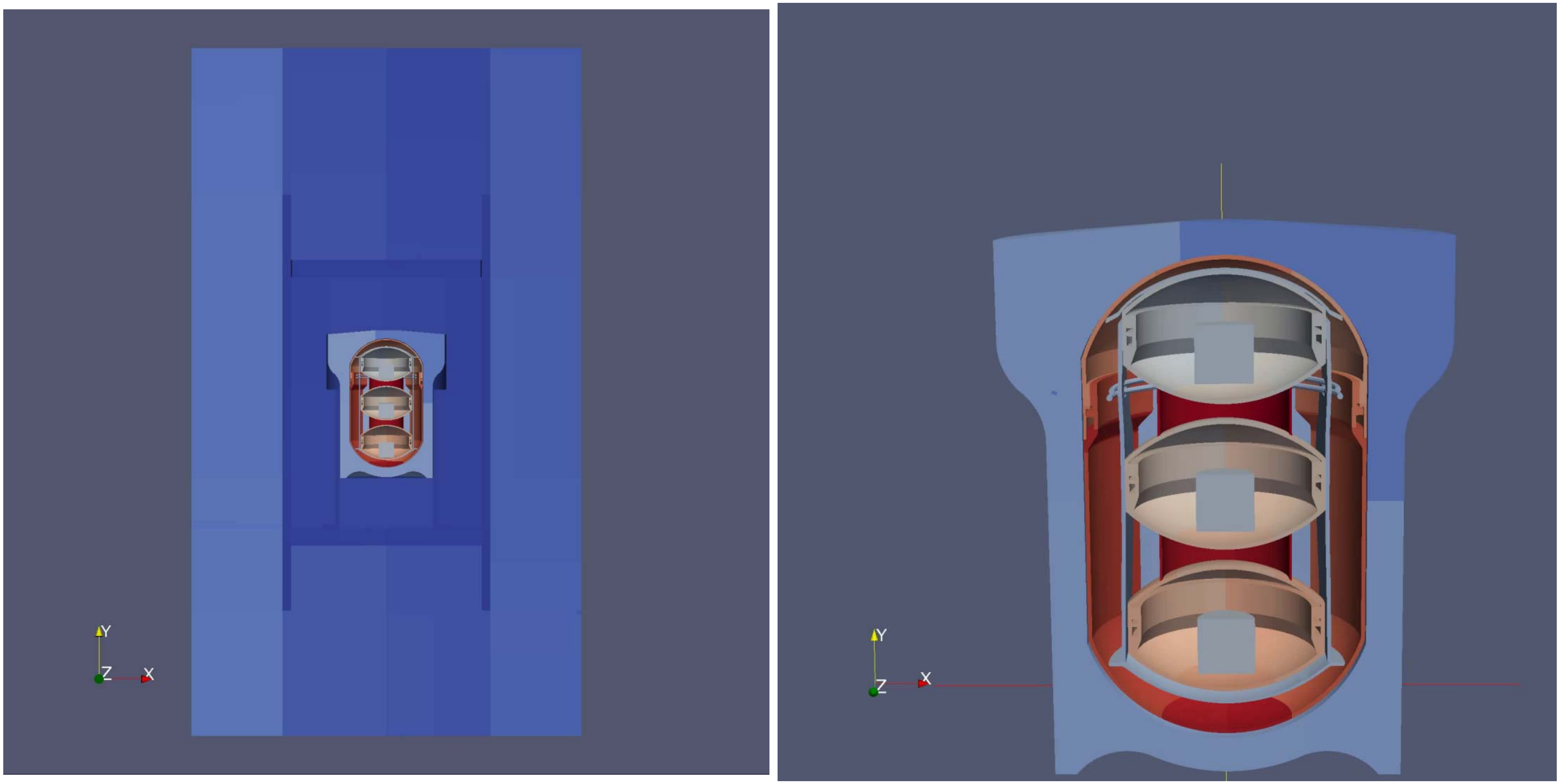
Representative Sample of Air Transport Accident Cases





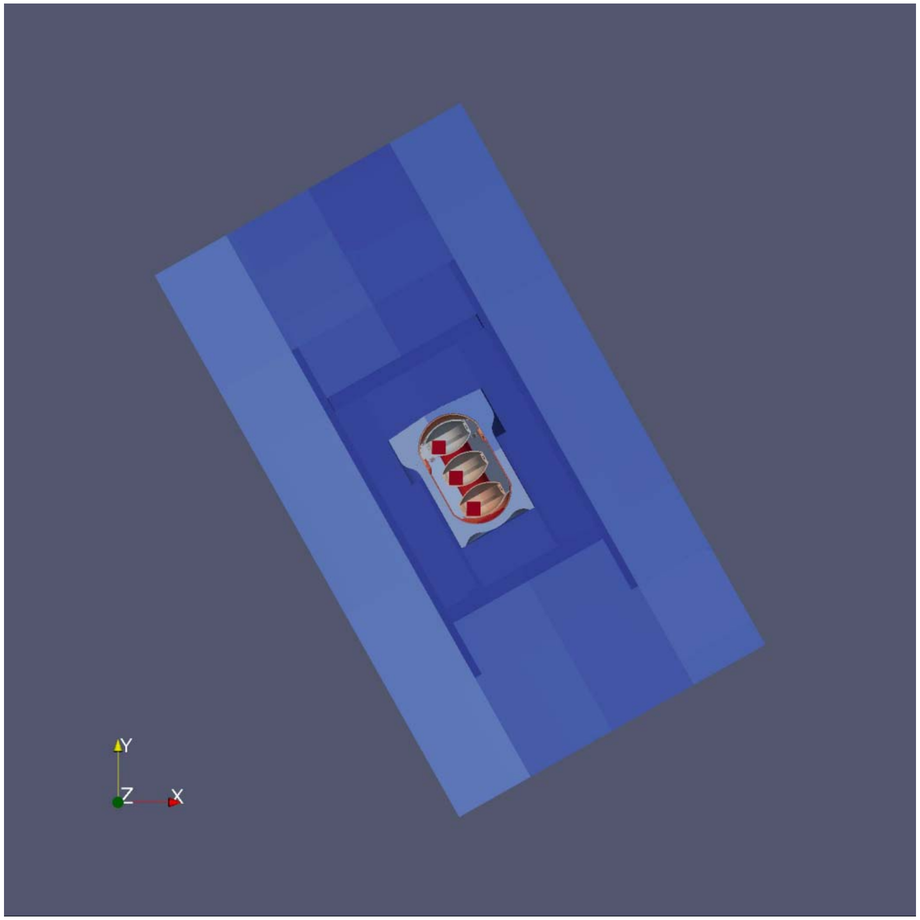
HSRun10

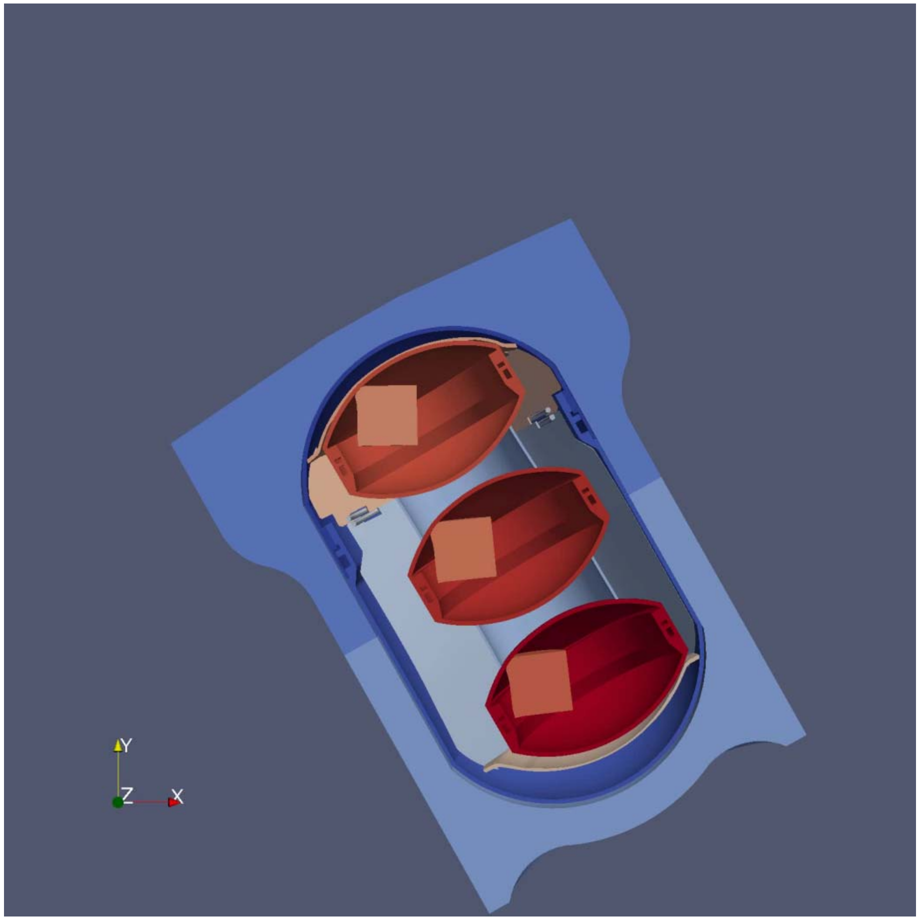
Representative Sample of Air Transport Accident Cases



HSRun11

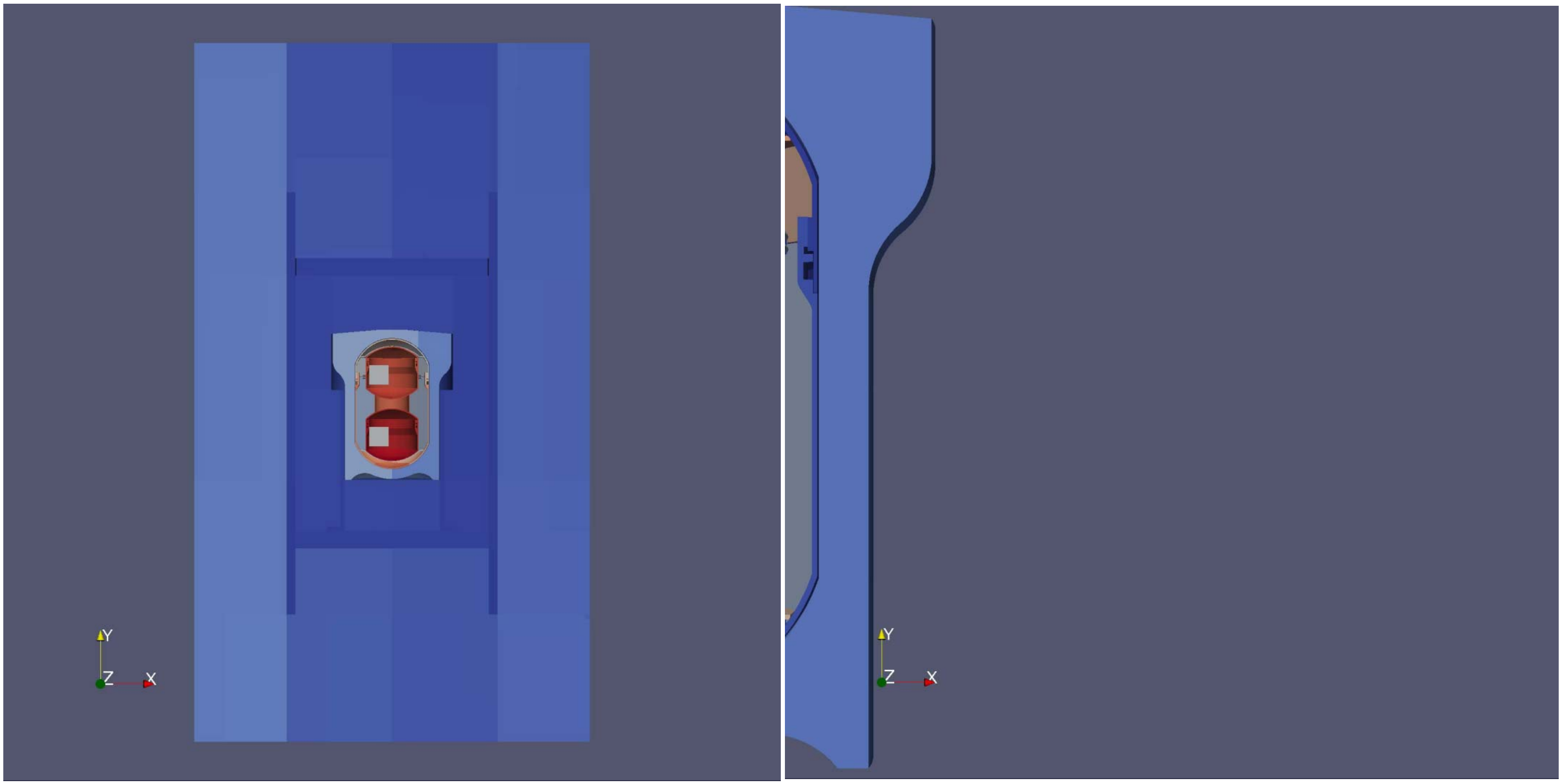
Representative Sample of Air Transport Accident Cases





HSRun15

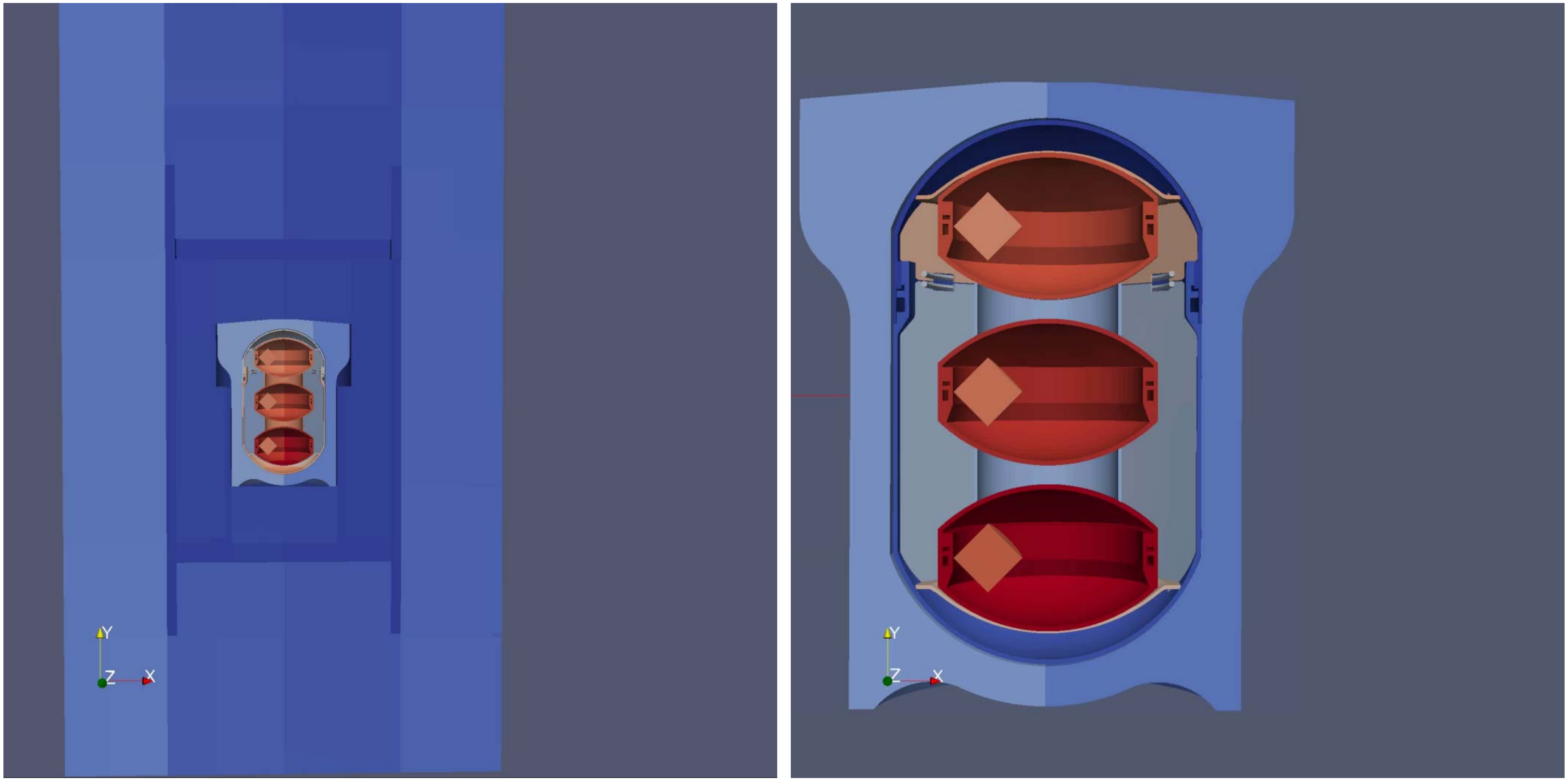
Representative Sample of Air Transport Accident Cases



HSRun18

Sandia National Laboratories

Representative Sample of Air Transport Accident Cases



HSRun23

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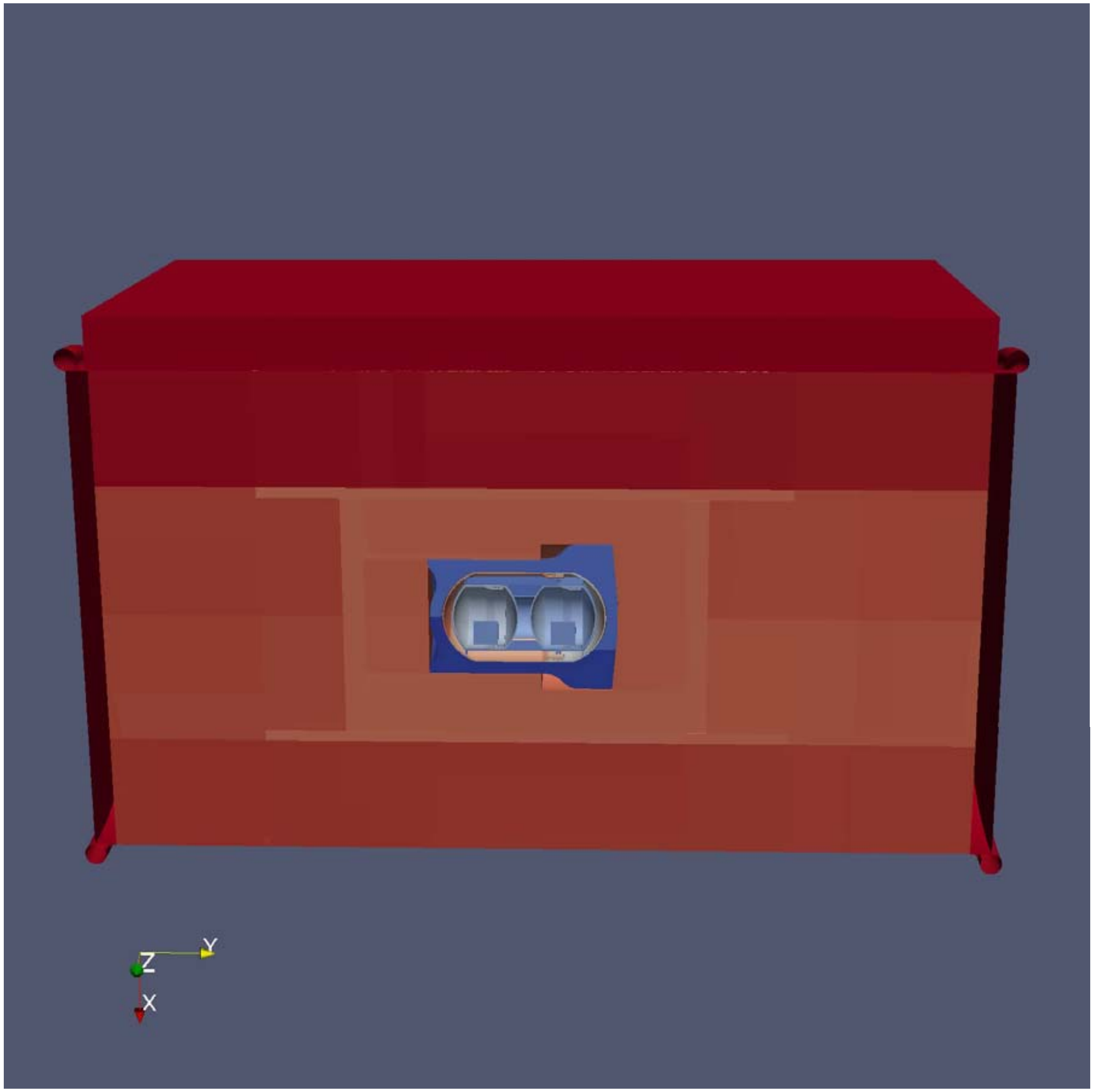
Representative Sample of HAC (Dynamic Crush) Accident Case

HACRun2



Conclusions

- **No leakage or seal area (or any other visible) deformation occurred in the TB-1 of the original PAT-1 certification tests (NCT, HAC, PAT tests), and based on analyses, none would occur with the new metal contents (except minimal localized denting).**
- **Thru-thickness TB-1 stresses were well below ASME allowables for dynamic crush.**
- **FEA results show that ductile tearing will NOT be initiated in the T-Ampoule eutectic barrier, based on the Tearing Parameter failure criterion (supplemented with stress-triaxiality vs. equivalent plastic strain locus testing).**
- **For NCT, HAC, and Pu Transport Accident Conditions, the area around the copper seal remained elastic.**

The analyses performed provide sufficient evidence that the PAT-1 container can safely transport the proposed solid metal contents.

QUESTIONS