INL/CON-24-76377-Revision-0

Drop Analysis of a Department of Energy Standard Canister Containing Fort Saint Vrain SNF

March 2024

Changing the World's Energy Future

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Idaho National Laboratory

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U.S. Department of Energy
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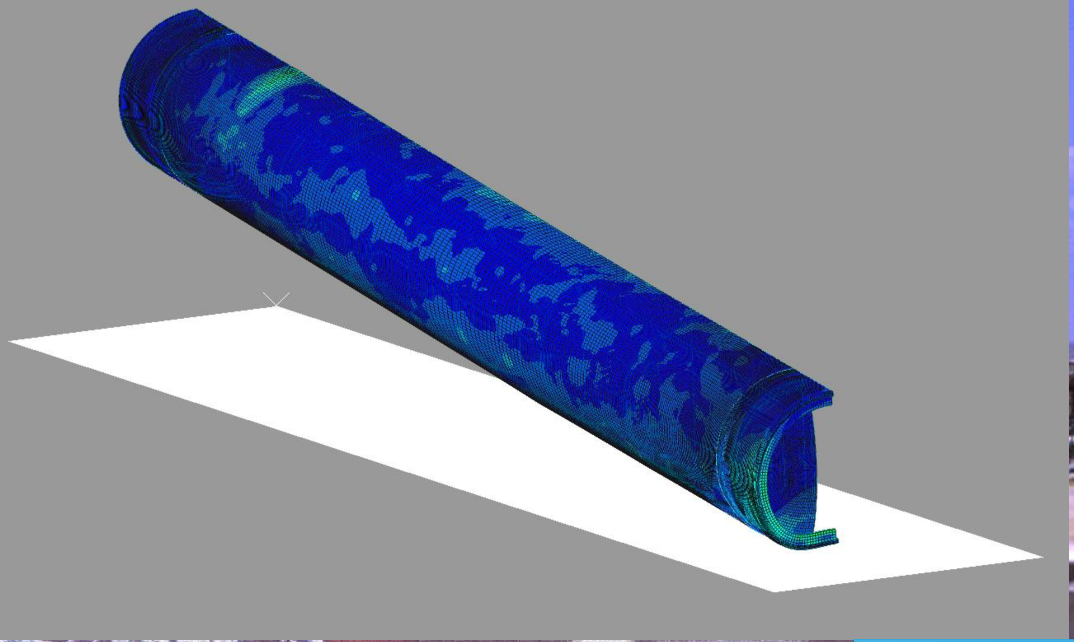
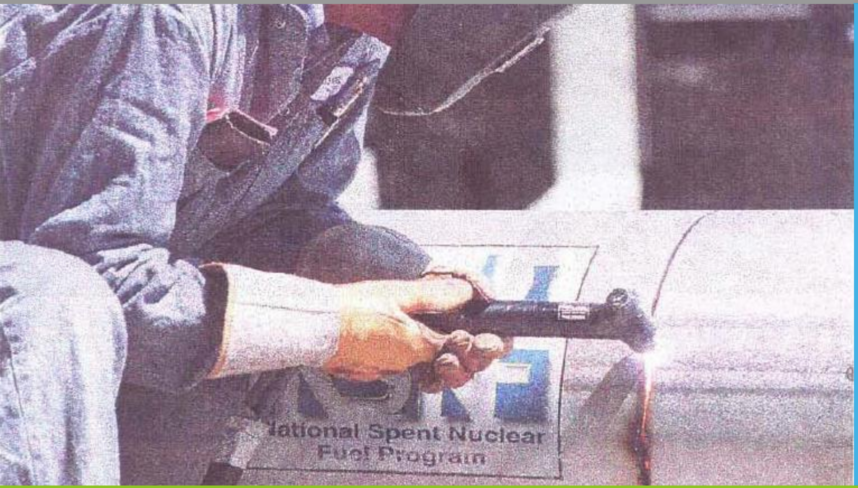


March 12th, 2024

D. Devin Imholte, Idaho National Laboratory

Peter Sakalaukus, Pacific Northwest National Laboratory

WM2024



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INL Idaho National Laboratory

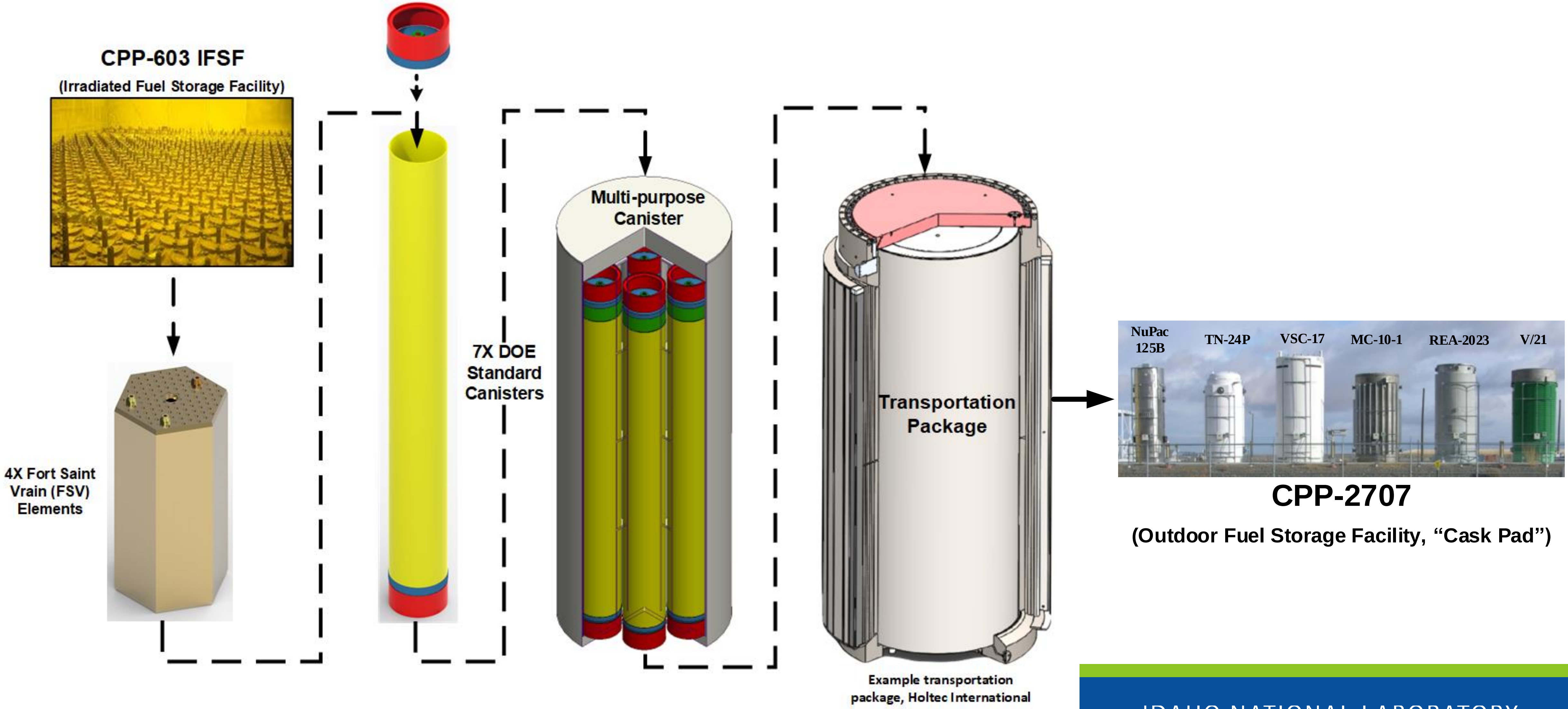
DOE SNF Road-Ready Demonstration Project

- 1995 Department of Energy (DOE)-Idaho Settlement Agreement
- *Strategic Framework for DOE-managed Spent Nuclear Fuel* (SNF) → Road-Ready Dry Storage (RRDS)*
- Road-Ready Demonstration Project**
  - Idaho Environmental Coalition-led with Battelle Energy Alliance support
  - Develop hardware, processes, and regulatory framework for packaging SNF for RRDS

*Road-ready dry storage meaning packages capable of long-term storage, transportation, and disposal with minimal handling. [1]

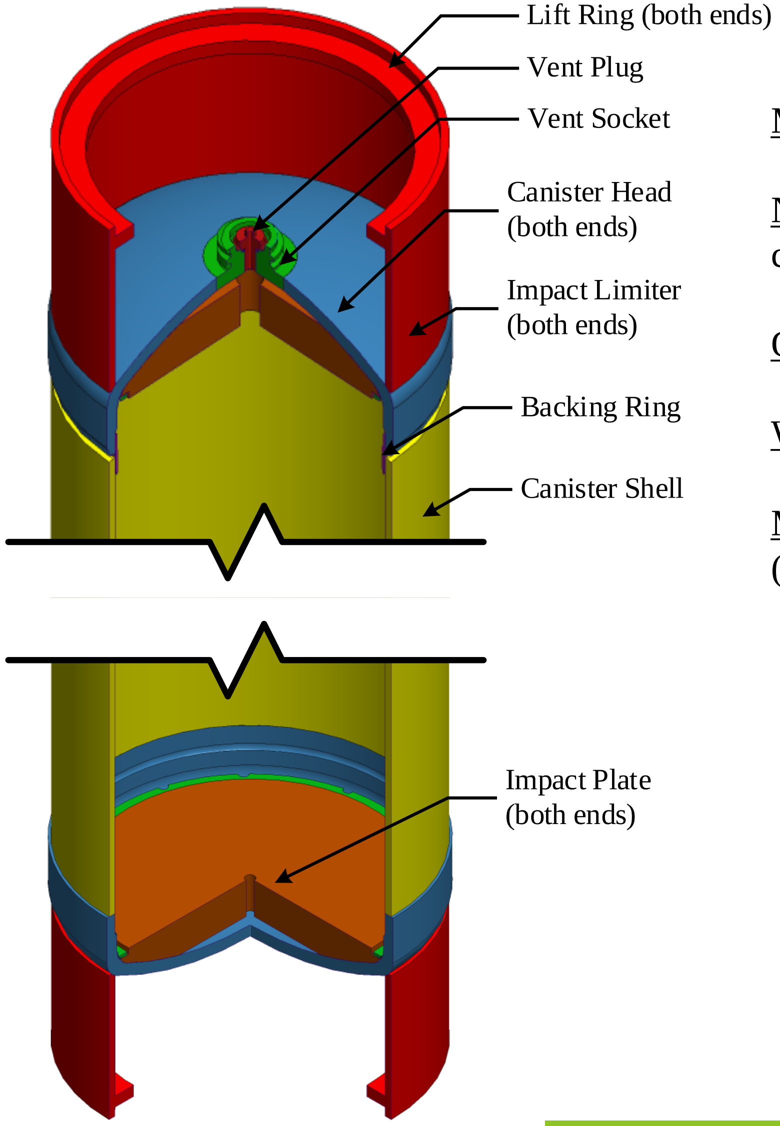
**Formerly DOE SNF Packaging Demonstration

DOE SNF Road-Ready Demonstration Objectives



DOE Standard Canister

- Sealed canister for diverse SNF
- No safety credit to SNF characterization
- Certified with the storage and transport system.
- Stainless steel
- Impact protection
- No shielding



Material: 316L Stainless Steel

Nominal Outside Diameter: Ø45.7 cm (Ø18 in.)

Overall Length: 3.6 m (15 ft.)

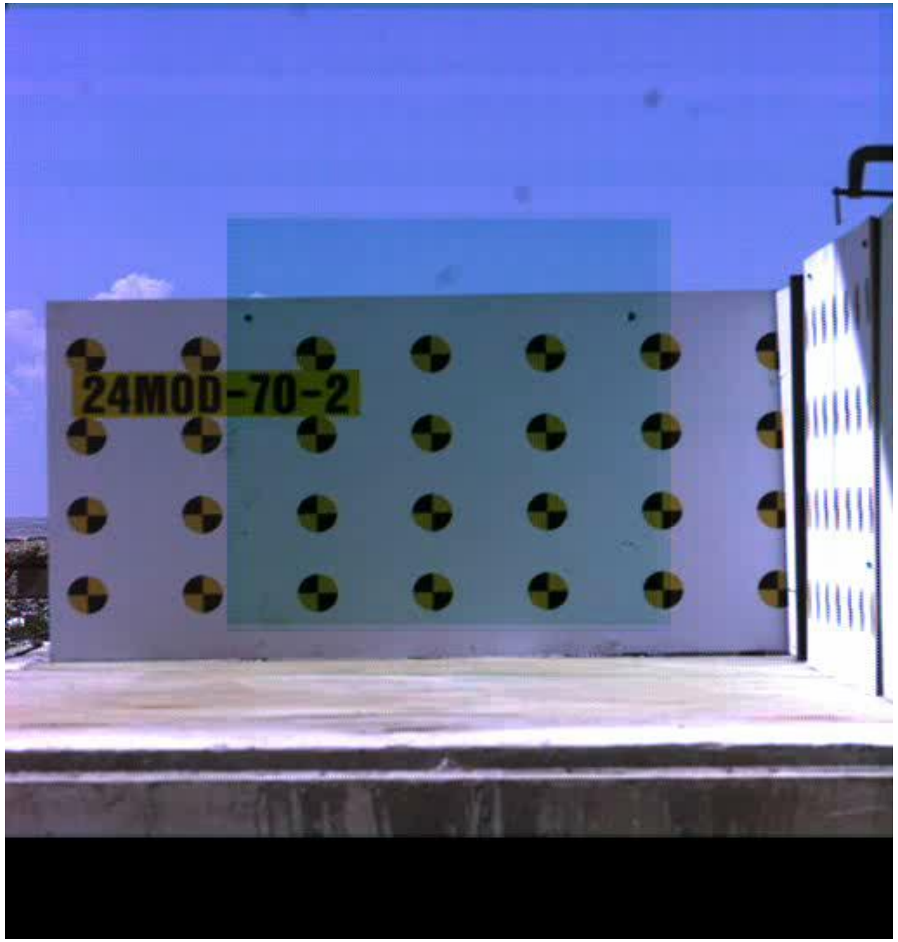
Wall Thickness: 0.95 cm (3/8 in.)

Maximum Gross Weight: 2,720 kg (6,000 lb)

DOE Standard Canister Drop Testing & Analysis Campaigns

- 10 CFR 71.73 drop events
- 1999
  - Gen. 1 NSNFP Design
  - 9X Ø18” canisters
- 2004
  - Gen. 2 ISF Facility Design
  - 2X Ø24” canisters
- All canisters **“leaktight”** via post-drop helium leak test

1999 Full-scale drop test at Sandia National Laboratories in New Mexico [2]

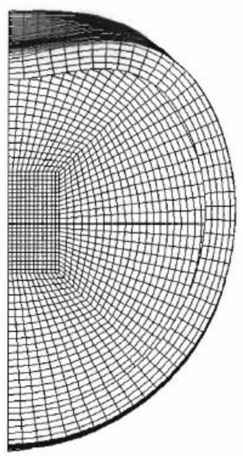


2004 full-scale drop video at Sandia National Laboratories in New Mexico [3]

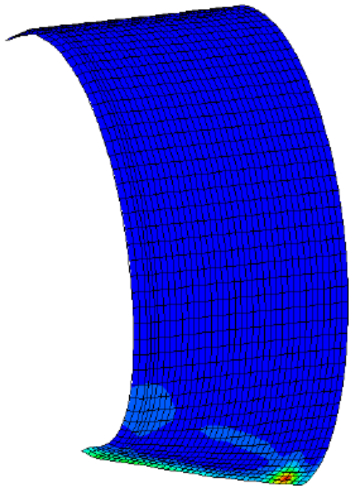
ISF – Idaho Spent Fuel
NSNFP – National Spent Nuclear Fuel Program

DOE Standard Canister Drop Analysis

- Finite Element Analysis (FEA) of DOE Standard Canisters
  - Abaqus Explicit
- Drop test and quasi-static material testing comparison → **no predicted containment rupture**
- 1999 and 2004 drop analyses cited in Yucca Mountain license application



2004 Finite Element Model [4]



1999 Finite Element Model [2]

Yucca Mountain Repository SAR Docket No. 63–001 DOE/RW-0573, Rev. 1

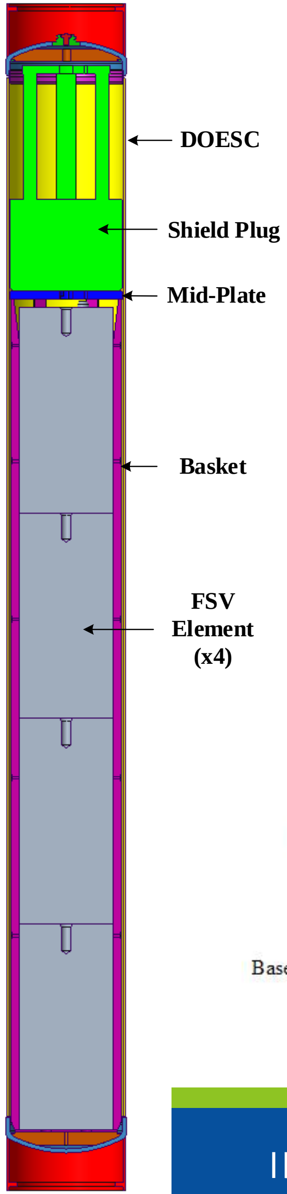
Table 1.5.1-27. Calculated Peak Equivalent Plastic Strains for Drop Events Evaluated

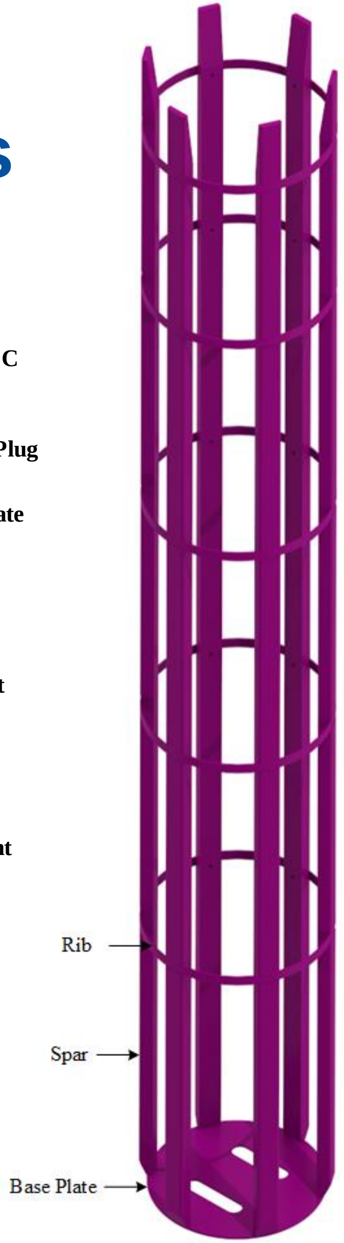
Drop Event	18 in. Standardized Canister[a]	24 in. Standardized Canister[a]
30 ft vertical	7% outside[b] 3% midplane[b] 6% inside[b]	6% outside[c] 0.6% midplane[c] 4% inside[c]
30-ft center of gravity over the corner; 6° for the 18-in. standardized canister and 7° for the 24-in. standardized canister	9% outside[b] 3% midplane[b] 10% inside[b]	0.7% outside[c] 0.1% midplane[c] 0.6% inside[c]
30 ft horizontal	40% outside[b] 15% midplane[b] 26% inside[b]	34% outside[c] 16% midplane[c] 22% inside[c]
30 ft at 45°	33% outside[b] 9% midplane[b] 36% inside[b]	48% outside[c] 22% midplane[c] 42% inside[c]
30 ft worst orientation	57% outside[b] 19% midplane[b] 42% inside[b]	57% outside[c] 23% midplane[c] 48% inside[c]
40 in. horizontal onto a 6-in. post	39% outside[b] 14% midplane[b] 40% inside[b]	16% outside[c] 15% midplane[c] 17% inside[c]
23 ft vertical	10% outside[b] 3% midplane[b] 6% inside[b]	6% outside[c] 0.6% midplane[c] 4% inside[c]
2 ft worst orientation	24% outside[b] 11% midplane[b] 13% inside[b]	23% outside[c] 15% midplane[c] 16% inside[c]
23-ft edge-to-collar drop	Not applicable[g]	Not applicable[g]
2-ft drop simulating the drop onto the edge of a waste package with toppling onto the opposite edge	20% outside[i] 7% midplane[i] 18% inside[i]	Not performed

Yucca Mountain license application [5]

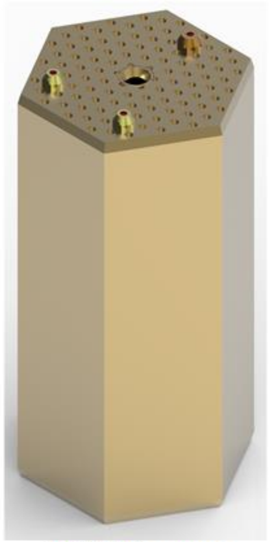
Updated DOE Standard Canister Drop Analysis

- **New Analysis** for DOE SNF Fuel Road-Ready Demonstration Project
- Forms a portion of a Nuclear Regulatory Commission (NRC) Topical Report
- **New Loading** Configuration
  - 4X Fort Saint Vrain (FSV) Elements
  - Shield Plug
  - Basket
- American Society of Mechanical Engineers (ASME) Boiler & Pressure Vessel (B&PV) Code Section III [6] **Strain-Based Acceptance Criteria**
- Updated Material Properties



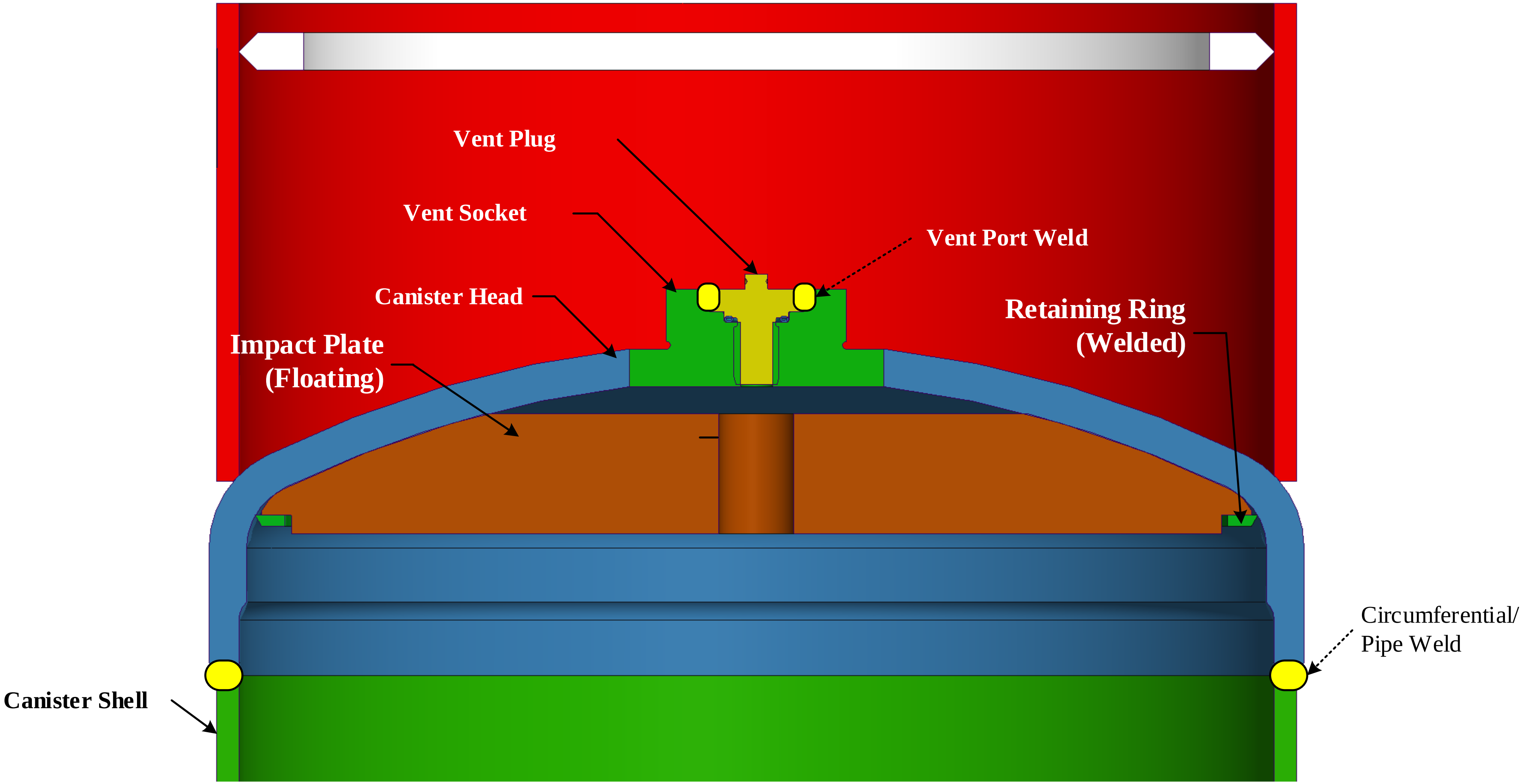


Basket


FSV Element

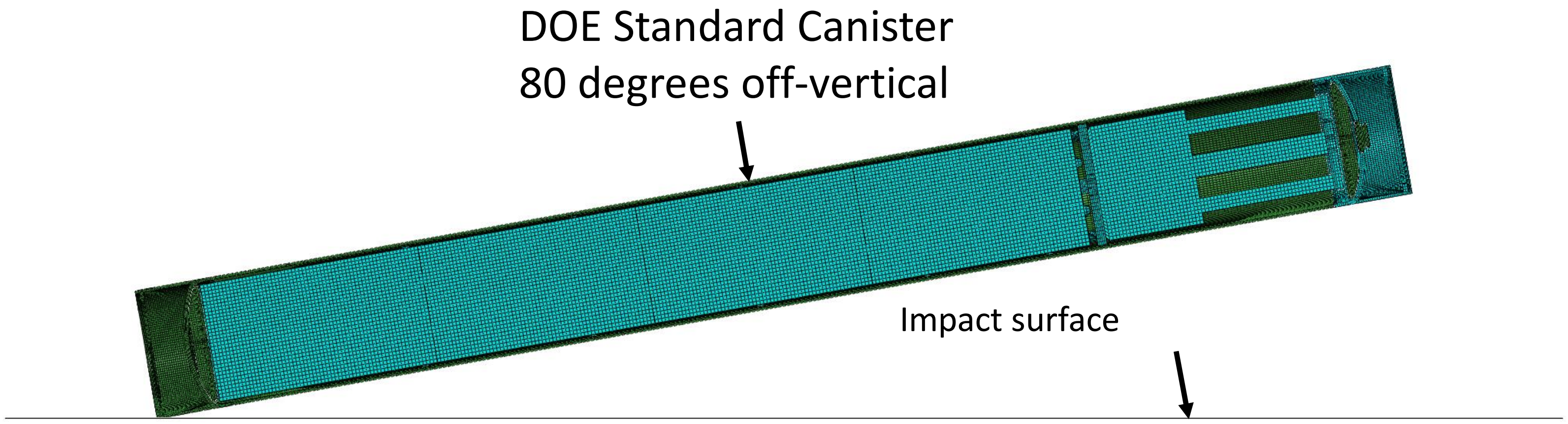

Shield Plug

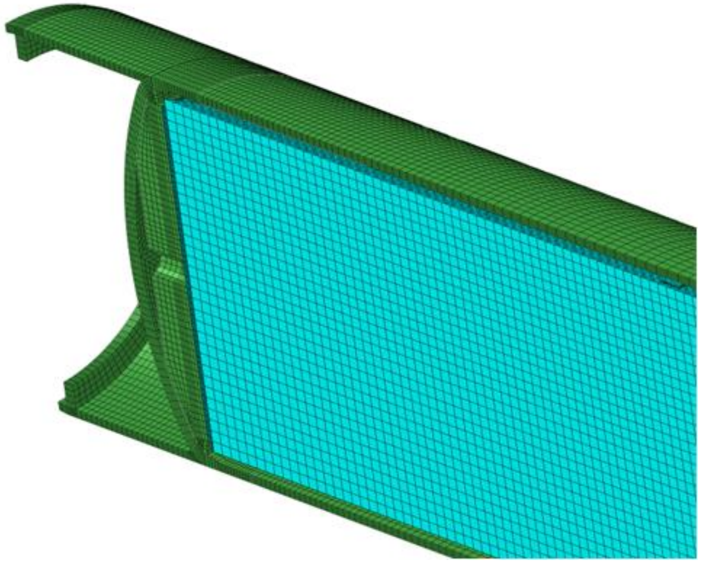
DOE Standard Canister Notable Design Features



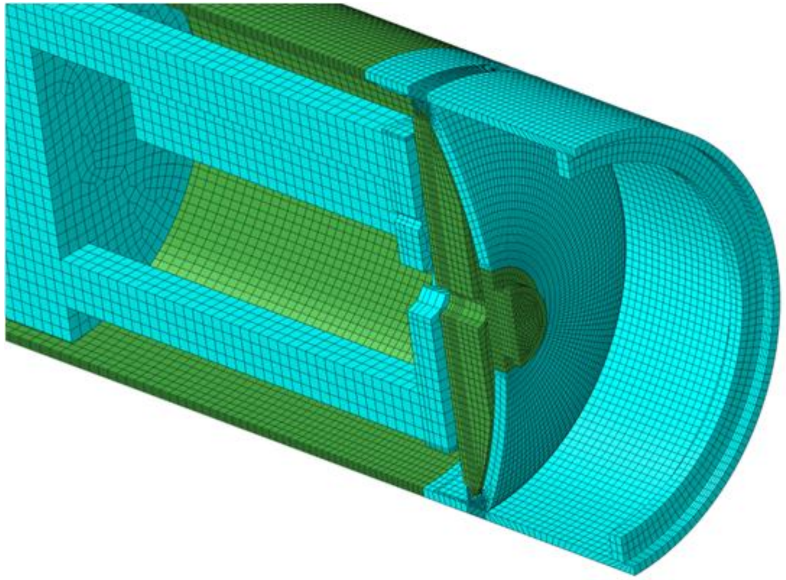
Finite Element Model Description

- 453,130 brick elements (reduced integration)
- Materials
  - 316L (Containment, Basket, Shield Plug)
  - H-327 Graphite (FSV fuel)
- Room temperature mechanical properties
- Internal Pressure: 50 psi
- 30 ft. drop height





Canister Bottom



Canister Top

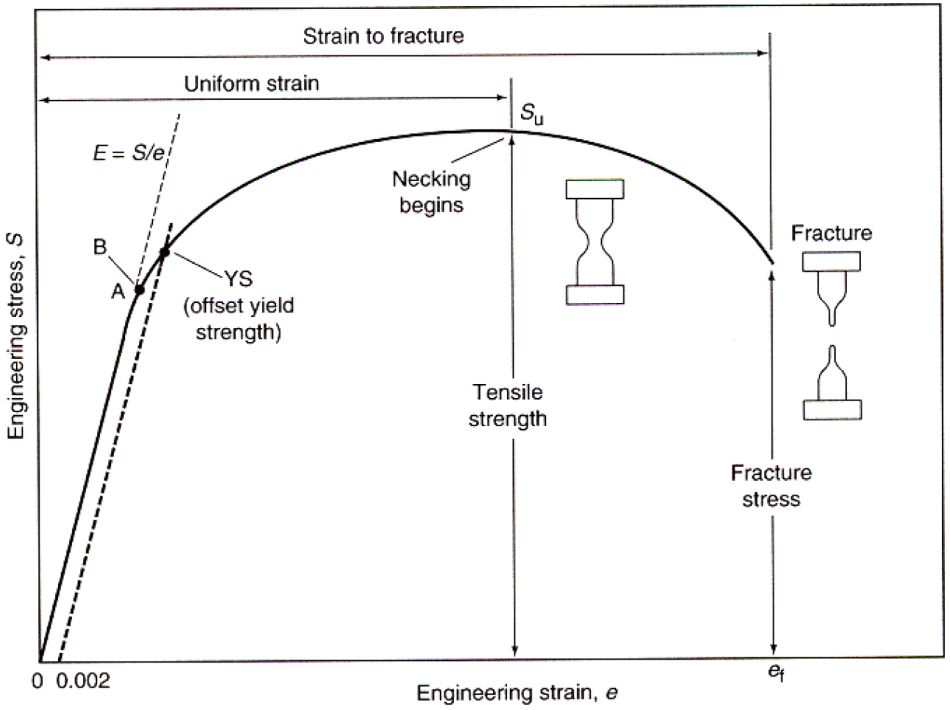
Strain-Based Acceptance Criteria

- Stress-based acceptance criteria → elastic
- Energy-limited impact events/accidental drops → inelastic/plastic
- Stress triaxiality factor (TF)

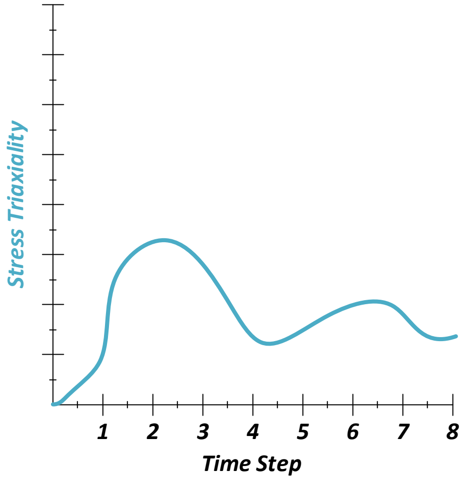
$$TF \propto \frac{\textbf{Hydrostatic Stress}}{\textbf{Deviatoric Stress}}$$

- Equivalent plastic strain (ε^{pl})

$$\varepsilon^{pl} = \int_0^t \sqrt{\frac{2}{3}\dot{\varepsilon}_{pl} \cdot \dot{\varepsilon}_{pl}}$$



Engineering Stress-Strain Curve [7]



Normalized Principal Stresses			Calculated TF	Description
σ_1	σ_2	σ_3		
1	0	0	1	Uniaxial tension
1	1	0	2	Biaxial tension
1	1	1/4	3	Triaxial tension
1	1/2	1/2	4	Triaxial tension
1	1	1/2	5	Triaxial tension
1	1	1	∞	Triaxial tension
1	-1	0	0	Tension/compression
1	-1/2	0	0.378	Tension/compression
1	1	-1	0.5	Biaxial tension / compression
1	-1	-1	-0.5	Tension / compression / compression
-1	-1	-1	-∞	Triaxial compression

ASME B&PV Code Section III Appendix E-E, “Strain-Based Acceptance Criteria Definitions and Background Information”
ASME B&PV Code Section III Appendix FF, “Strain-Based Acceptance Criteria for Energy-Limited Events”

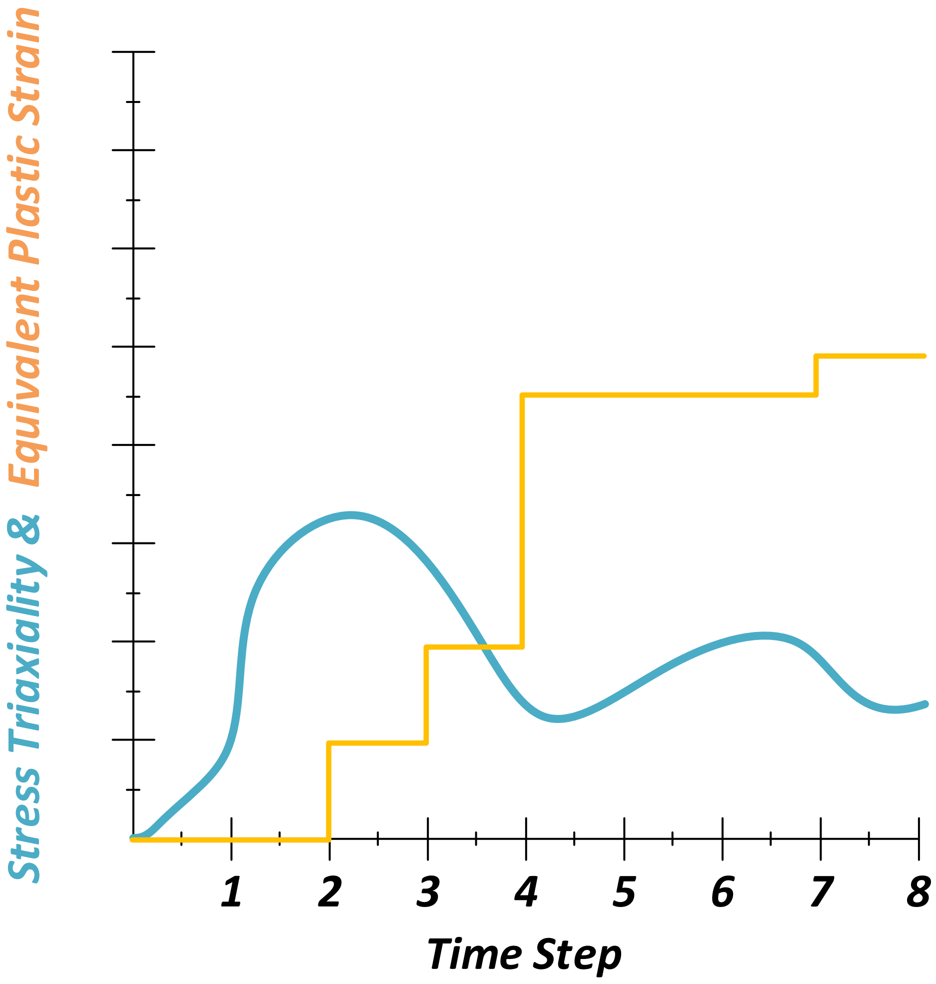
Strain-Based Acceptance Criteria

- Average (thru-wall) Strain Limit

$$\left(\varepsilon^{pl}\cdot TF\right)_{avg} \le \begin{Bmatrix} \text{away from discontinuity, } 0.67\cdot\varepsilon_{uniform} \\ \text{near discontinuity, } 0.85\cdot\varepsilon_{uniform} \end{Bmatrix}$$

- Maximum Strain Limit

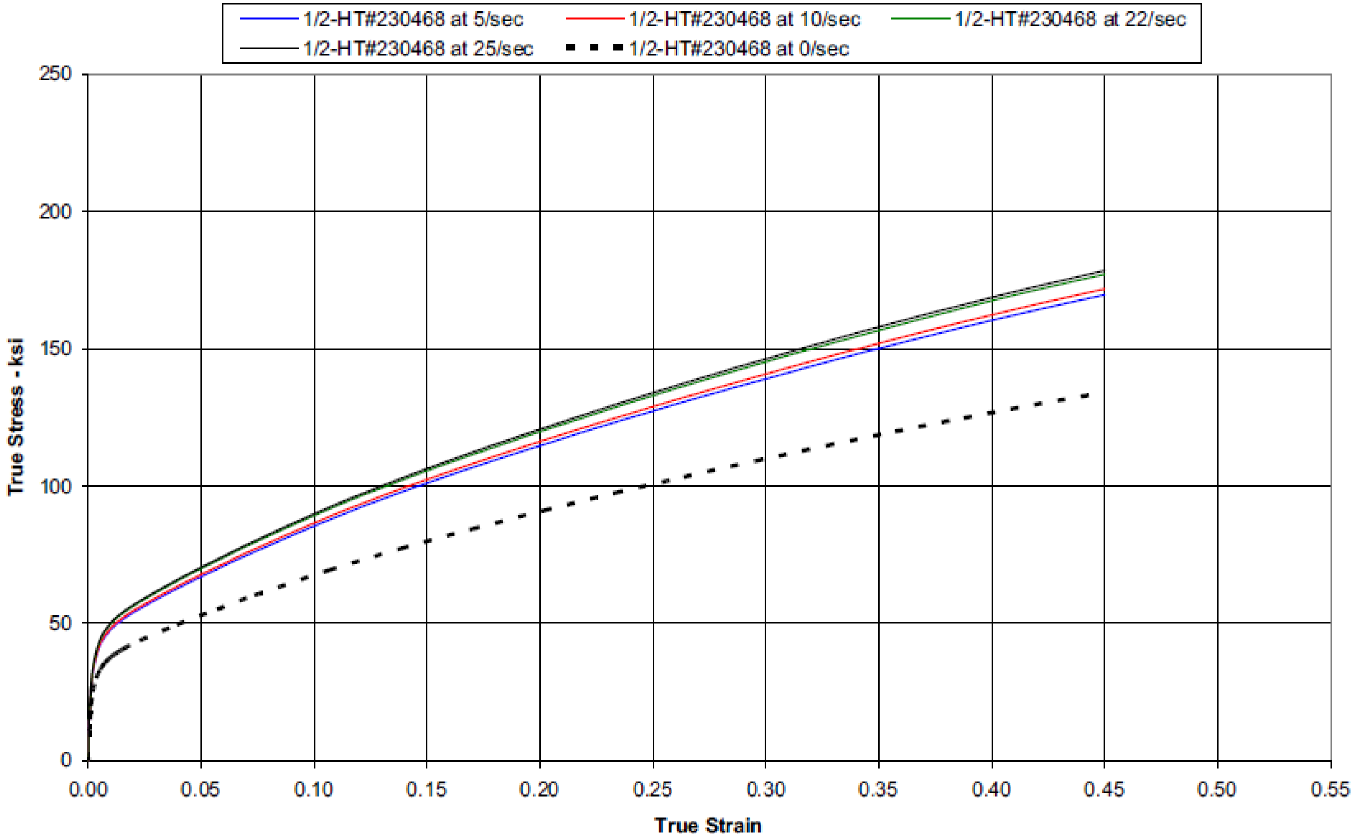
$$\left(\varepsilon^{pl}\cdot TF\right)_{max} \le \left\{\varepsilon_{uniform} + 0.25\left(\varepsilon_{fracture} - \varepsilon_{uniform}\right)\right\}$$



	Average Strain Limit	Maximum Strain Limit
Near Discontinuity	**0.31**	**0.83**
Away From Discontinuity	**0.39**	**0.83**

Strain Rate Data

- Previous analysis increased true stress-strain data by 20% to account for “dynamic strengthening”
- ASME B&PV Code has strain rate data
  - Up to 25 cycles/sec
  - 316/316L SST
  - Different temperatures



316L Heat 230468 True Stress-Strain Curve at Room Temperature at varying Strain Rates [7]

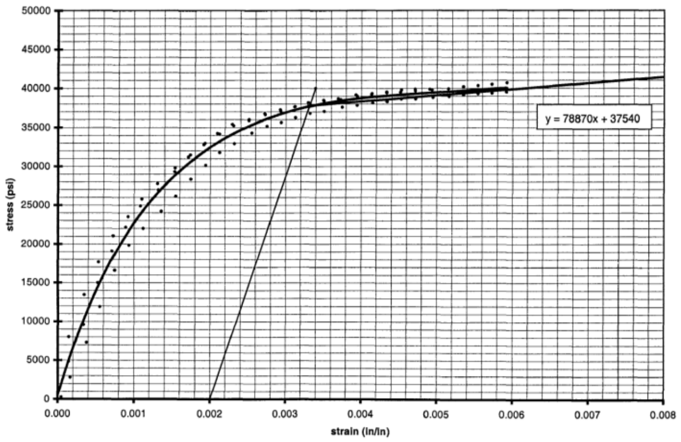


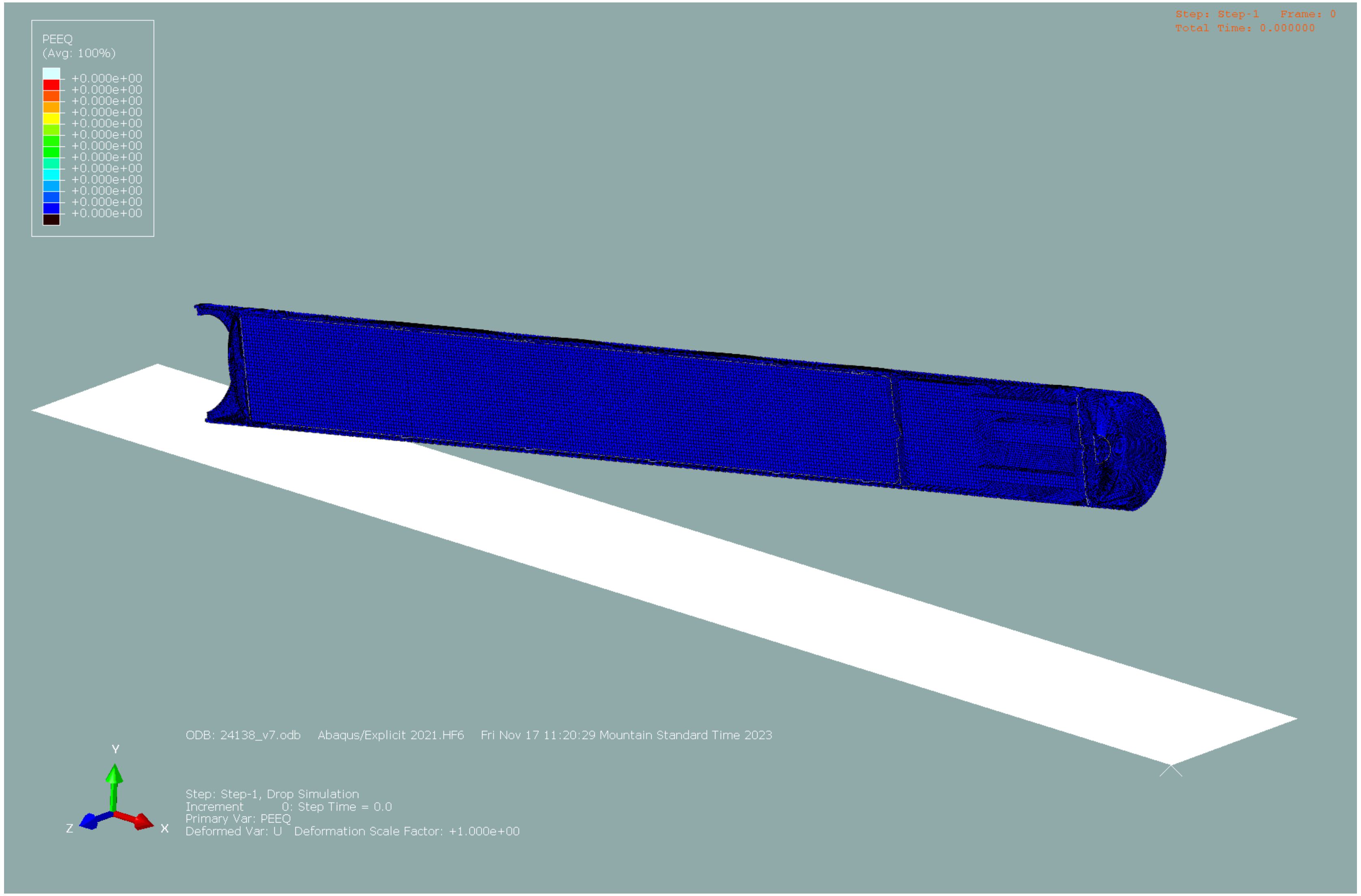
Figure 3. Stress-Strain curve for 18-inch SA-312 Pipe Material, HT# Y2613

Engineering Stress-Strain Curve for ASME pipe [2]

Strain rate (per sec.)	-20 °F	Room Temperature	300 °F	600 °F
304L Stainless Steel				
5	1.333	1.235	1.166	1.043
10	1.361	1.278	1.210	1.094
22	1.428	1.381	1.316	1.217
25	1.445	1.407	1.342	1.247
316L Stainless Steel				
5	1.275	1.265	1.162	1.040
10	1.296	1.281	1.187	1.070
22	1.346	1.321	1.247	1.140
25	1.359	1.331	1.262	1.158

Factors or specified strain rates [7]

Updated Finite Element Analysis Results



PEEQ = Equivalent Plastic Strain (ε^{pl}) output variable in Abaqus

Finite Element Analysis Results – Containment

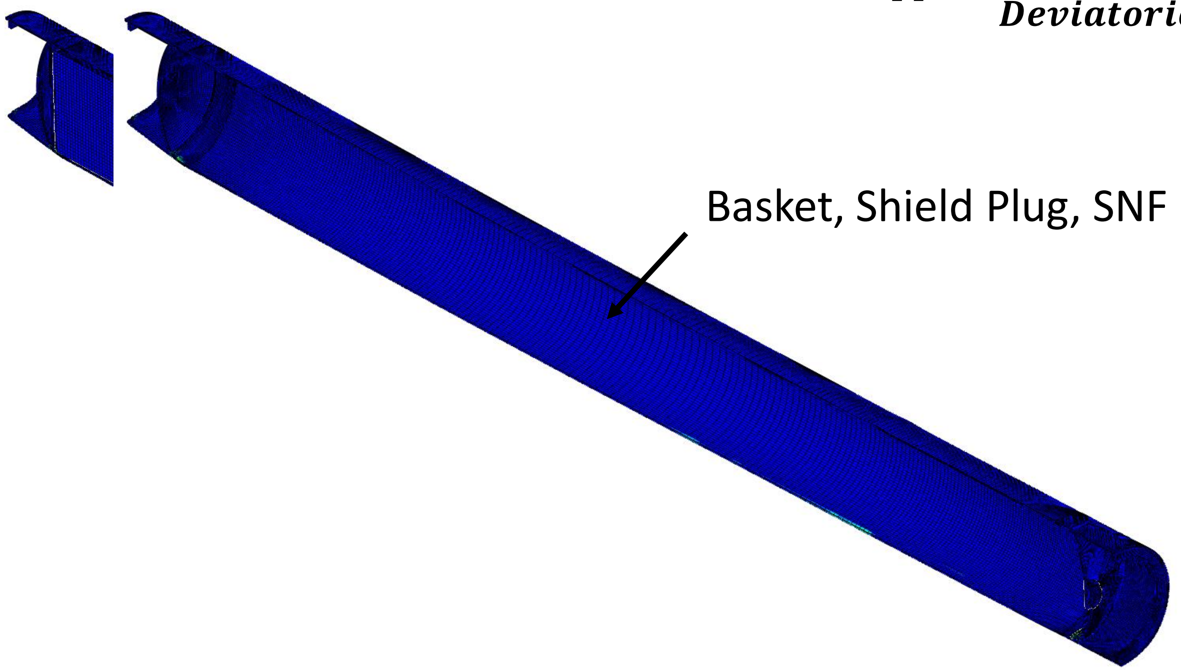
Output FEA Database (Canister + Contents) → **Containment Only** (Top Head, Bottom Head, Containment)
- Principal Stresses
- Equivalent Plastic Strain

→ Calculate stress triaxiality (TF) at each time step → Calculate $\varepsilon^{pl} \cdot TF$ → If D ε^{pl}<.0001, set $\varepsilon^{pl} \cdot TF$=0

$$\boldsymbol{TF} = \frac{\boldsymbol{Hydrostatic\ Stress}}{\boldsymbol{Deviatoric\ Stress}}$$

$$\left(\varepsilon^{pl} \cdot TF\right)_{max}$$

$$\left(\varepsilon^{pl} \cdot TF\right)_{avg}$$



Basket, Shield Plug, SNF removed

$$\left(\varepsilon^{pl}\right)_{t=1} = .15$$

$$\left(\varepsilon^{pl}\right)_{t=2} = .15$$

$$\left(\varepsilon^{pl}\right)_{t=3} = .20$$

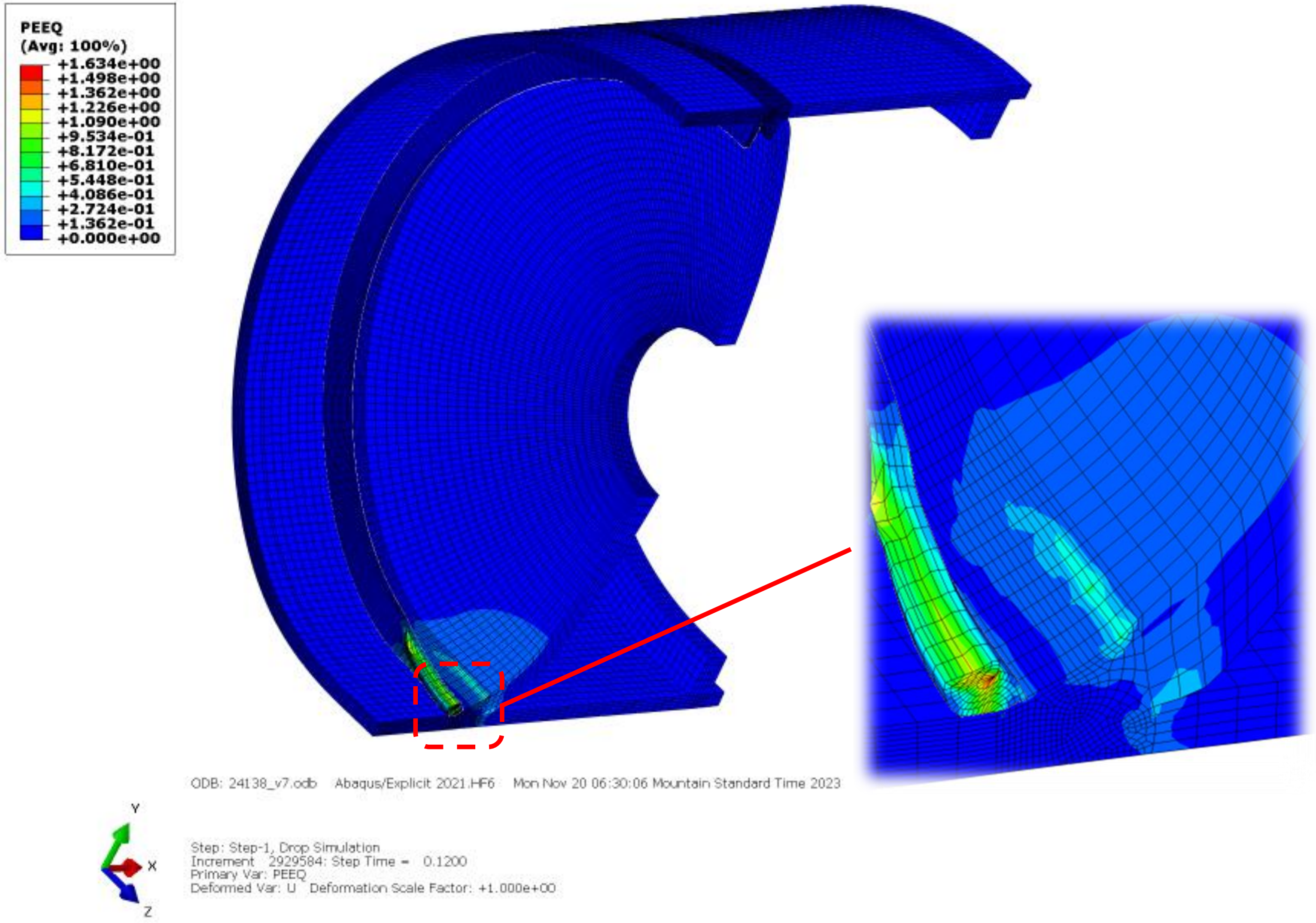
$\Delta\varepsilon^{pl} < .0001$

No plastic deformation occurring, $\varepsilon^{pl} \cdot TF$=0

$\Delta\varepsilon^{pl} = .05$

Plastic deformation **is** occurring, $\varepsilon^{pl} \cdot TF$=0.2

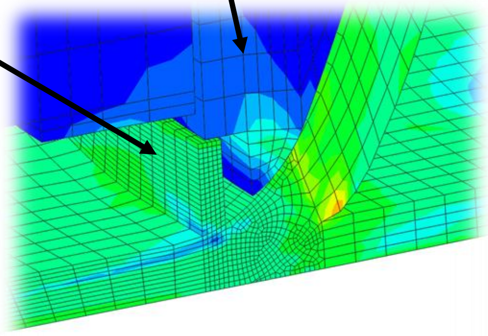
Finite Element Analysis Results – Top Head



Impact Plate

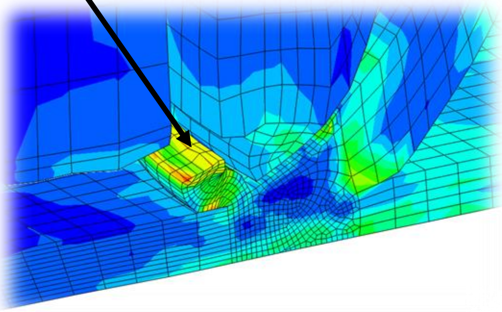
Retaining Ring

t=.042 sec



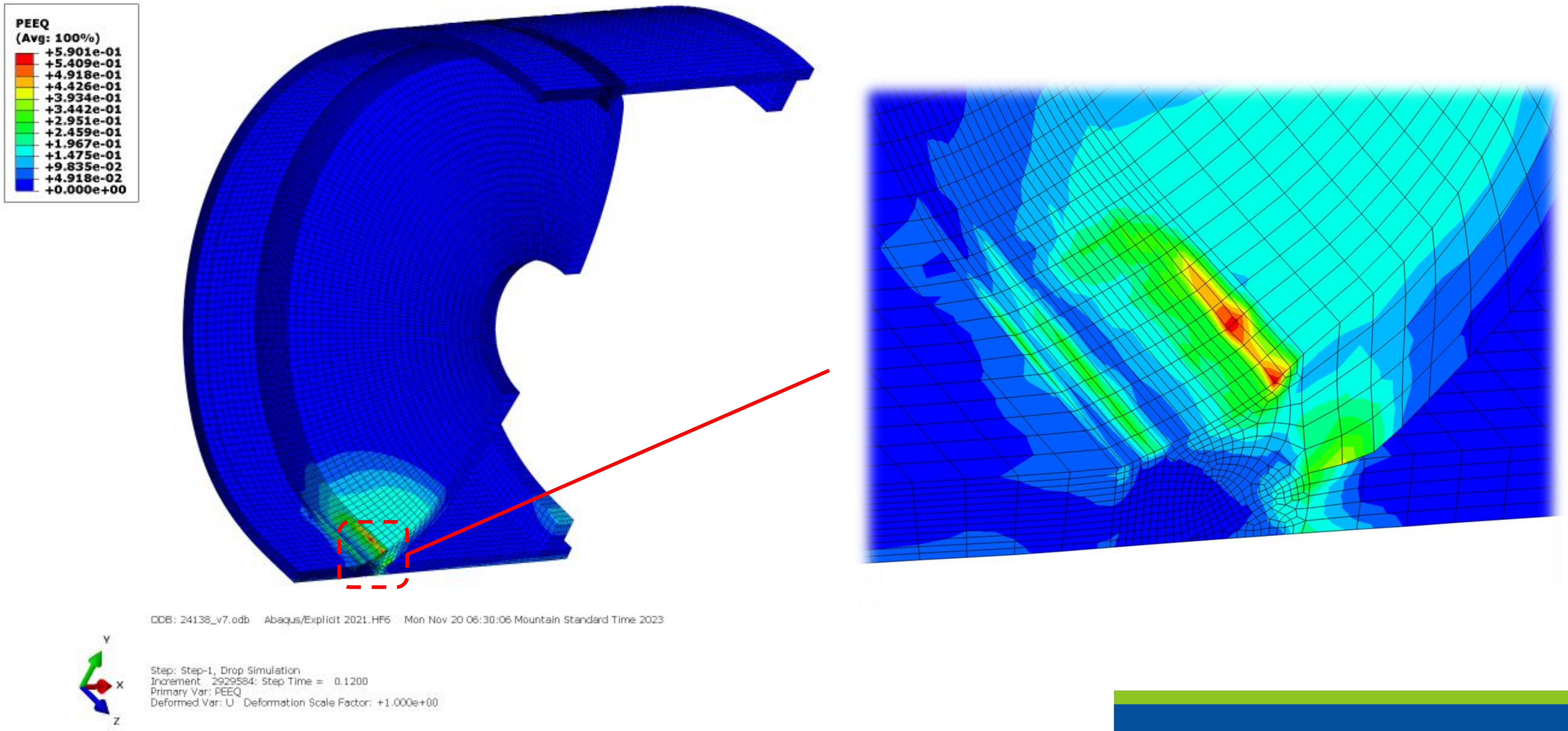
Retaining Ring

t=.048 sec



PEEQ = Equivalent Plastic Strain (ε^{pl}) output variable in Abaqus

Finite Element Analysis Results – Top Head (No Retaining Ring)



PEEQ = Equivalent Plastic Strain (ε^{pl}) output variable in Abaqus

Finite Element Analysis Results Summary

Containment Component	Average (mm/mm)	Average Limit (mm/mm)	Maximum (mm/mm)	Maximum Limit (mm/mm)
Top Head (with retaining ring)	0.50	0.39	**1.64**	.83
Top Head (without retaining ring)	0.09	0.31	0.35	
Main Shell	0.26	0.31	0.36	
Bottom Head	0.06	0.39	0.64	

Scope of Strain-Based Acceptance Criteria

- ASME B&PV Code Appendix FF, Para. FF-1126: “Strain-based acceptance criteria shall **not** be applied to”:
  - **“Structural or nonstructural attachments to the containment”**
- Retaining ring → structural attachment [WB-1132.1(c)(1) & WC-1132.1(c)(1)]
- Alternative criteria must be applied to the retaining ring (e.g., stress-based)

Welding of Impact Plate Retaining Ring on Ø24” ISF Facility Canisters

Conclusion

- New drop analysis for Road-Ready Demonstration Project
- NRC Topical Report needs new drop analysis
- Updated Drop Analysis
  - ASME B&PV Code strain-based acceptance criteria
  - Strain rate material properties
  - FSV SNF loading
- Preliminary FEA results show containment does not exceed Code limits
- Further analysis is needed to evaluate the retaining ring and other drop scenarios

Questions?

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References

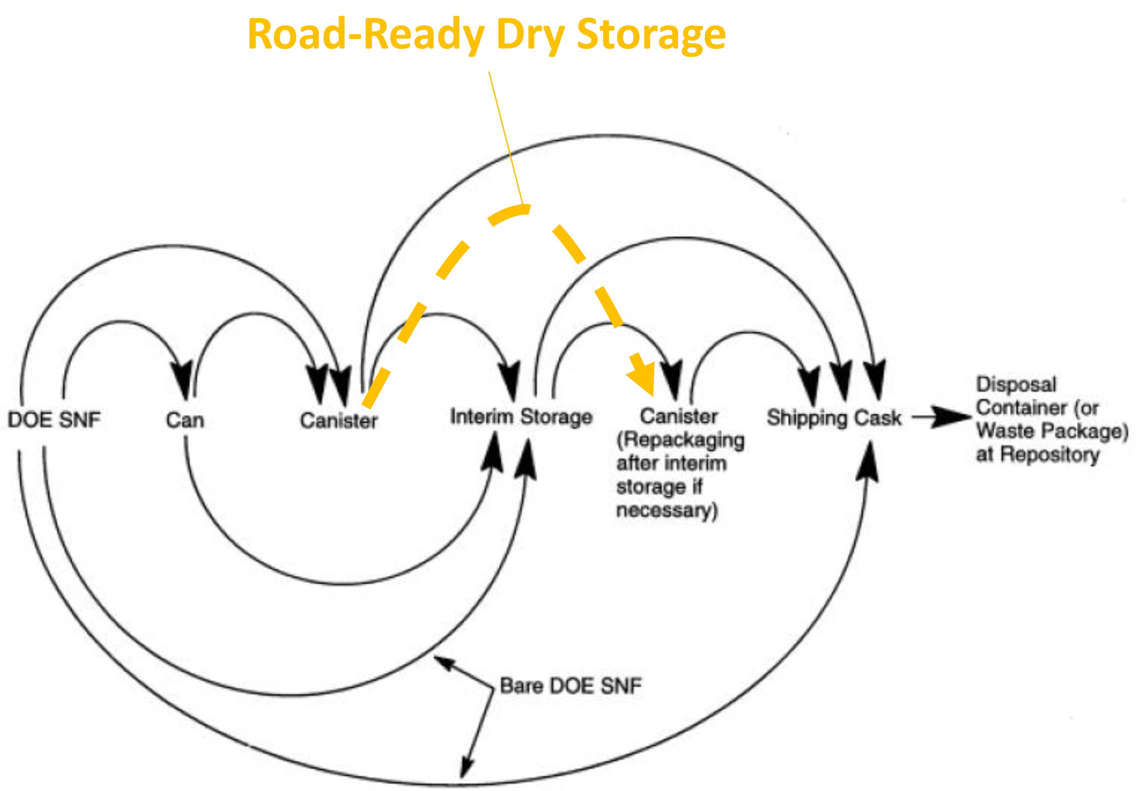
1. U.S. Department of Energy, "Strategic Framework for DOE-Managed Spent Nuclear Fuel", 2021.
2. Idaho National Laboratory, "FY1999 Drop Testing Report for the 18-inch Standardized DOE SNF Canister", EDF-NSNF-007, Rev. 2, 1999.
3. Idaho National Laboratory, "Drop Testing Representative 24-inch Diameter Idaho Spent Fuel Project Canisters", EDF-NSNF-045, Rev. 0, 2005.
4. Idaho National Laboratory, "Analytical Evaluation of the Idaho Spent Fuel Project Canister for Accidental Drop Events", EDF-NSNF-027, Rev. 0, 2003.
5. U.S. Department of Energy, "Yucca Mountain Repository Safety Analysis Report, Chapter 1: Repository Safety Before Permanent Closure", DOE/RW-0573, Rev. 2, 2008.
6. American Society of Mechanical Engineers, Boiler and Pressure Vessel Code. In *Strain-Based Acceptance Criteria Definitions and Background Information*, American Society of Mechanical Engineers: New York, NY, 2023.

References Cont’d

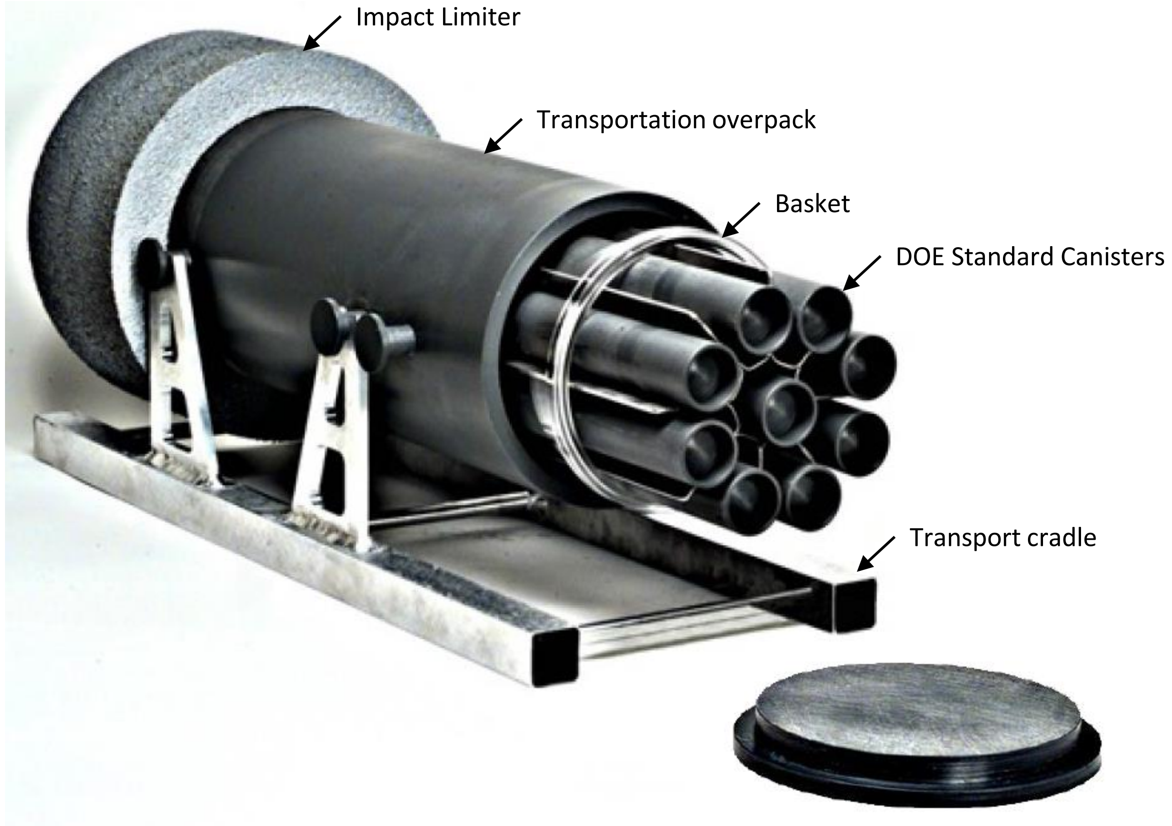
7. Morton D.K.; R. K. Blandford, "Impact Tensile Testing of Stainless Steels at Various Temperatures", INL/EXT-08-14082, 2008.

Extra Slides

Original DOE Standard Canister Concept



Potential DOE Standard Canister paths to repository disposal (DOE, 1999)



Transportation Cask Concept with DOE Standard Canisters loaded directly (no MPC/over-canister)

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