PAT-1 SAR Addendum Structural Analysis Overview for the NRC

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Methodology

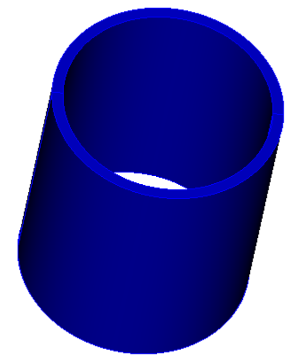
- **The PAT-1 package has been certified by the NRC (since 1978) for air transport of 2 kg powdered PuO_2.**
  - **SAR Addendum is to add solid metal to the contents list.**
- **The only new requirement is dynamic crush.**
- **NCT analyses establish the initial position of contents for accident simulations.**
- **The integrity of a thin eutectic barrier is shown to be maintained using 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.**

Requirements and Acceptance Criteria

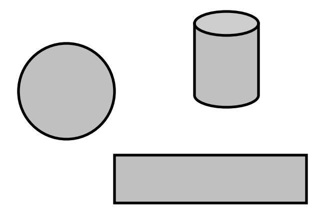
- **Overall Program-Defined Package Constraints:**
  - **PAT-1 already meets all regulatory criteria (except dynamic crush) for the same mass with oxide contents.**
  - **AQ-1 overpack to remain the same; same TB-1 provides containment throughout NCT, HAC, air transport environments.**
  - **Total contents mass within TB-1 (fissile and structure) not to exceed 4.4 lb; 25 watts heat generation.**
  - **Contents subcritical; radiation limits on container.**
  - **T-Ampoule is a eutectic barrier only (not for Pu containment) and maintains integrity.**

Materials to be Shipped

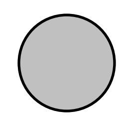
- **Electro-refined Pu bulk material**
  - **Machined hollow cylinder form**



- **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**



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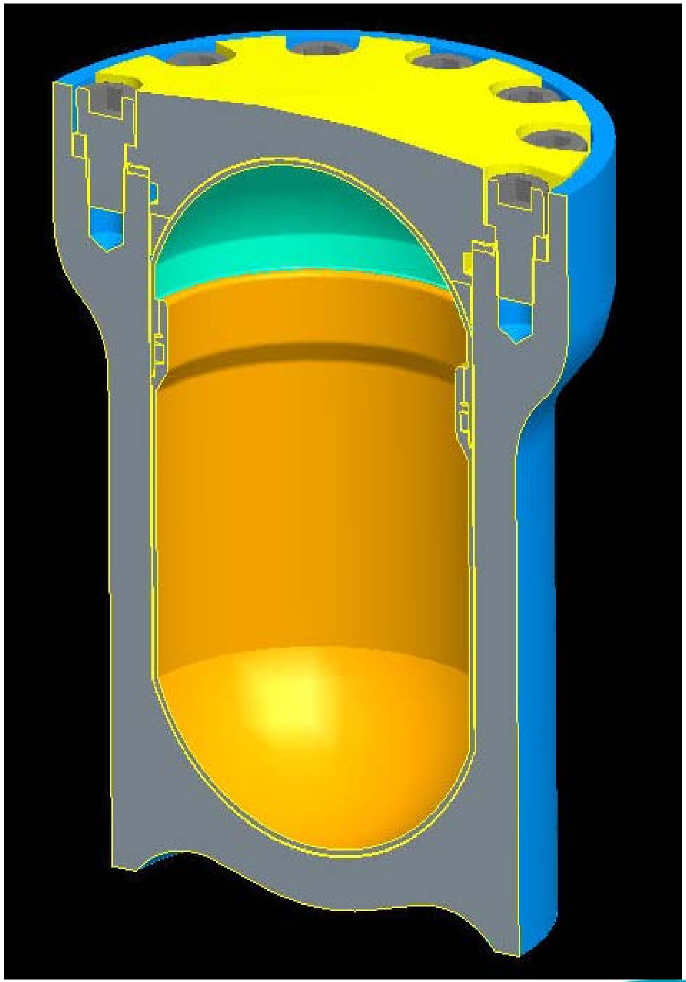
TB-1 Containment Vessel
(Shown with T-Ampoule)

Attributes:

- PH13-8Mo stainless steel
- 12 fasteners
- Copper gasket and O-ring
- 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



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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
- Minimum 0.060" wall thickness
- Contents include bulk Pu metal and sample containers supported by titanium structure
- Maximum gross weight of 4.6 lbs (2.1 kg)

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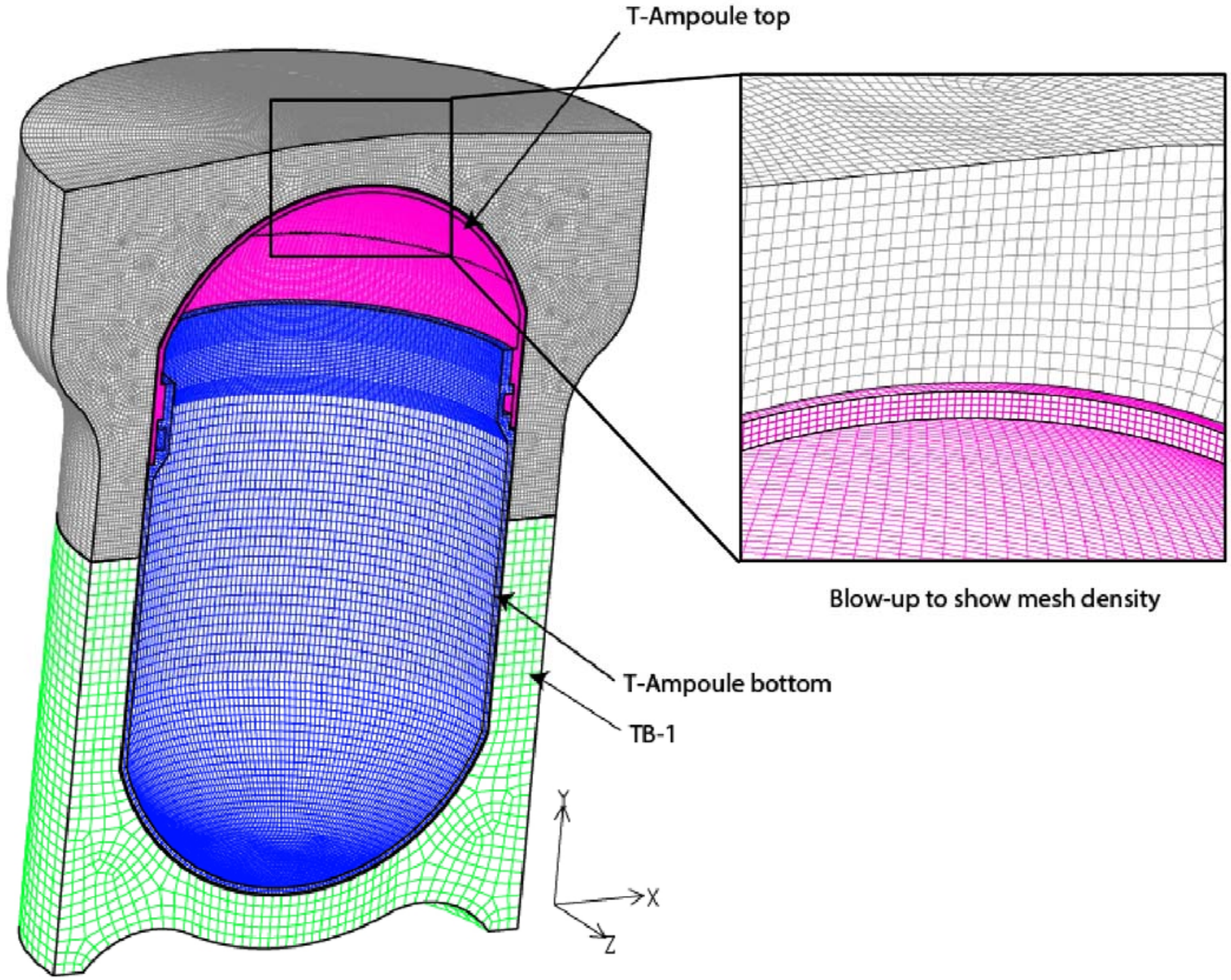
TB-1 and T-Ampoule PRONTO Model



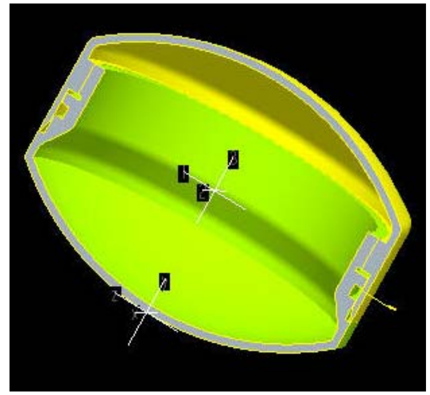
?40,000 TB-1 ?lements

?0,000 T-Ampoule ?ments

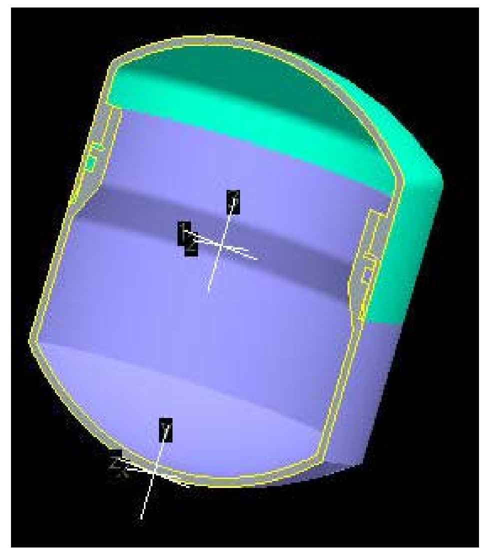
Sample Containers (SC)

Attributes:

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



SAMPLE CONTAINER SC-1

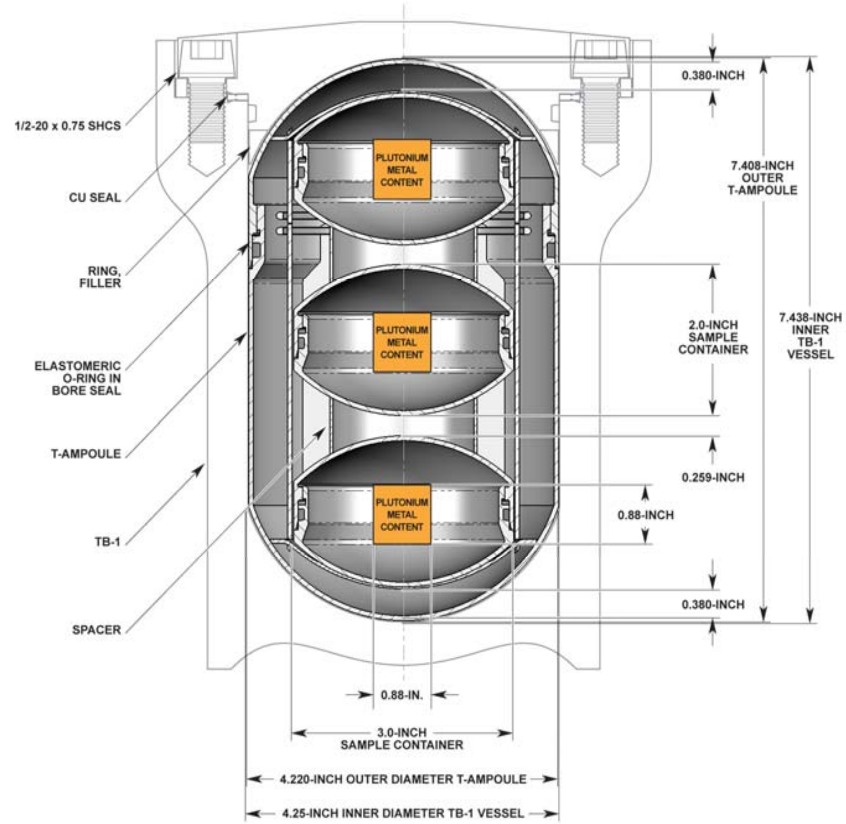


SAMPLE CONTAINER SC-2

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**

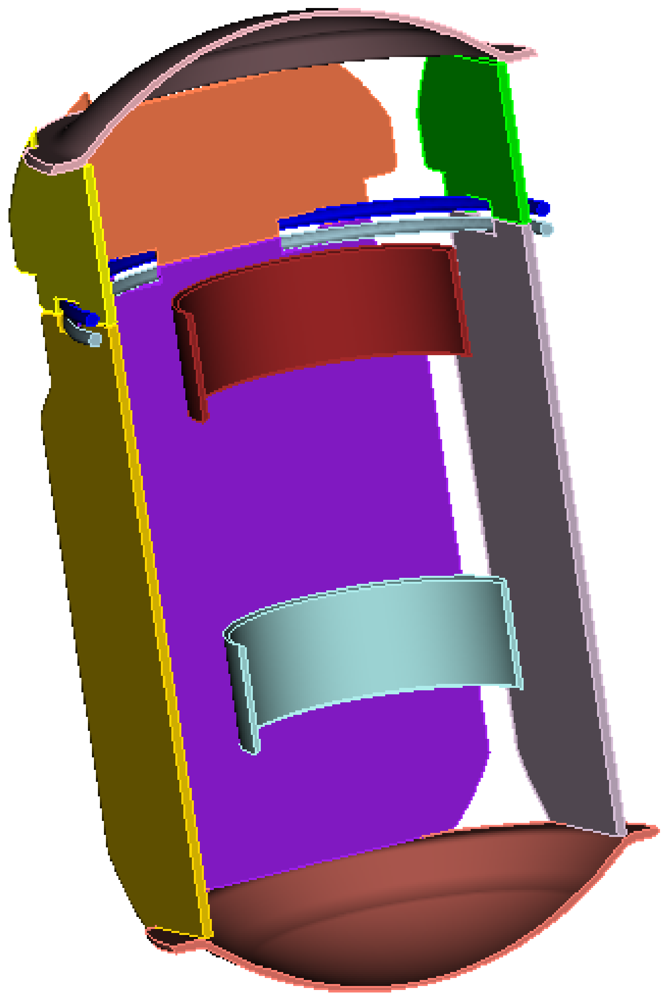


Three SC-1 Sample Containers in T-Ampoule

Sample Containers Cradle

Attributes:

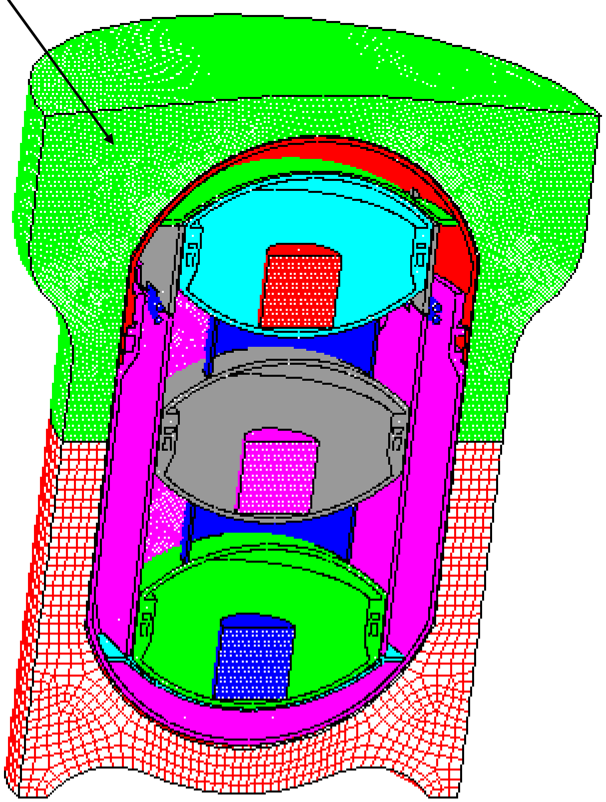
- Sharp titanium legs and asymmetric edges can unfortunately cause localized stress risers in contact with T-Ampoule
- Ti-6Al-4V construction (~0.06(
- No welding



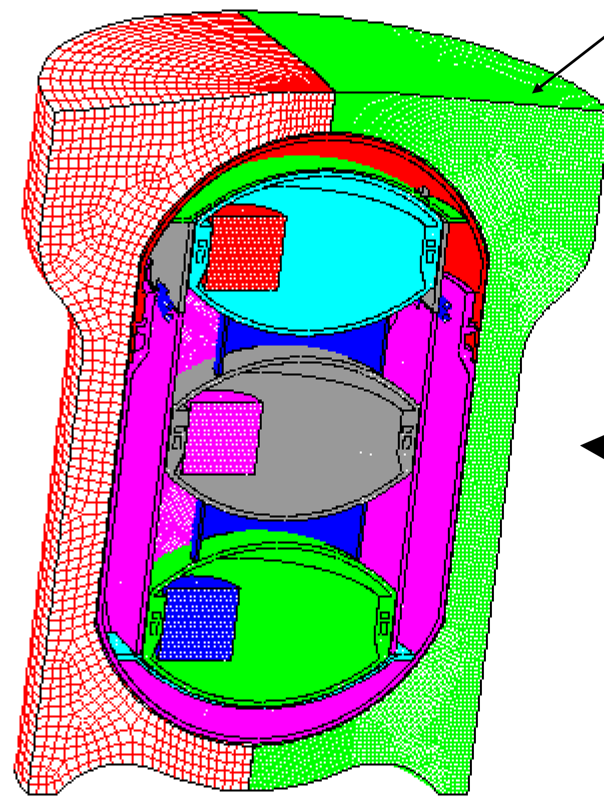
Three SC-1 Lumped Pu Contents Models

Impacting end

High density mesh



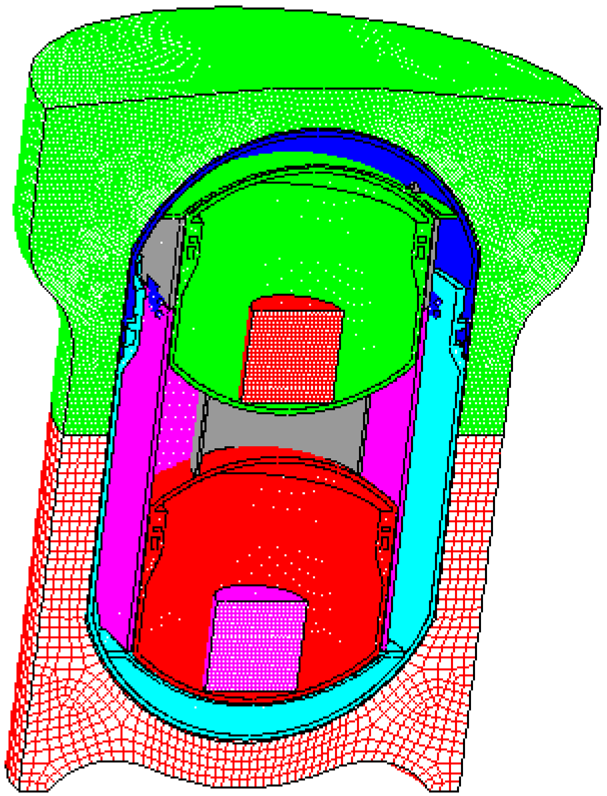
High density mesh

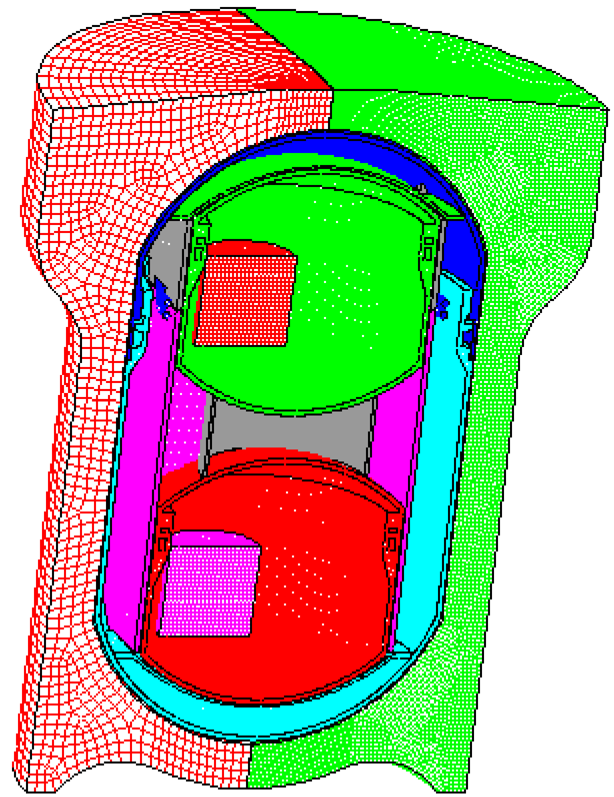


Side impact

Assume worst-case locations of contents; no Ta foil

Two SC-2 Lumped Pu Contents Models





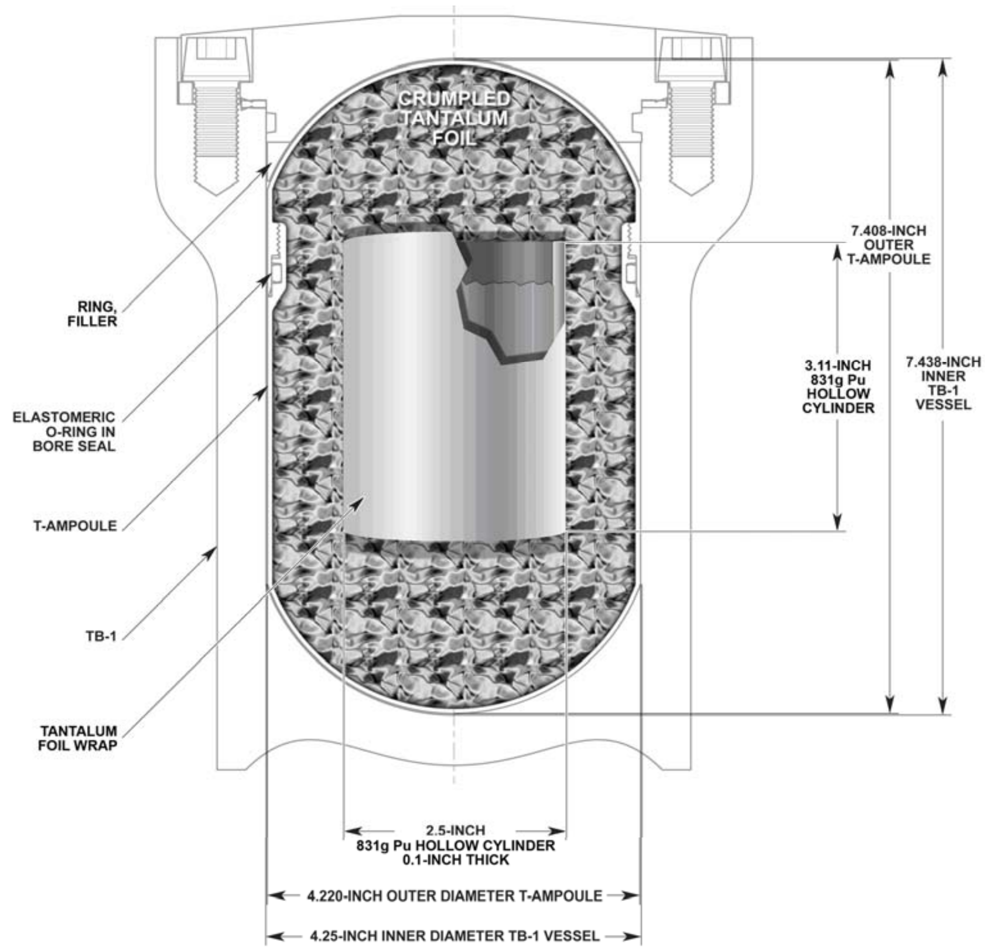
Note larger Pu cylinders with higher mass

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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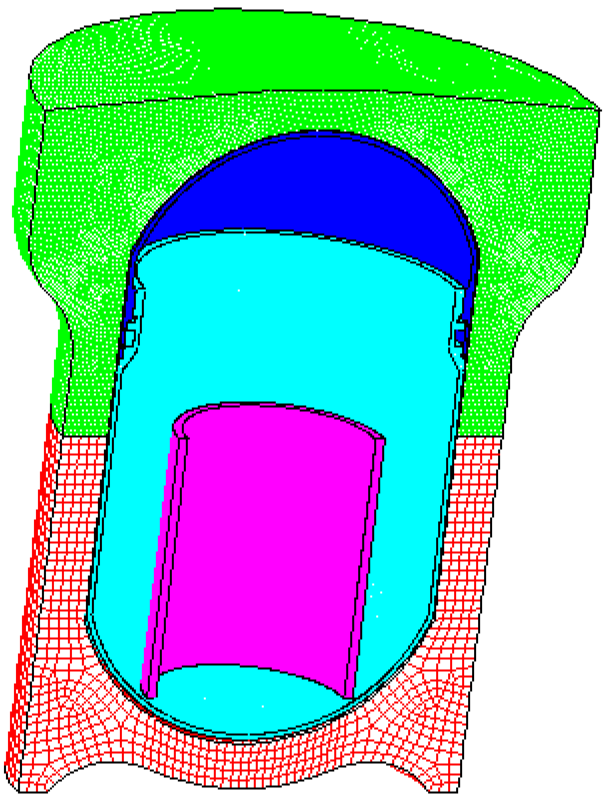
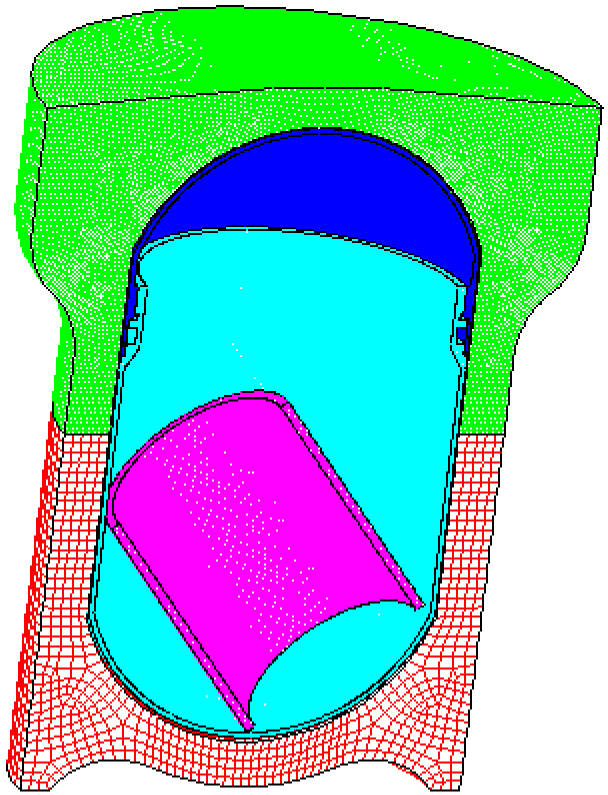
831 g ER Cylinder Models



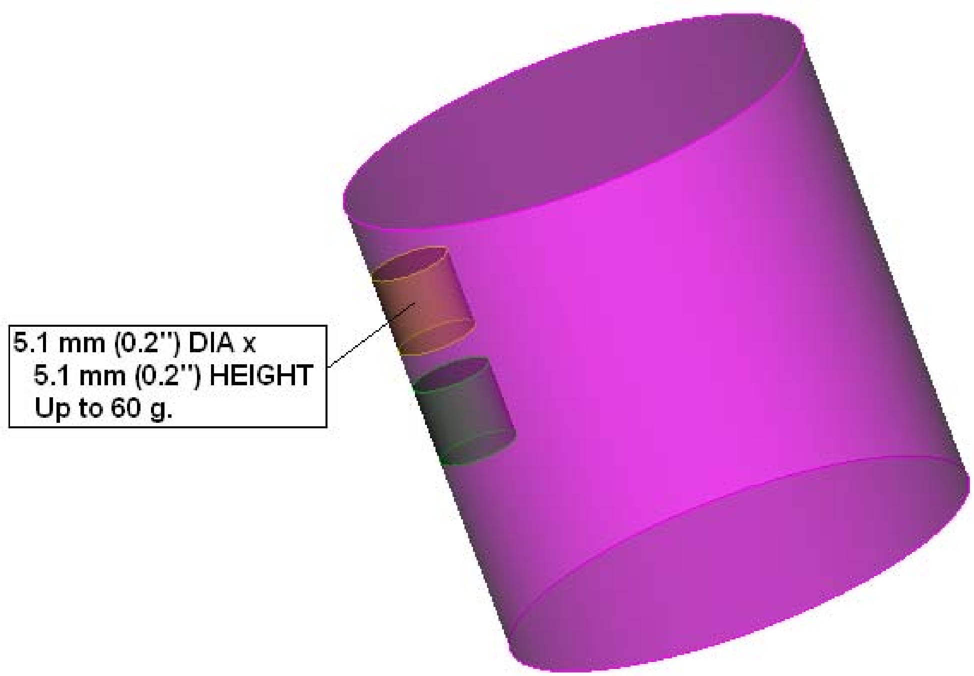


LANL-Defined Composite Sample Configuration 1: Small Pu Cylinders

One configuration:

The individual cylinders (at 1.7 grams each) are combined into a single cylinder of 16.85 mm dia x 16.85 mm height weighing 60 grams using the strength of Be metal.

Up to 35 individual 1.7 gram cylinders (59.5 grams) could be packaged in each sample container.

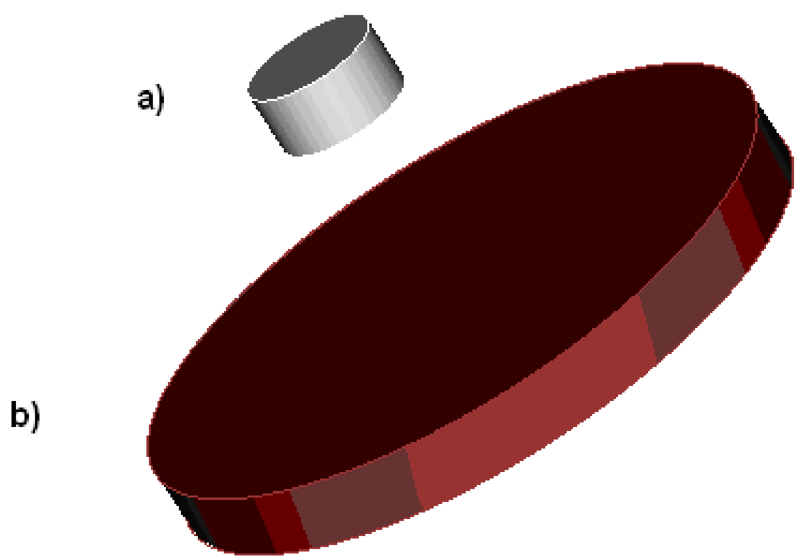


LANL-Defined Composite Sample Configuration 2: Composite Disk

Two configurations:

a) 12 mm dia x 6 mm thick (weighing 10.8 g using Pu density) with beryllium metal strength.

b) b) 45 mm dia x 2.37 mm thick (weighing 59.9 g using Pu density) with beryllium metal strength.



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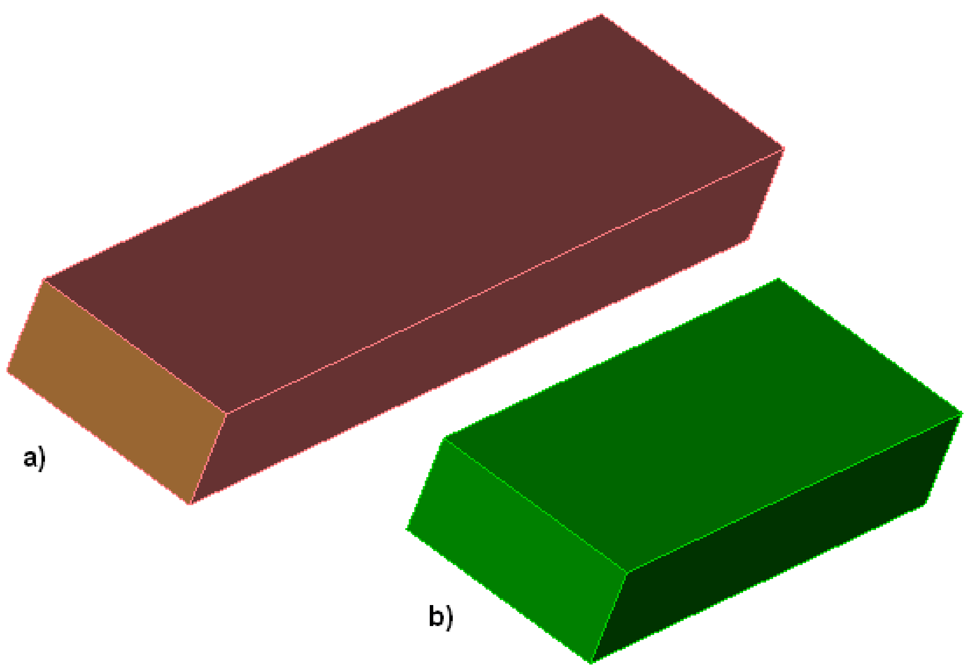
LANL-Defined Composite Sample Configuration 3: Flat Composite Plate

Two Configurations:

a) **50 mm length x 6 mm thick x 12.5 mm wide composite plate (weighing 59.6 g using Pu density) with beryllium metal strength.**

b) **b) 30 mm length x 6 mm thick x 12.5 mm wide composite plate (weighing 35.8 g using Pu density) with beryllium metal strength.**

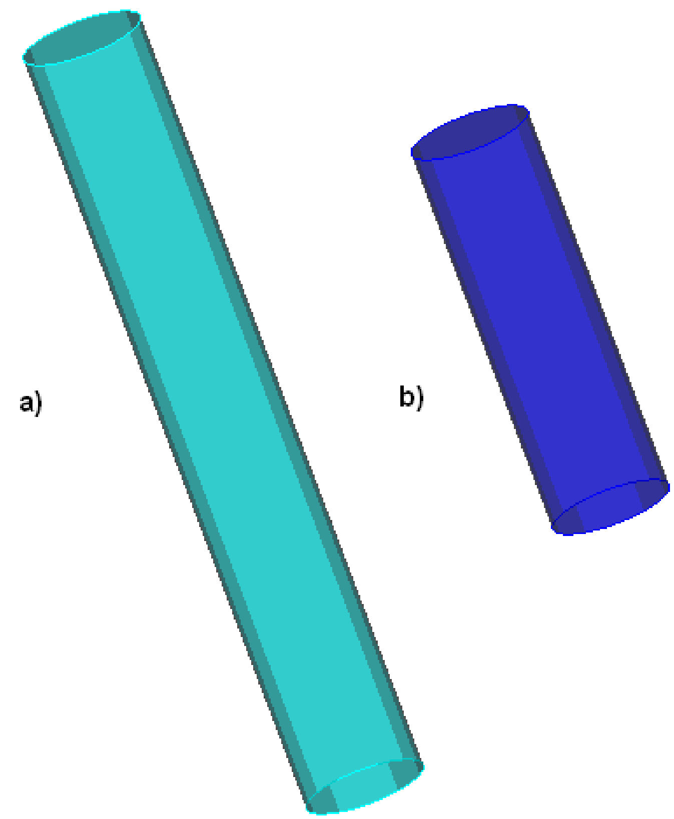


LANL-Defined Composite Sample Configuration 4: Long Pu Cylinders

Two Configurations:

a) 8.9 mm dia x 60 mm length (weighing 59.3 grams using Pu density) with beryllium strength.

b) b) 7.62 mm dia x 26 mm length (weighing 18.9 grams using Pu density) with beryllium strength.

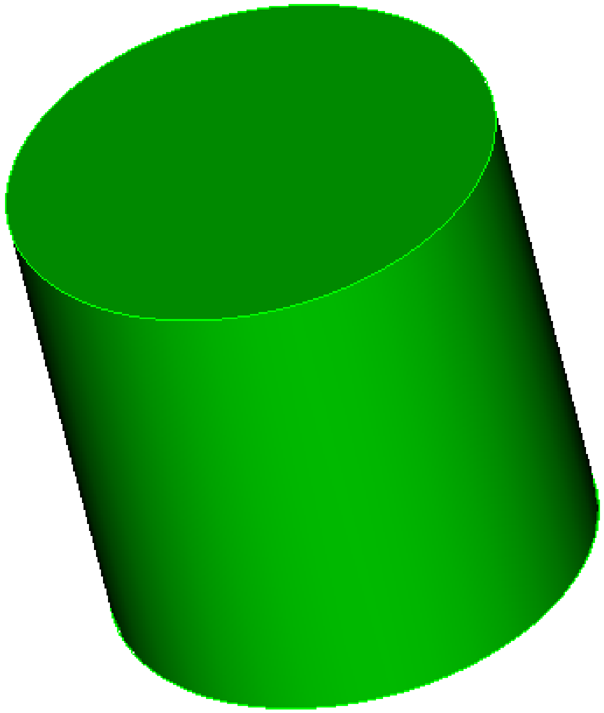


“Bounding” Composite

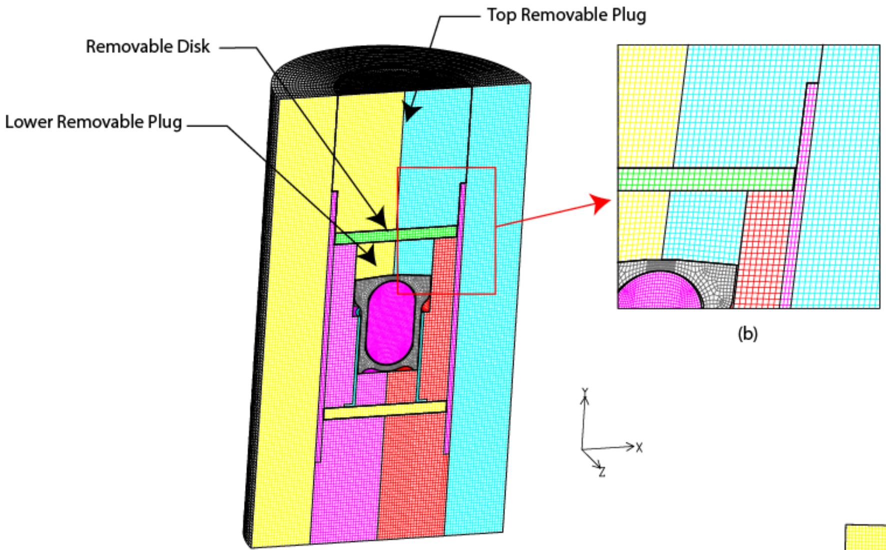
A single cylinder of 16.85 mm dia x 16.85 mm height weighing 60 grams (density of Pu) using the strength of Be metal.

This compact and strong shape maximizes net impact velocity and provides a conservatively sharp impact edge.

Cylinders always rotated to impact CGOC (sharpest).

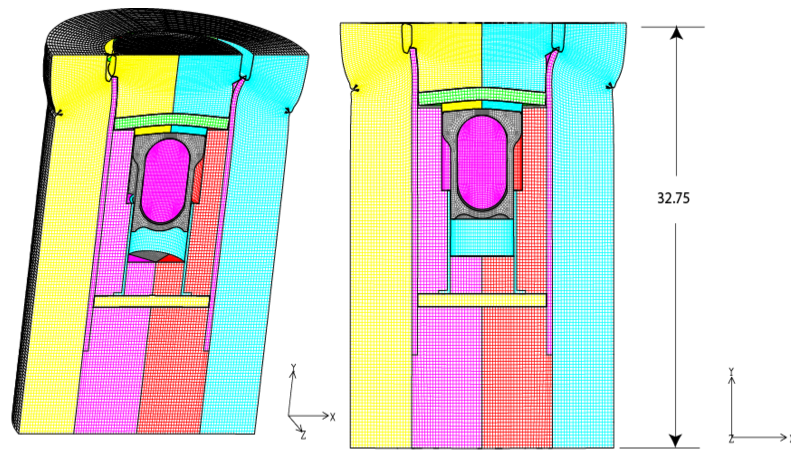


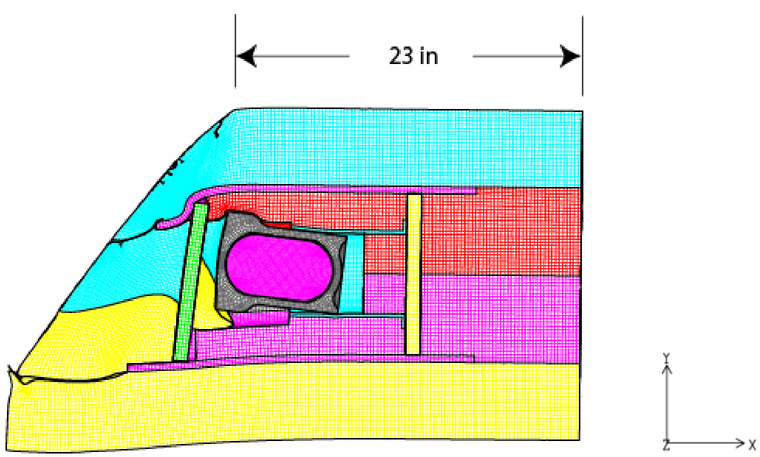
Full Package Analysis: Overpack Calculation Has Been Validated with Certification Tests

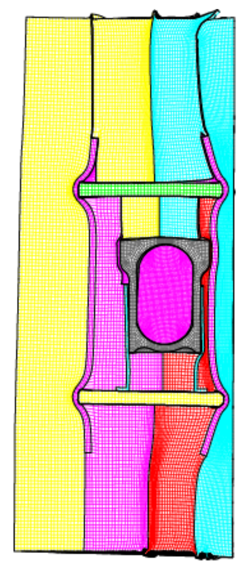


(b)

(a)

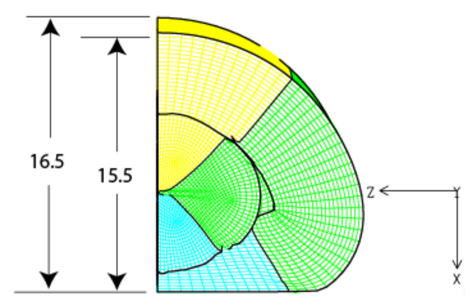






(a)

Overpack deformation at 445 ft/s



(b)

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.**
- **Be composite shape is bounding.**
- **ER cylinders assume strongest dimensions.**
- **Ductile crack propagation is not modeled; assume "failure" at ductile crack** *initiation.*

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Acceptance Criteria

- **TB-1 containment vessel must**
  - **be "essentially leak tight" in air transport accidents ($<A_2$/wk)**
  - **meet thru-wall ASME stress limits for NCT and HAC**
    - **NCT and HAC limits already accepted via certification tests**
    - **HAC dynamic crush is new requirement since original SAR**

- **T-Ampoule eutectic barrier must maintain integrity.**

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:**

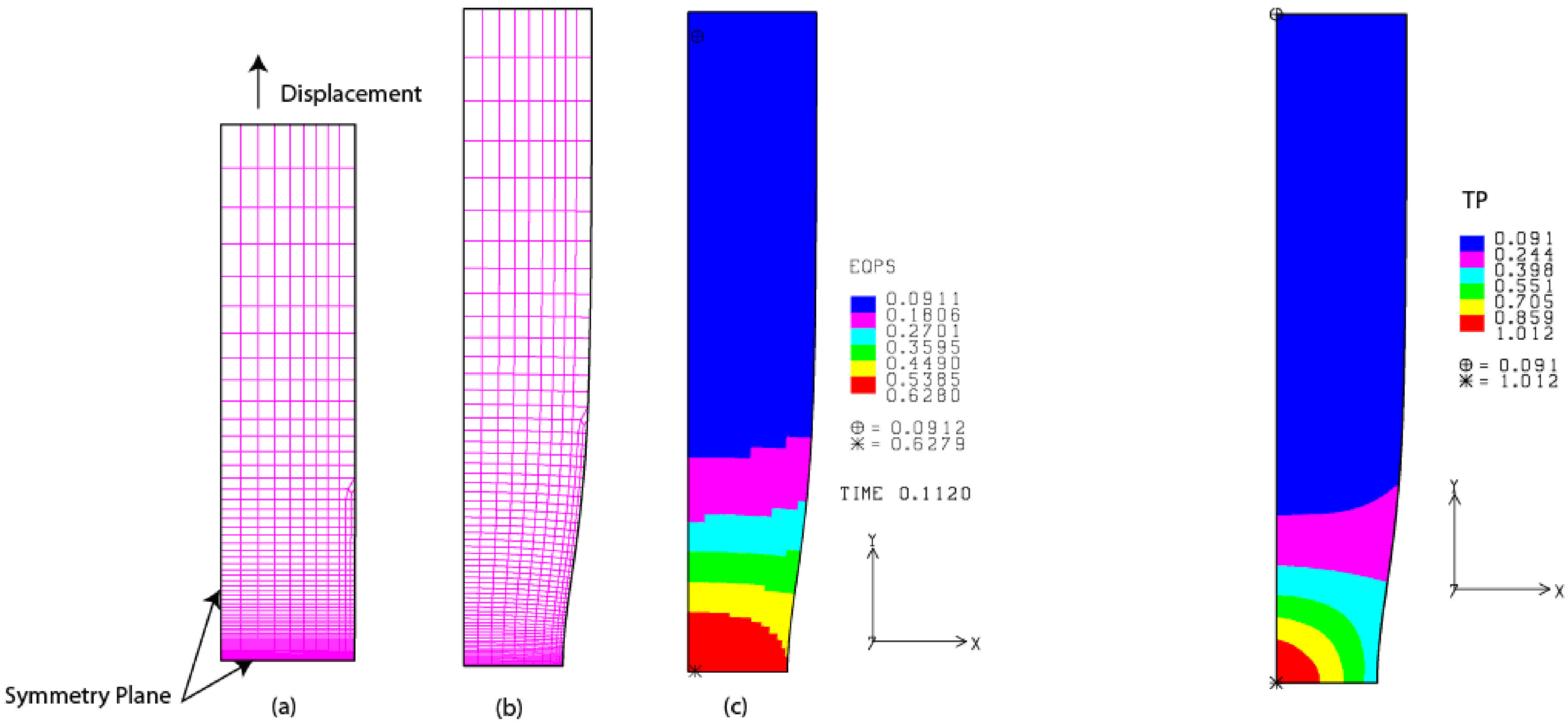
$$TP = \int_0^{\bar{\varepsilon}_{pf}} \left\langle \frac{2\sigma_1}{3(\sigma_1 - \sigma_H)} \right\rangle^4 d\bar{\varepsilon}_p$$

- **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.**

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 the 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



Combined Model Results

- Example of Full Models for High Speed and HAC.
- Sample Runs (only 5 chosen out of total 53 analyses)
  - High Speed 2 Amp (45 deg) Side Impact
  - High Speed 831 g ER Cylinder Angled for End Impact
  - High Speed 831 g ER Cylinder CGOC Impact
  - Be Composite High Speed 3 Amp (45 deg) Side Impact
  - HAC 2 Amp (45 deg) CGOC Impact
- In no case does the impact of the contents induce ductile tearing of the eutectic barrier.

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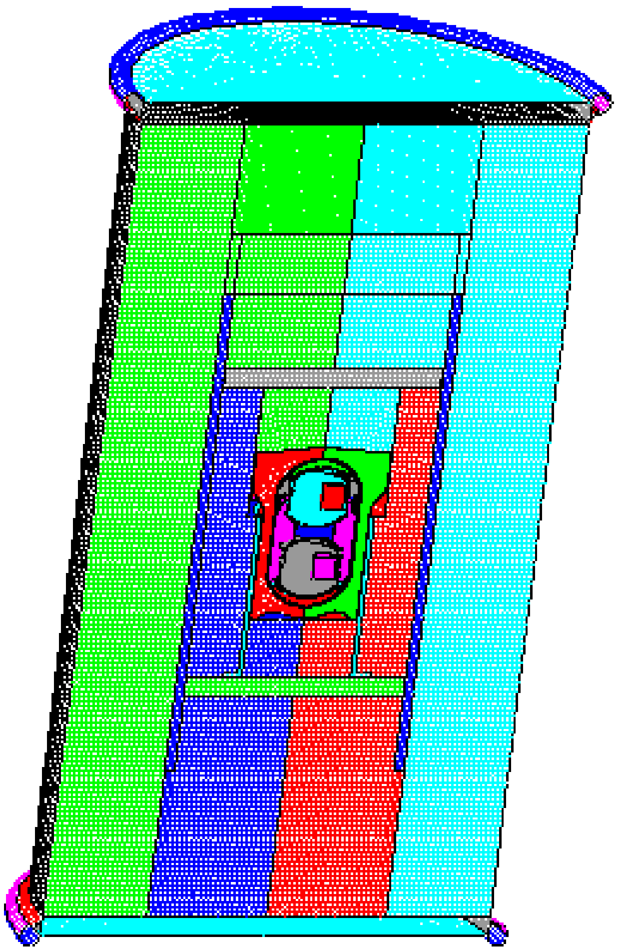
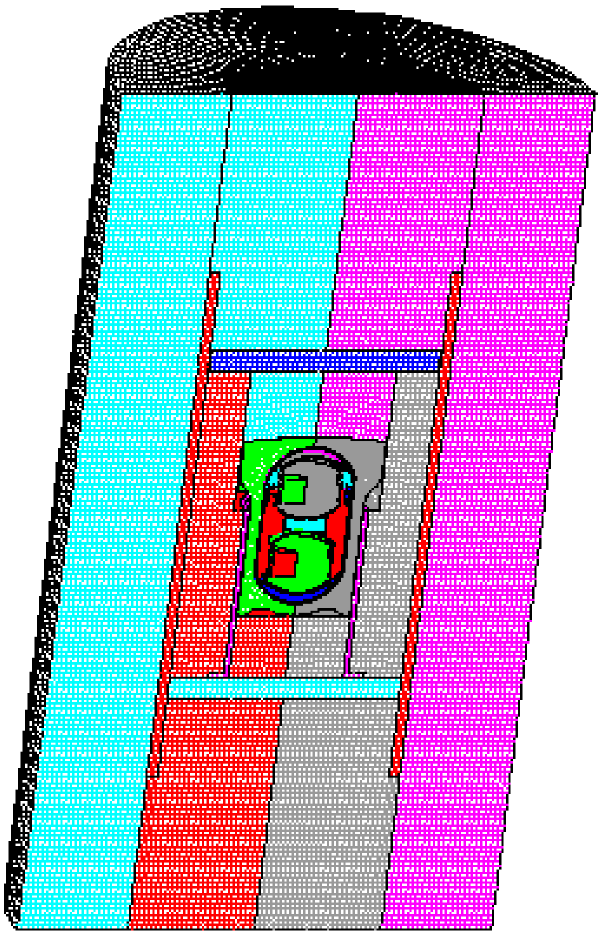
Example of Full Models (Approximately 2,000,000 Elements)

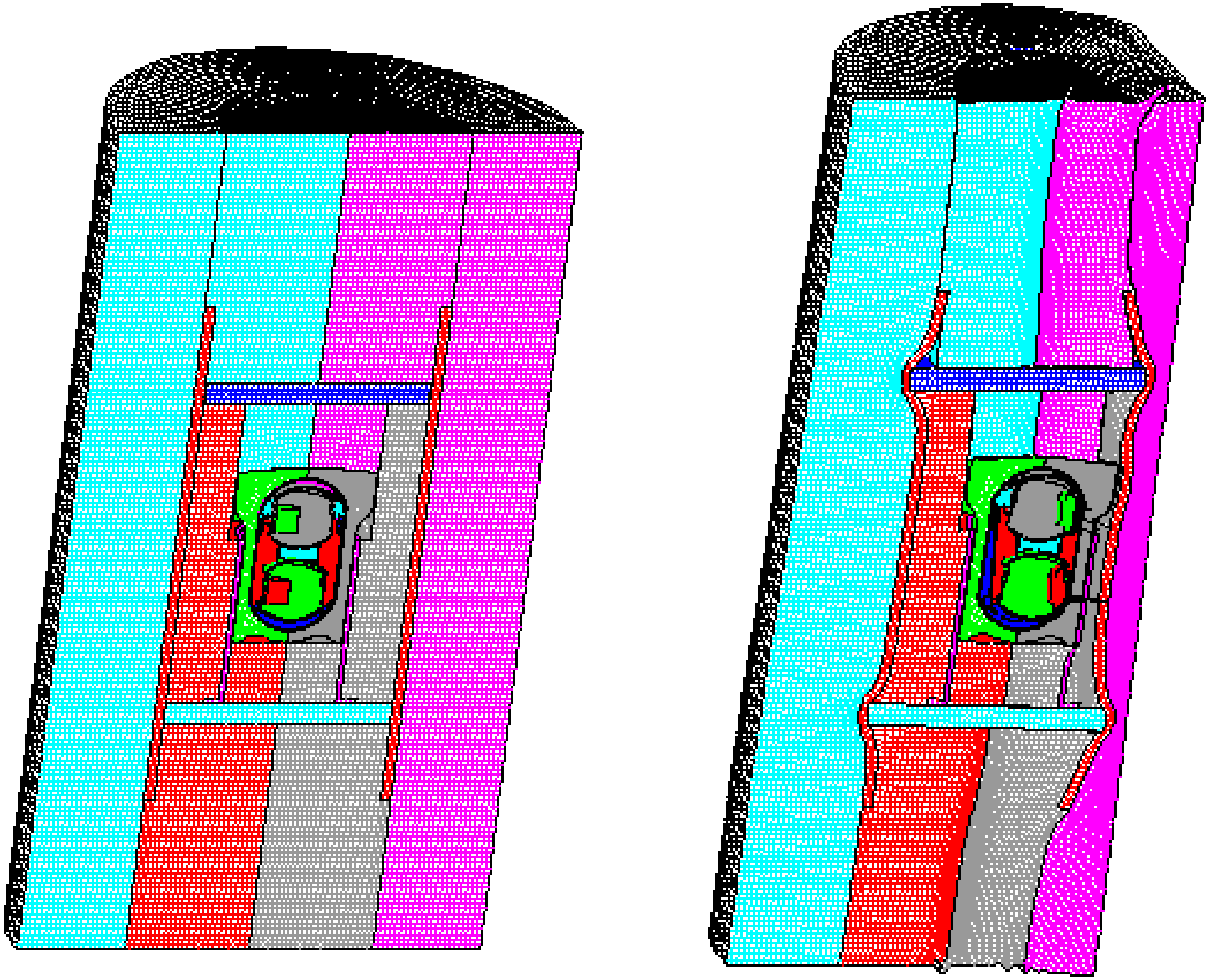


HAC and NCT



High Speed

High Speed 2A (45 deg) Side Impact



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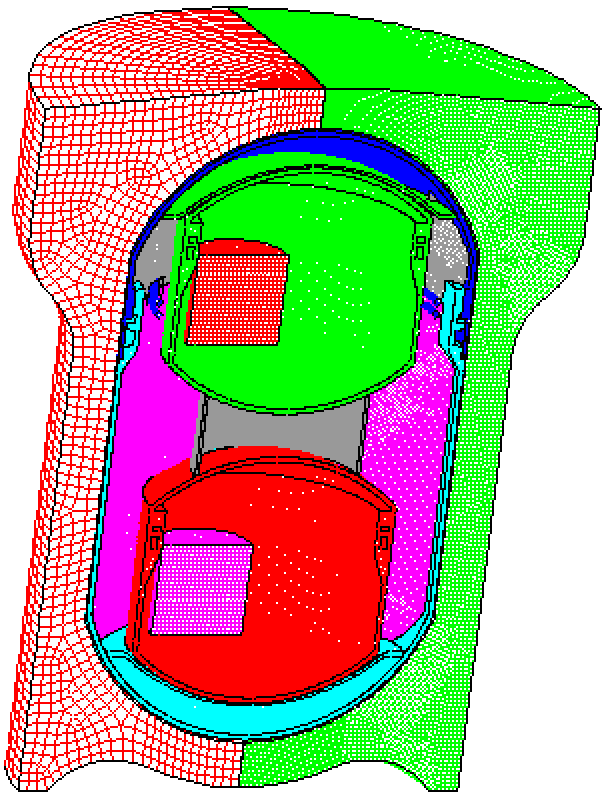
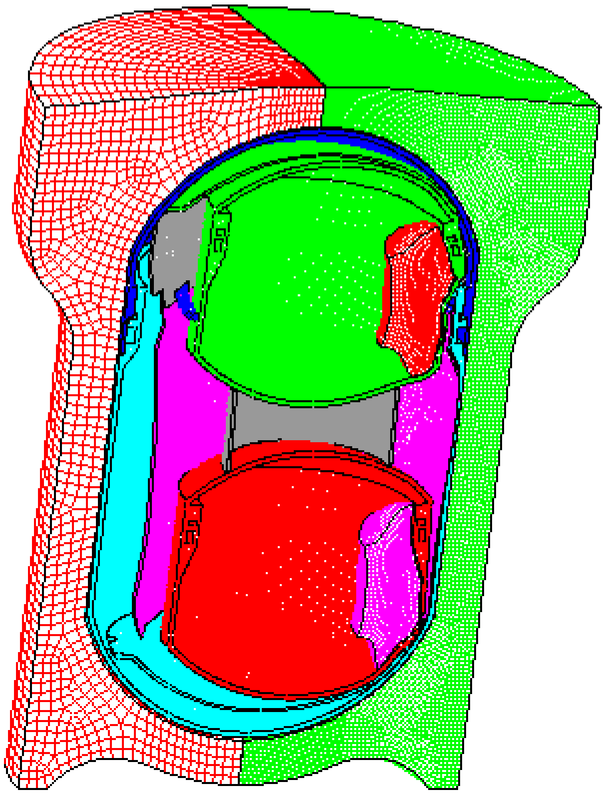
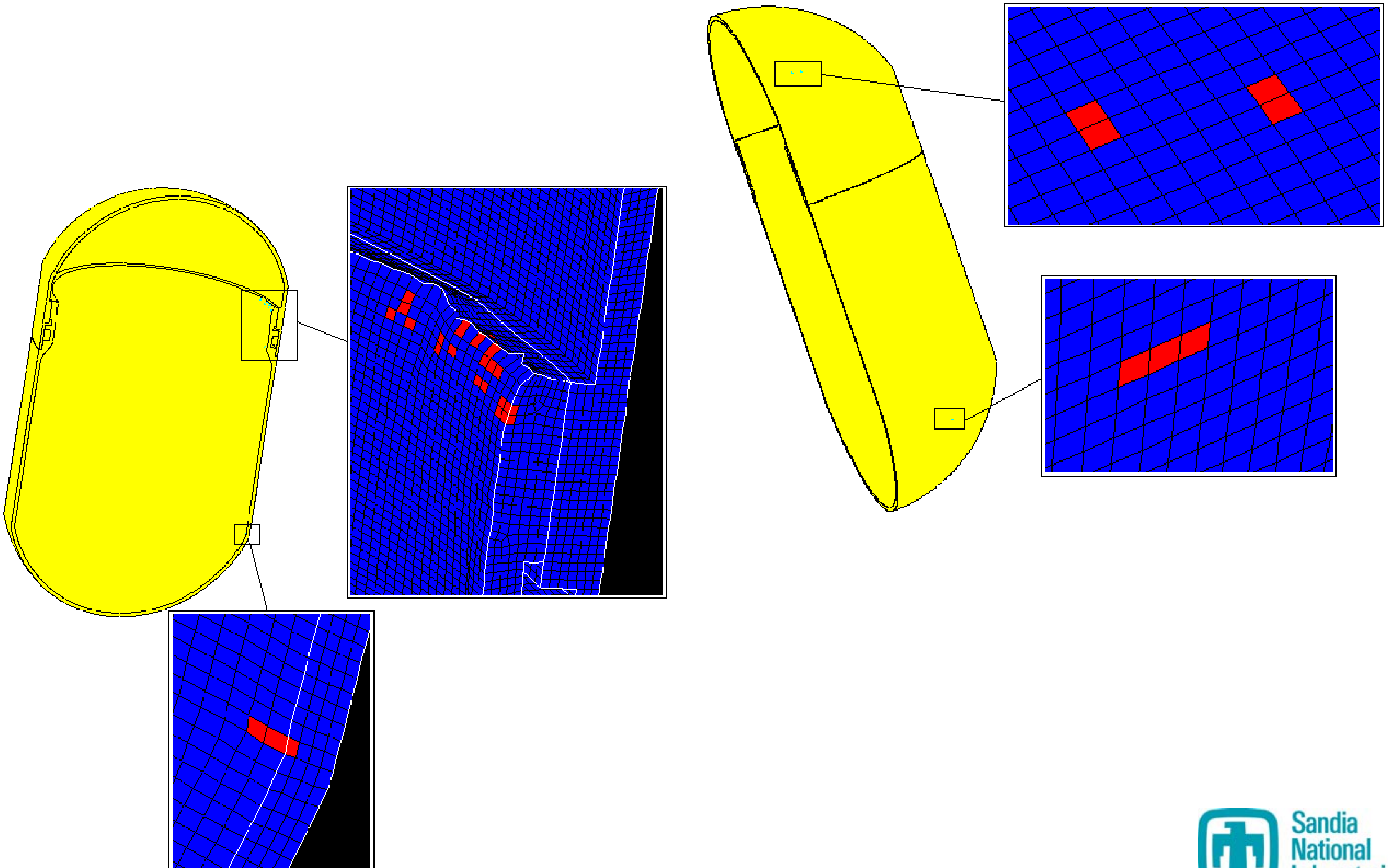
High Speed 2A (45 deg) Side Impact

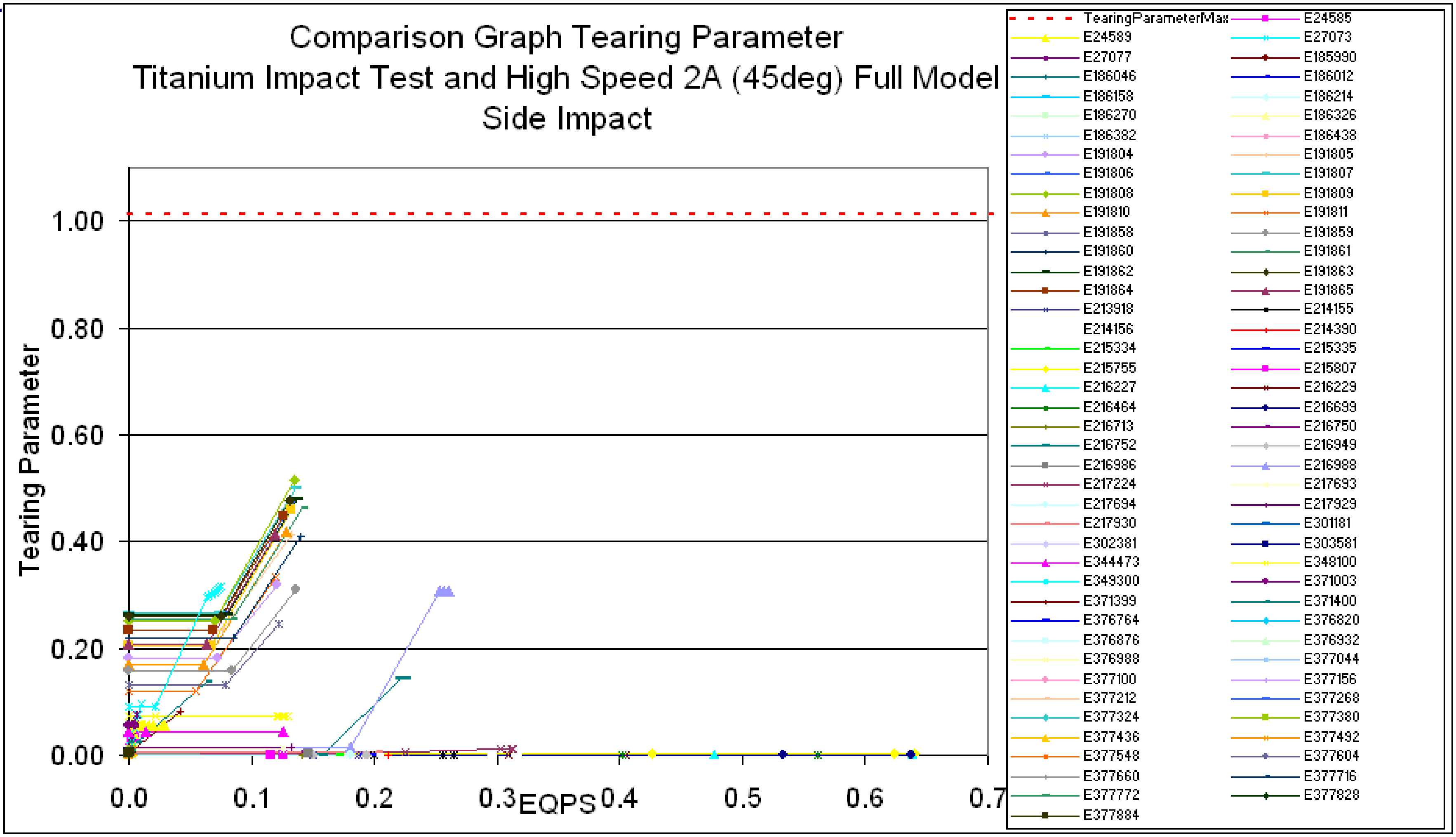




High Speed 2A (45 deg) Side Impact



High Speed 2A (45 deg) Side Impact

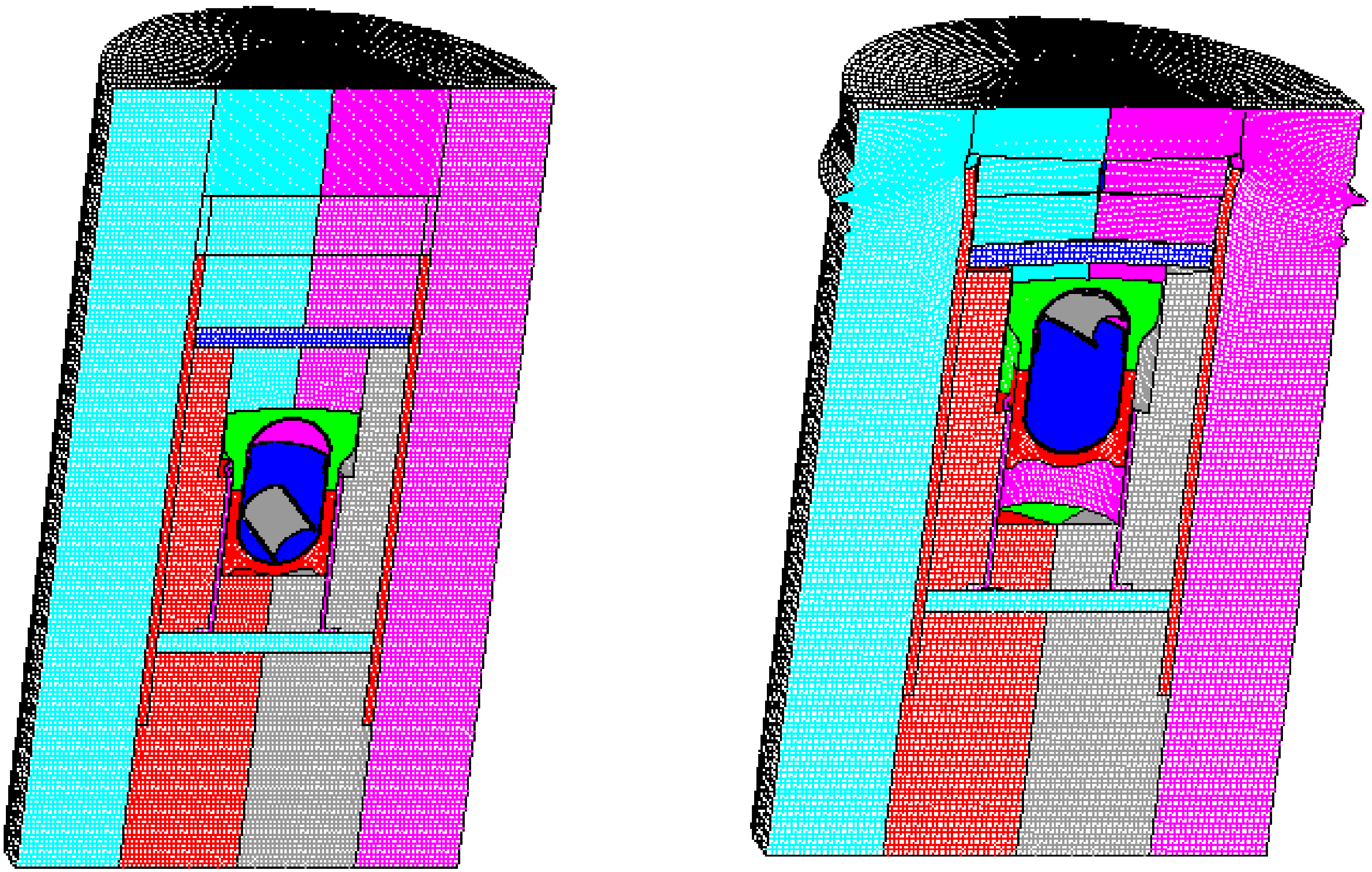


0 Elements Exceed the Critical Tearing Parameter

Friction Variation

- **Plus or minus 33% on friction coefficient (from referenced 0.30) were analyzed for the 2 Ampoule side impact 45-degree rotated case:**
  - **0.40 dynamic friction yielded very similar results for both T-Ampoule Tearing Parameter and TB-1 EQPS**
  - **0.20 dynamic friction also yielded similar results for TB-1 EQPS, but much reduced T-Ampoule Tearing Parameter (peaking around <0.2 vs. 0.5)**

Cylinder – 831 g (Angled End Impact)



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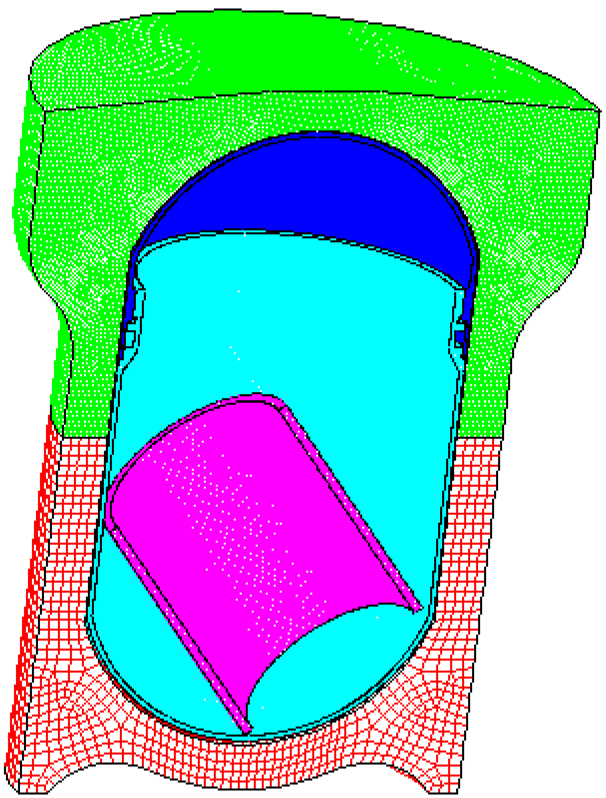
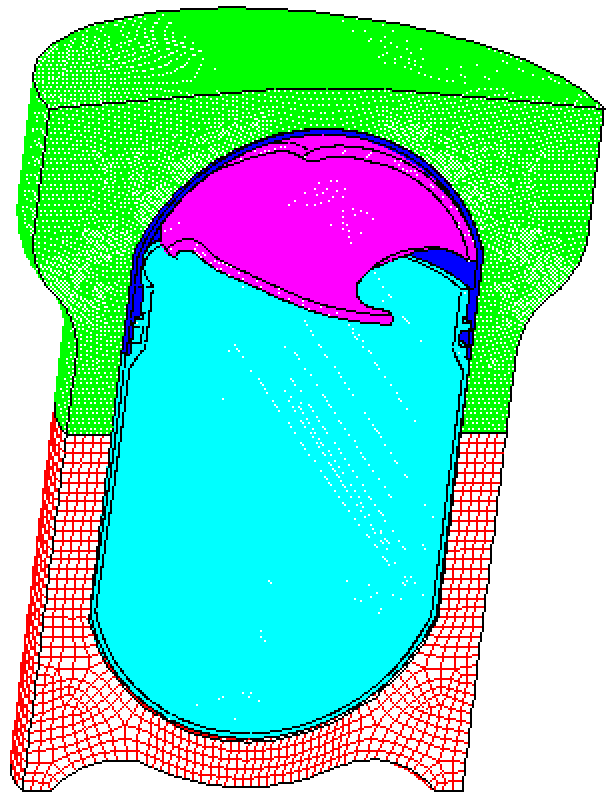
Cylinder – 831 g (Angled End Impact)





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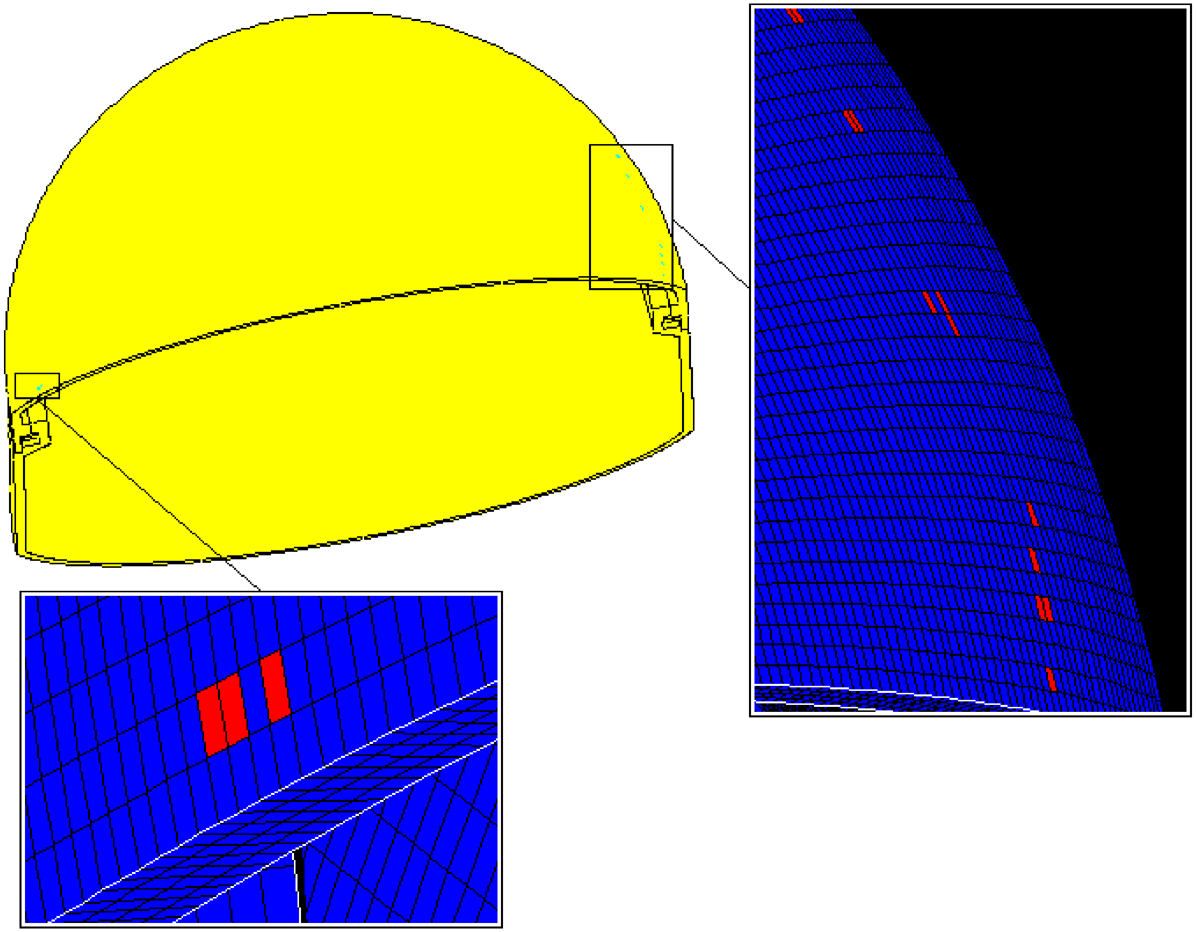
Cylinder – 831 g (Angled End Impact)



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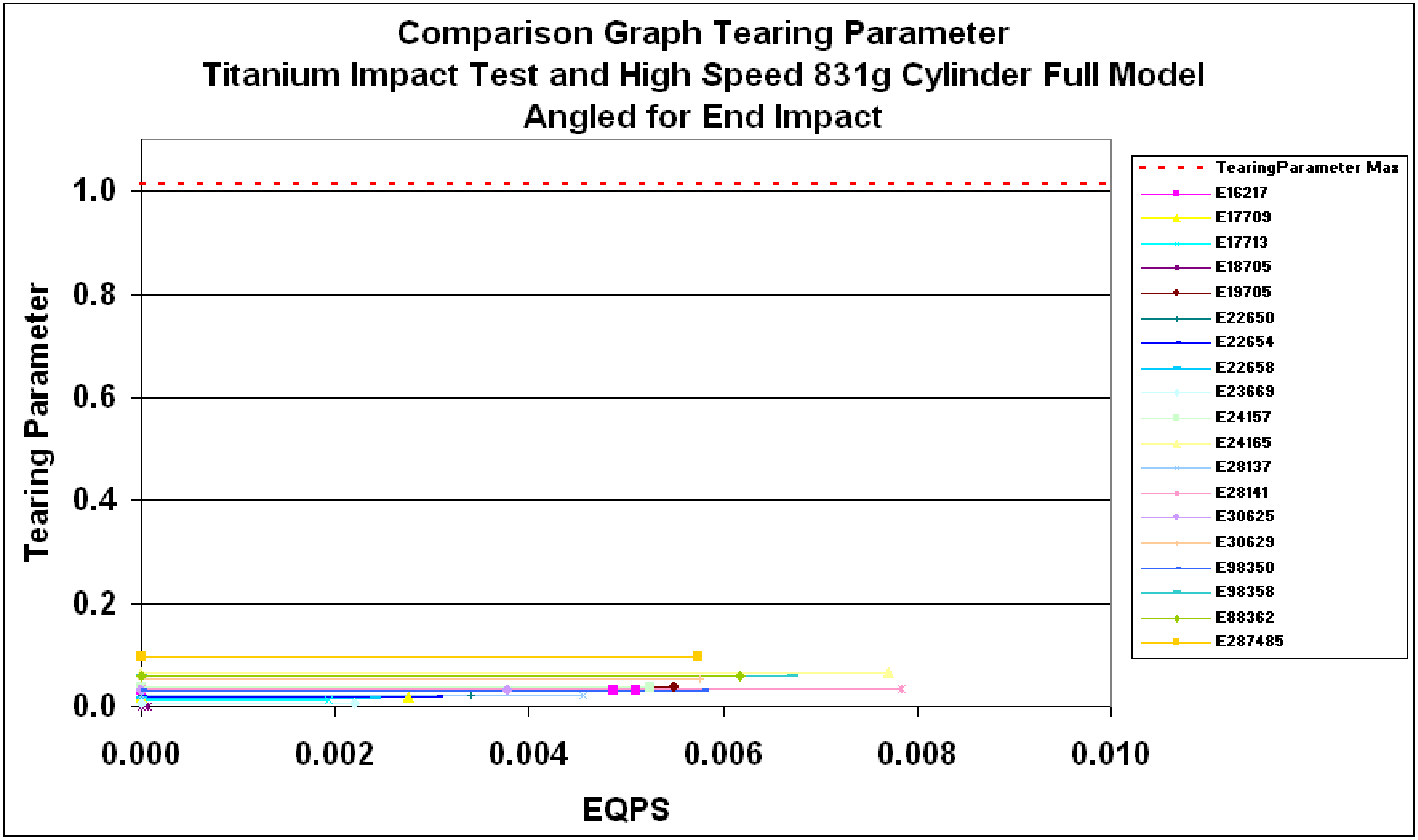
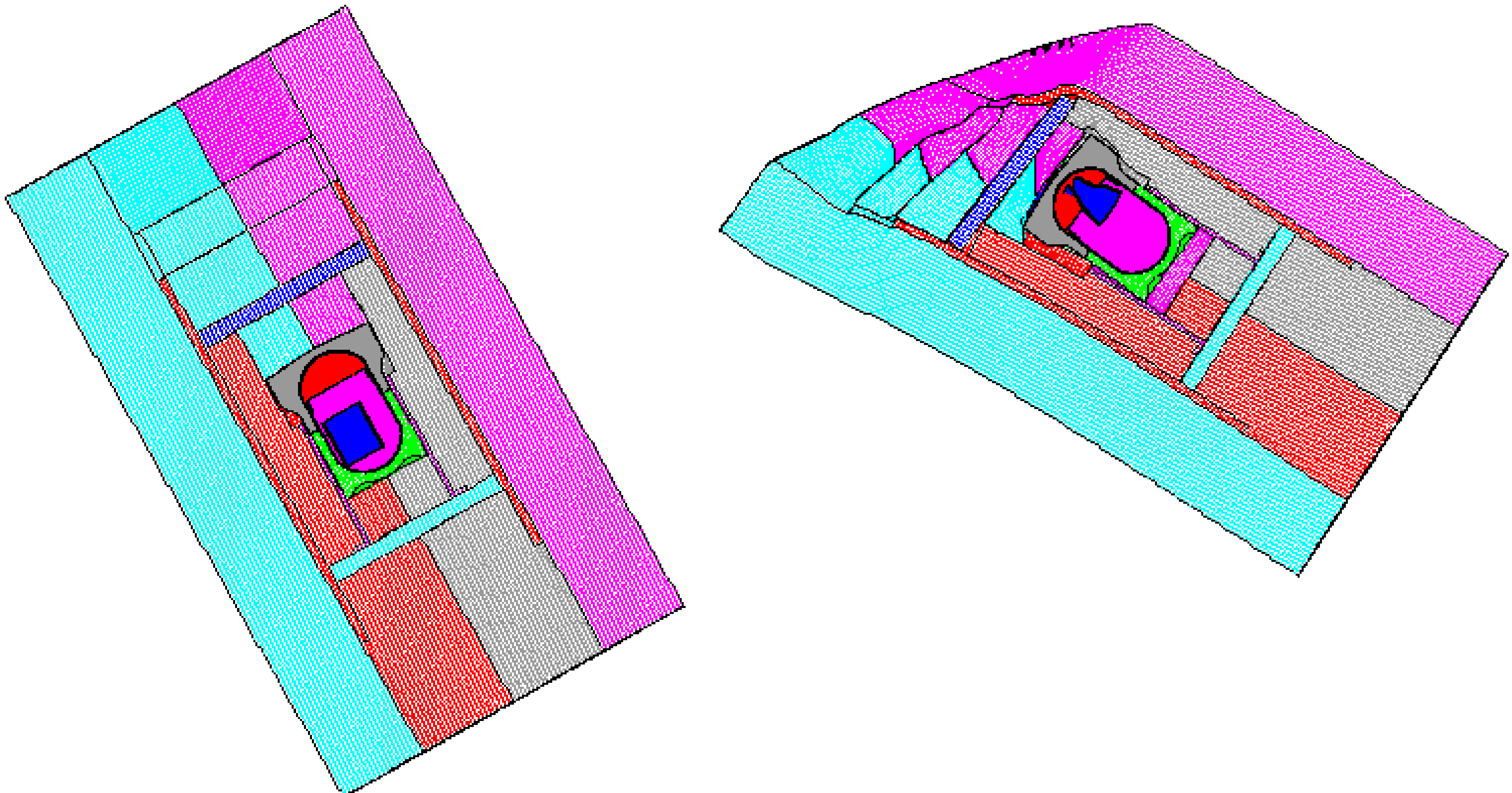
Cylinder – 831 g (Angled End Impact)



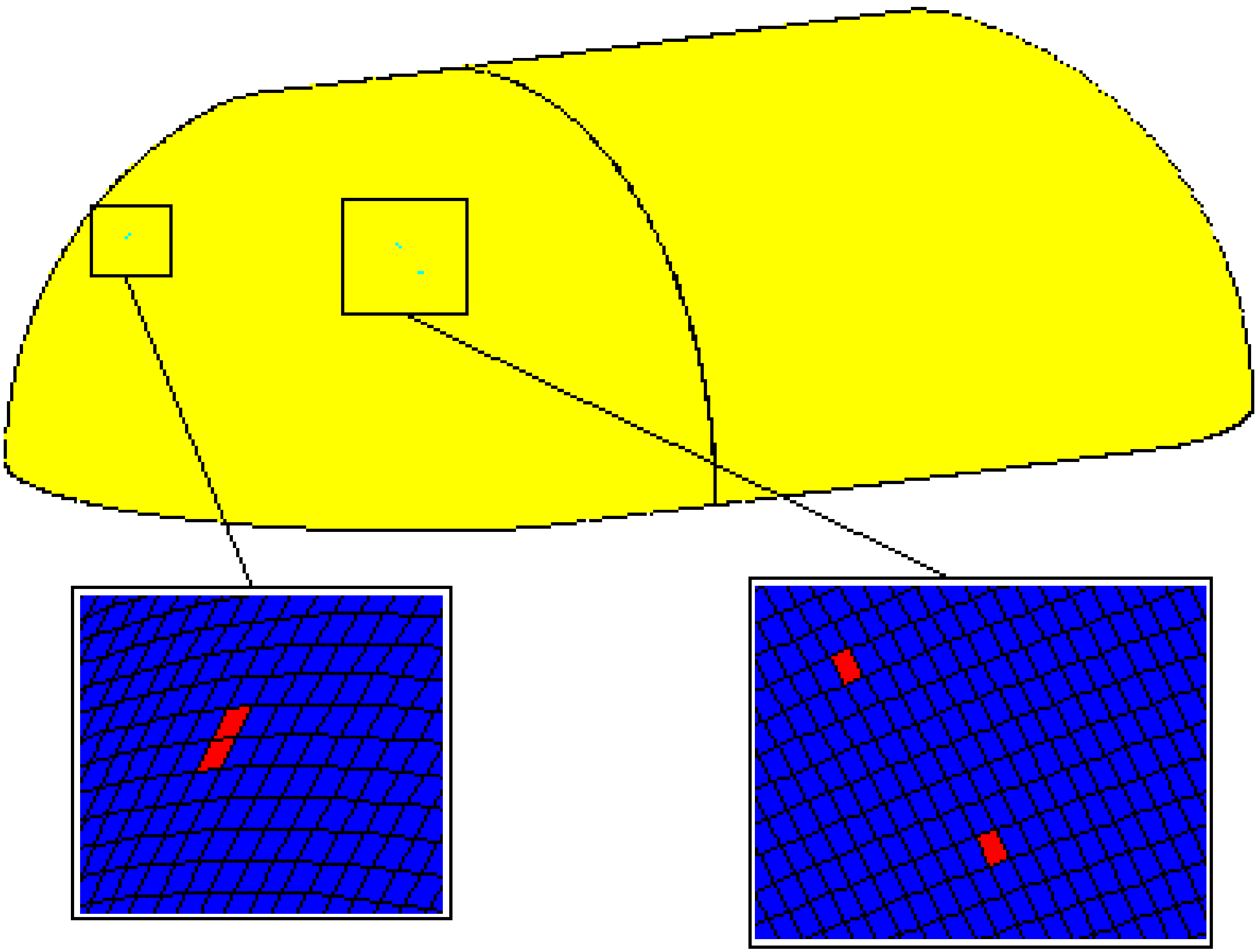
0 Elements Exceed the Critical Tearing Parameter

Cylinder – 831 g (CGOC Impact)



0 Elements Exceed Critical Tearing Parameter

Cylinder – 831 g (CGOC Impact)



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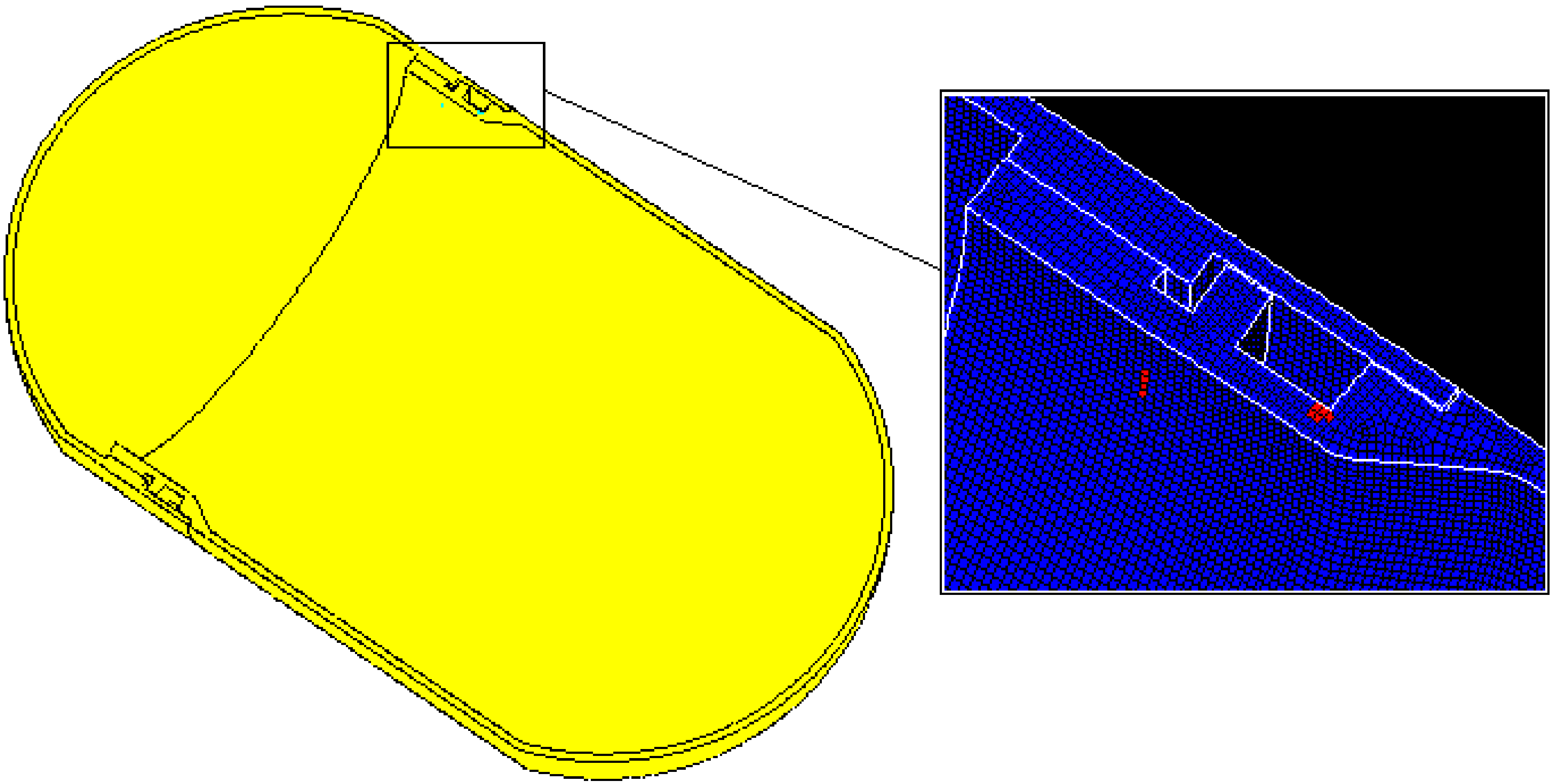
Cylinder – 831 g (CGOC Impact)



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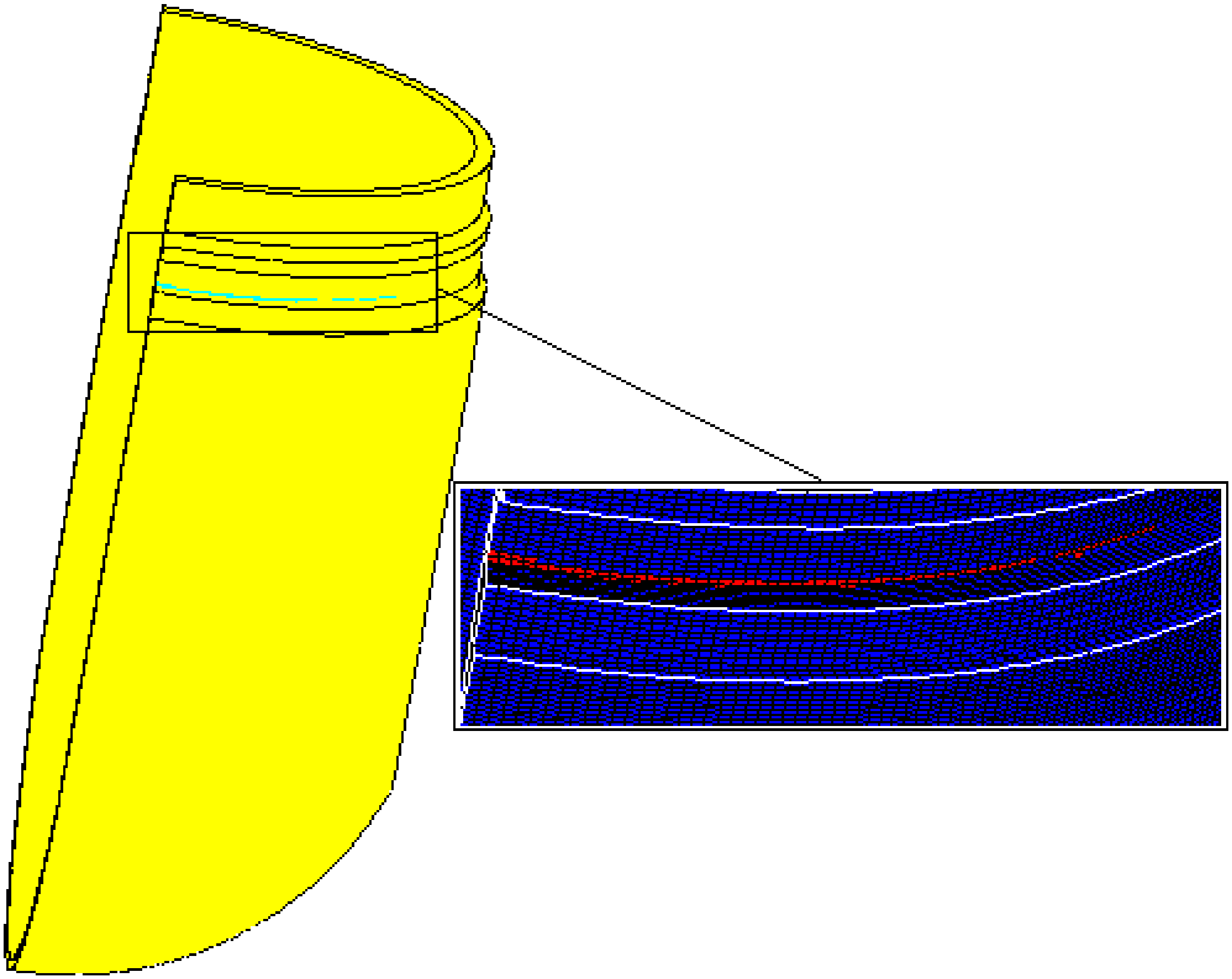
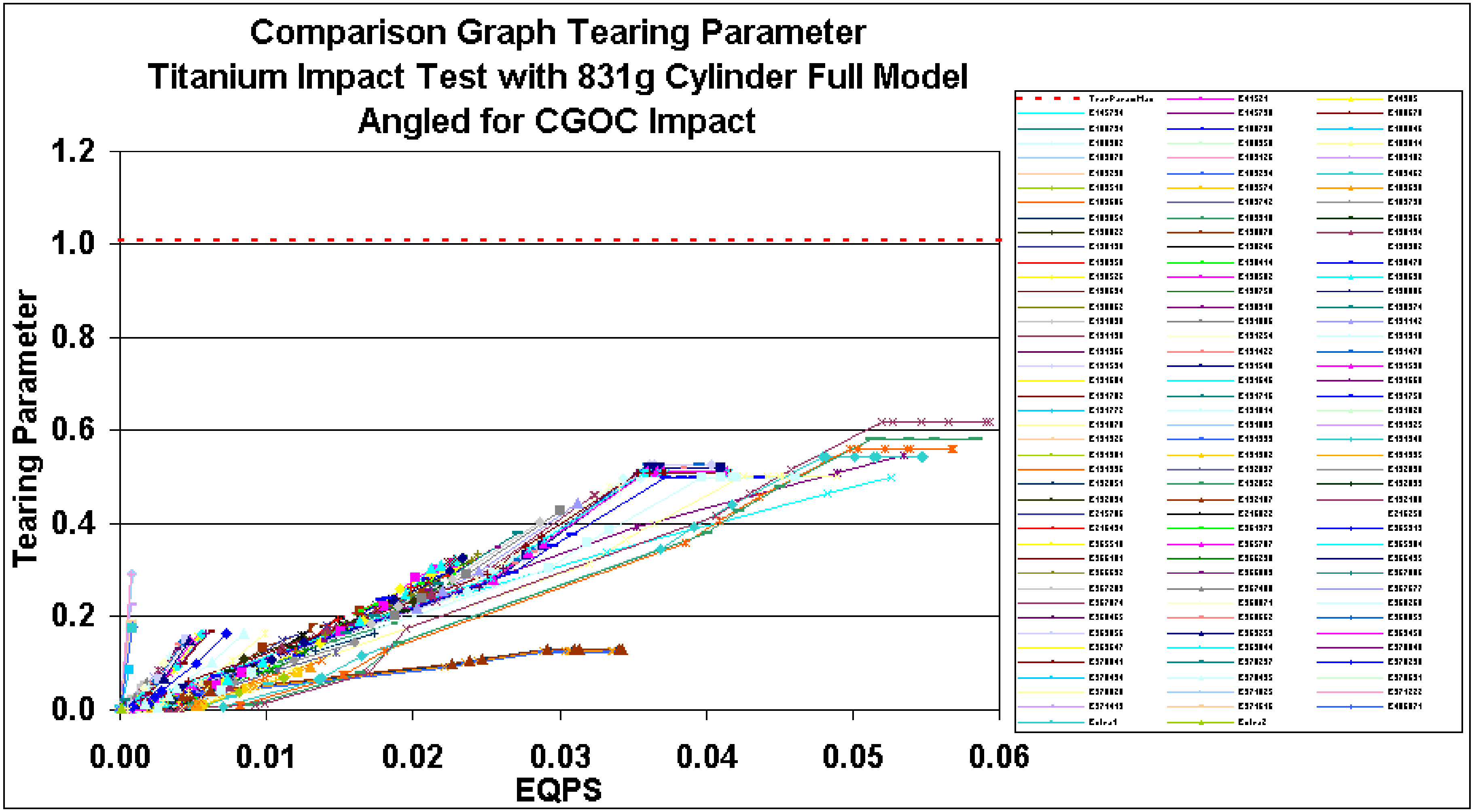
Cylinder – 831 g (CGOC Impact)

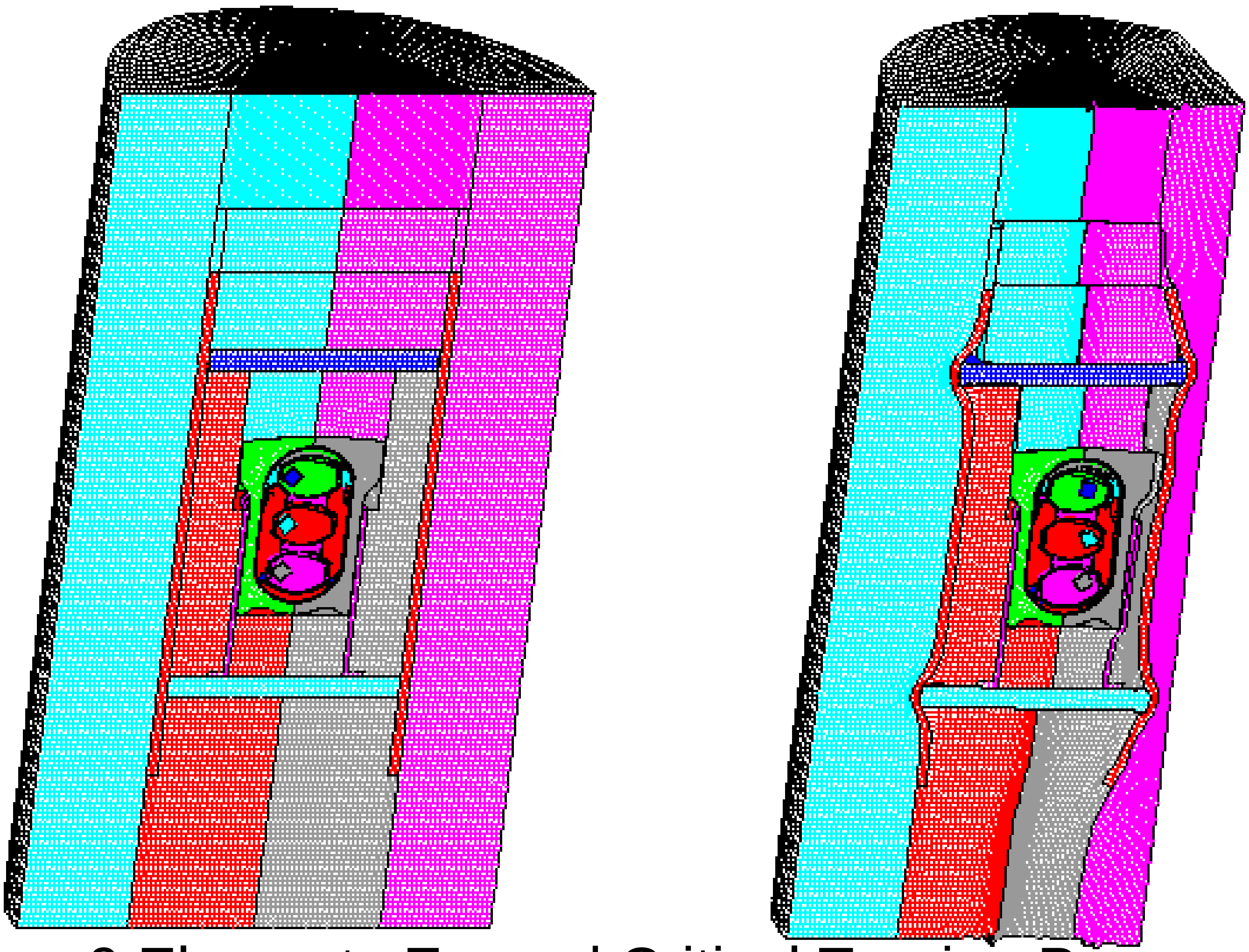


Cylinder – 831 g (CGOC Impact)



0 Elements Exceed the Critical Tearing Parameter

Be Composite Cylinder (45 deg) Side Impact



0 Elements Exceed Critical Tearing Parameter

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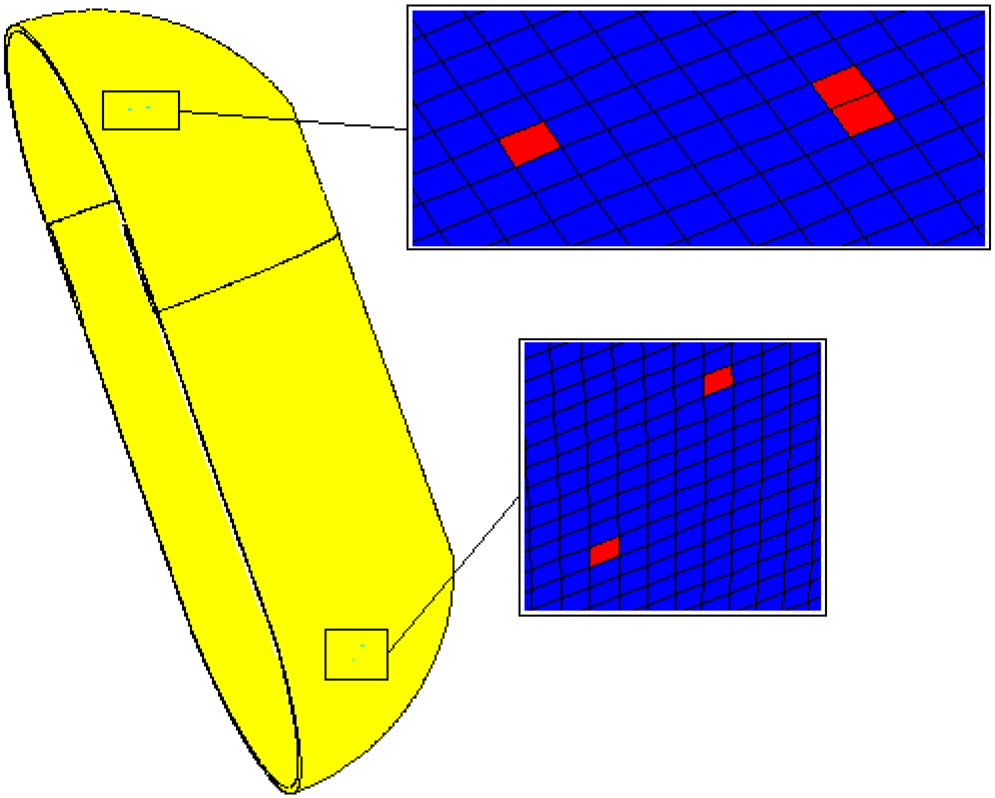
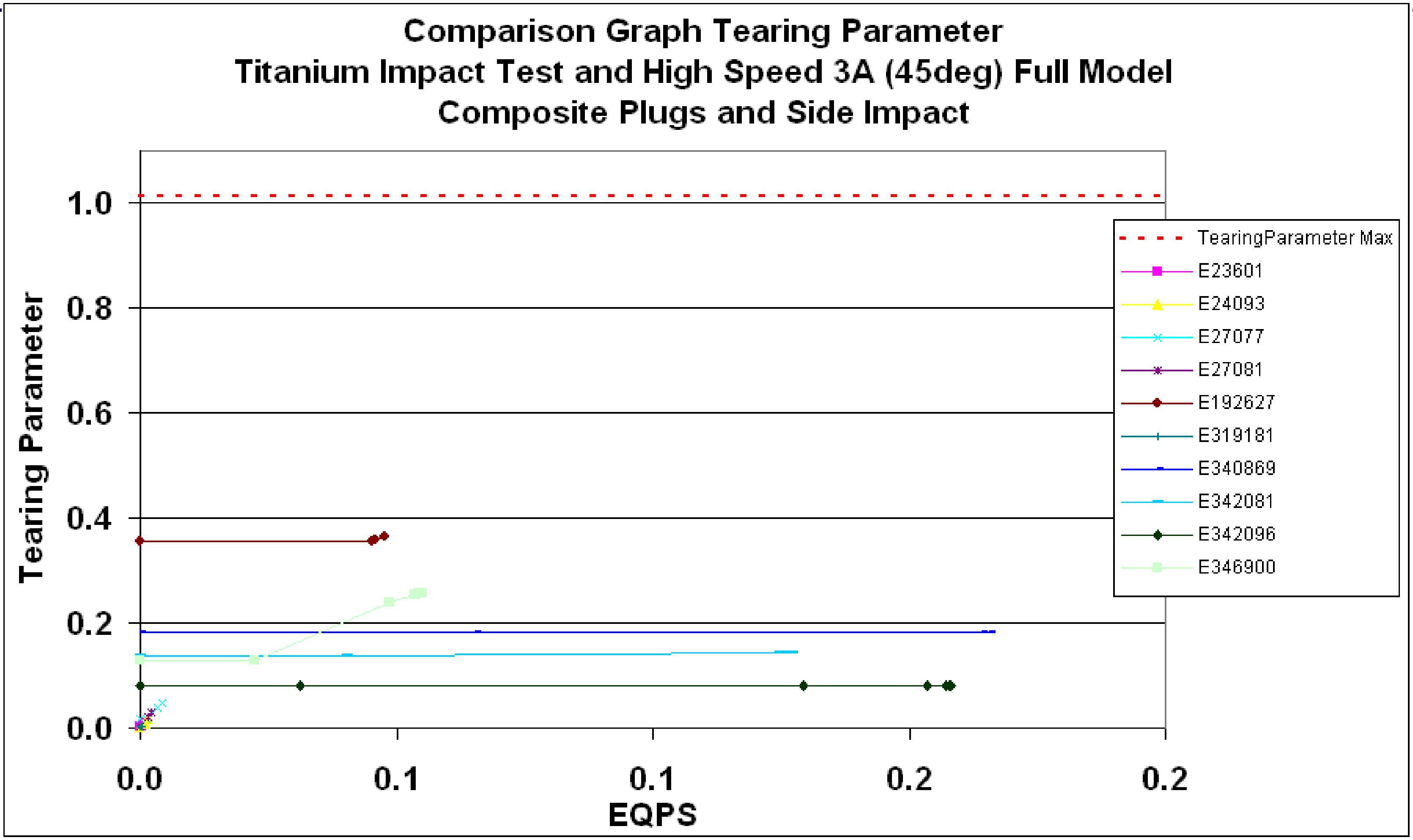
Be Composite Cylinder (45 deg) Side Impact

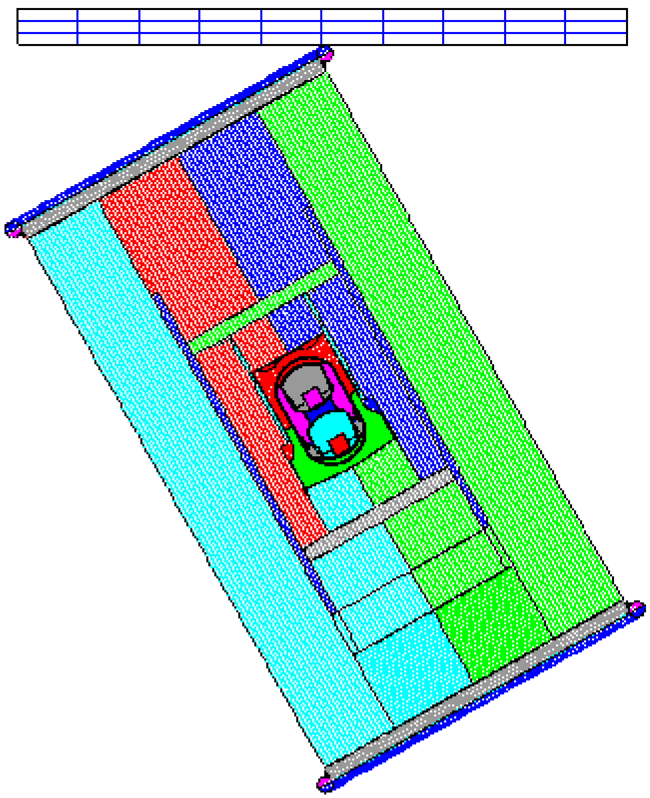


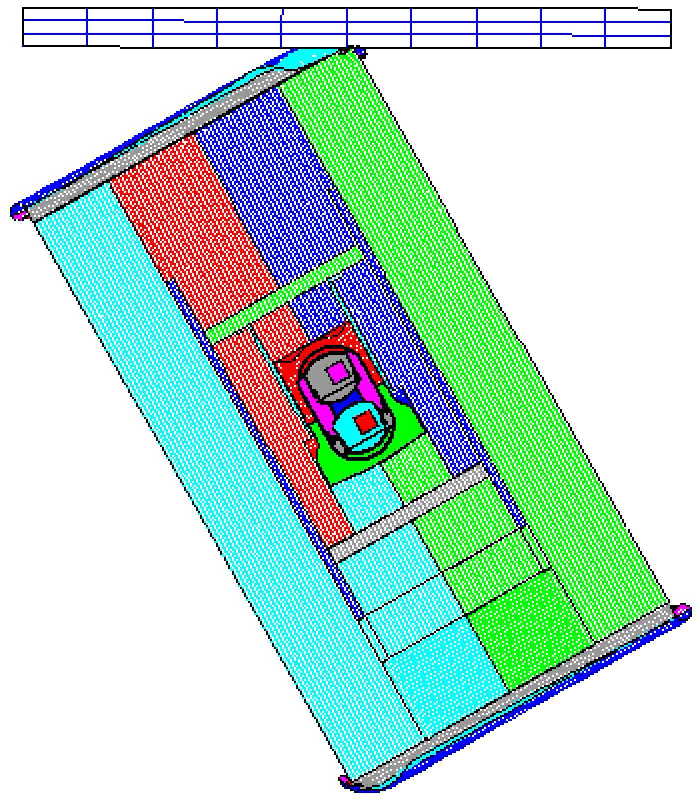
Be Composite Cylinder (45 deg) Side Impact



0 Elements Exceed the Critical Tearing Parameter

HAC – 2A (45 deg) CGOC Impact





No Elements Extend Beyond the B-W Locus

0 Elements Exceed ASME Stress Limits in the TB1

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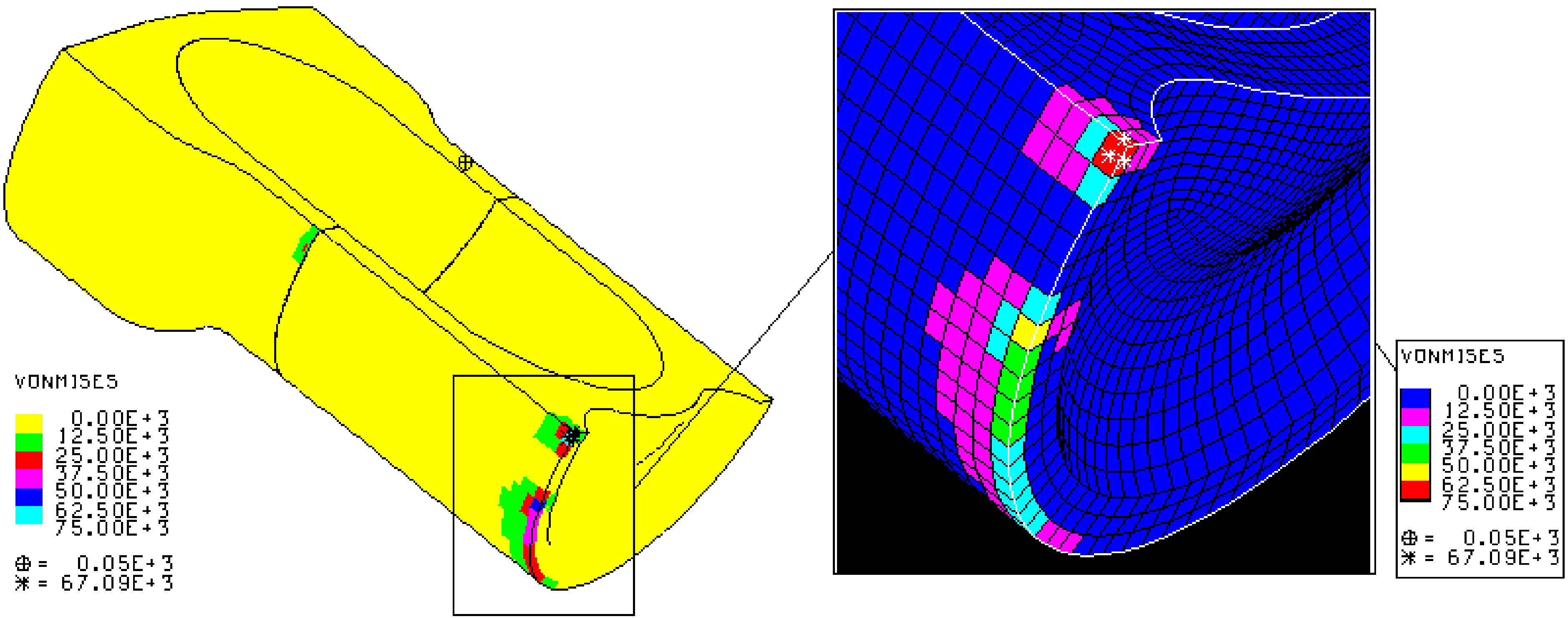
HAC – 2A (45 deg) CGOC Impact



0 Elements Exceed Thru-Thickness
ASME Stress Limits (107 ksi) in the TB1

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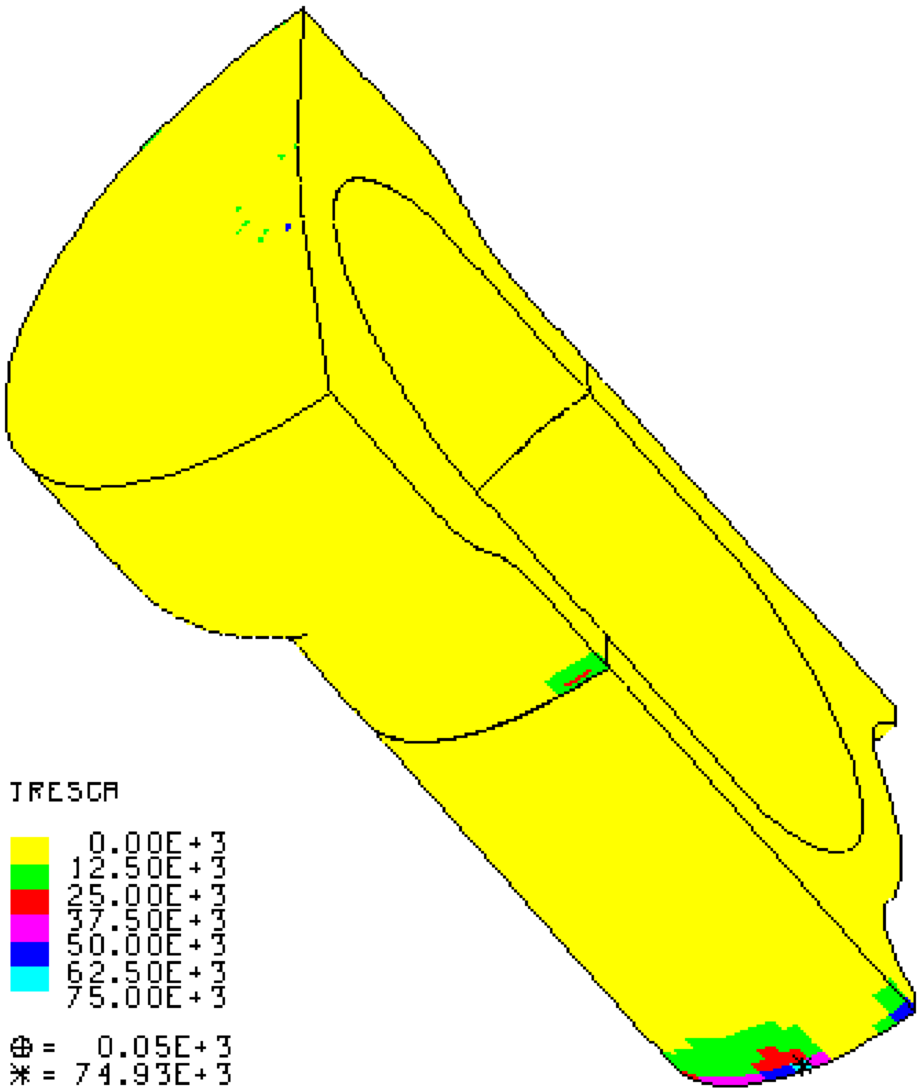

- **No elements violate ASME thru-thickness allowables for HAC: $0.7S_u$=107 ksi**
- **Similar results for end and side HAC dynamic crush impacts**

Conclusions

- **FEA results show that ductile tearing will NOT be initiated in the T-Ampoule eutectic barrier, based on the Tearing Parameter failure criterion**
- **No leakage or seal area (or any other visible) deformation occurred in the original PAT-1 certification tests, and based on analyses, none occur with the new metal contents (except minimal localized denting)**
- **Thru-thickness TB-1 stresses well below ASME allowables for dynamic crush**
- **The analyses performed provide sufficient evidence that the PAT-1 container can safely transport the proposed solid metal contents**

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