U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Three-Dimensional Finite Element Analysis of a Post-tensioned Concrete Containment with Ungrouted Tendons to Inform a Probabilistic Risk Assessment

By
Hernando Candra, Jose A. Pires (presenter)
Office of Nuclear Regulatory Research, Division of Engineering
US Nuclear Regulatory Commission

2nd International Conference on Technological Innovations in Nuclear Civil Engineering (TINCE 2014)
Paris, France
September 1-4 , 2014

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Disclaimer

Disclaimer

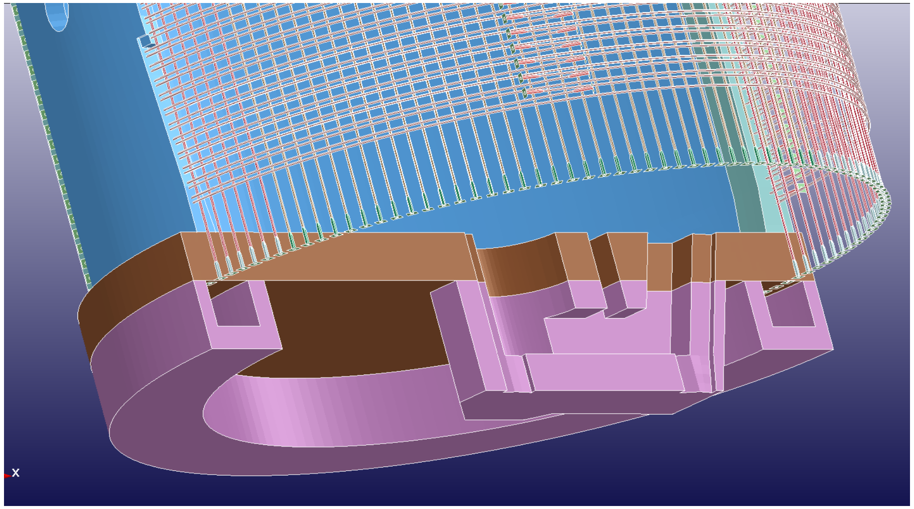
- This report was prepared under the auspices of an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for any third party's use, or the results of such use, of any information, apparatus, product, or process disclosed in this paper, or represents that its use by such third party would not infringe privately owned rights. The views expressed in this report are not necessarily those of the U.S. Nuclear Regulatory Commission.

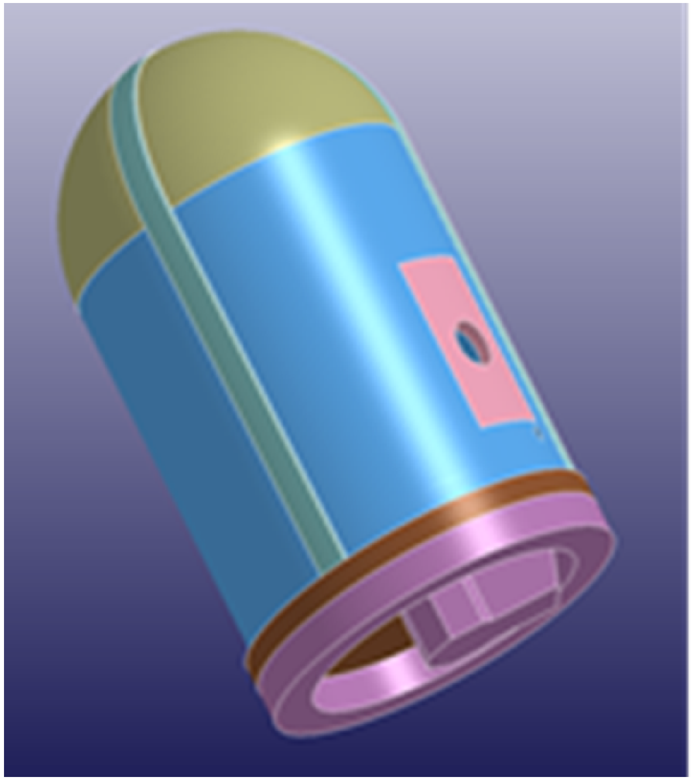
Introduction

- Three-dimensional finite element analysis of a prestressed concrete containment with ungrouted tendons for beyond-design basis internal pressurization
- Goals of the analysis
  - Illustrate results that would inform a Level 2 probabilistic risk assessment (PRA)
  - Assess modeling and analysis techniques
- Main results
  - Pressures at onset of leakage and evolution of leakage with internal pressure up to functional rupture
  - Structural internal pressure capacity estimates
  - Interpretation of results to inform a Level 2 PRA

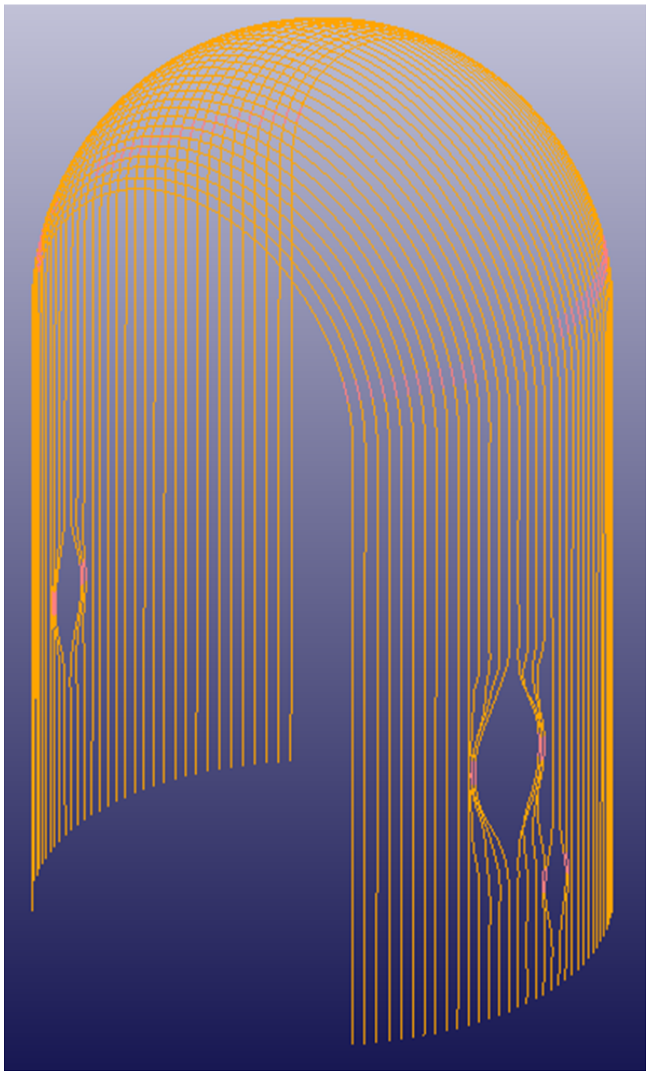
Containment Description and Modeling

- PWR large dry containment
- Cylindrical wall with hemispherical dome
- Ungrouted tendons
- Three buttresses that extend into the dome

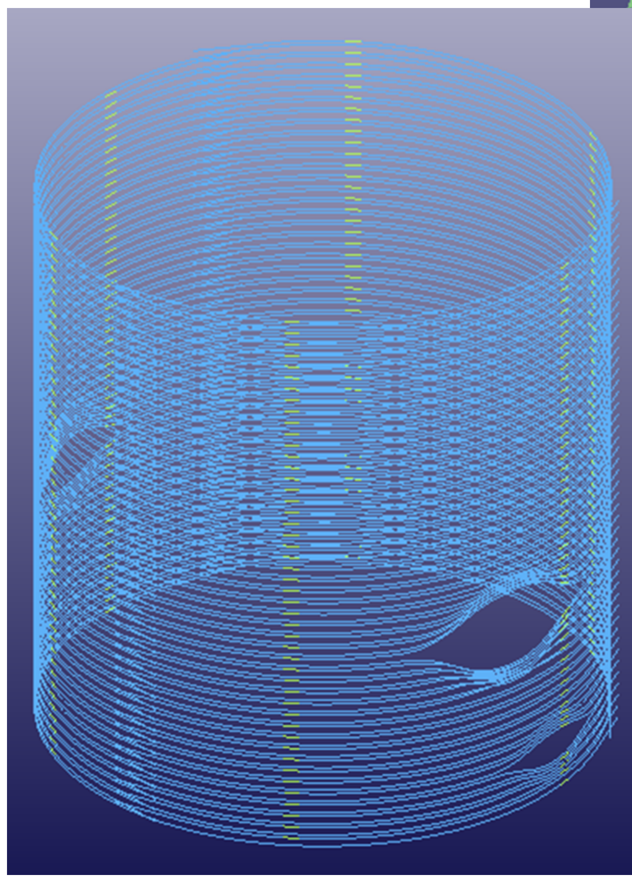




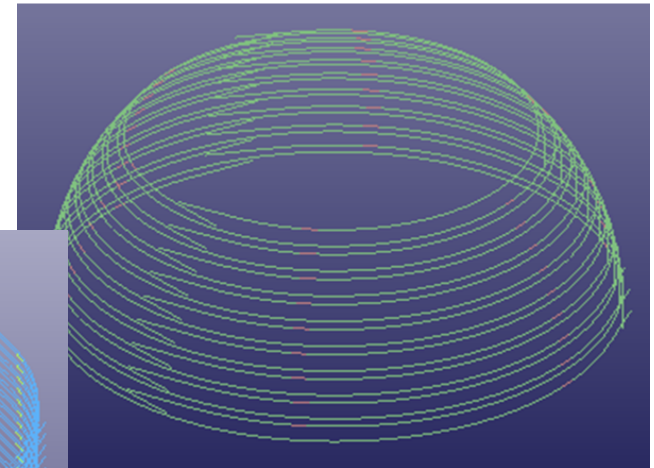
Containment Description and Modeling



Vertical Tendons



Hoop Tendons

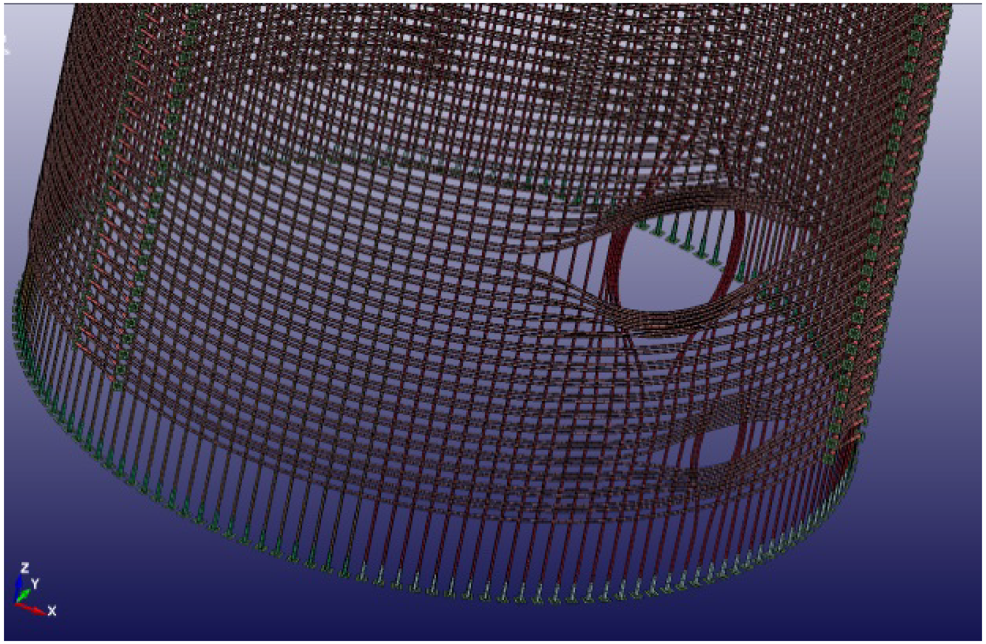


Dome Tendons

Containment Description and Modeling

- Explicit finite element analysis (LSDYNA code)
  - Contact modeling
  - Constrained Lagrange in solid options for modeling of materials embedded in concrete (reinforcing bars and tendon sleeves)

- Tendon sleeves embedded and constrained to concrete (master)
- Contact (Automatic nodes to surface)
  - Tendons inside sleeves (master)
  - Anchor plates' nodes to concrete segments (master)



Containment Description and Modeling

- Material models
  - Concrete – Winfrith (LSDYNA model 85)
  - Steel (all) – Elastoplastic with kinematic hardening
- Material properties
  - Best estimate of median material properties
- Liner

Yield stress	255MPa	(Yield strain ~ 1.3×10^{-3})
Post-yield modulus	2780MPa	
Failure strain	15%	(Cherry, 1996)

- Tendons

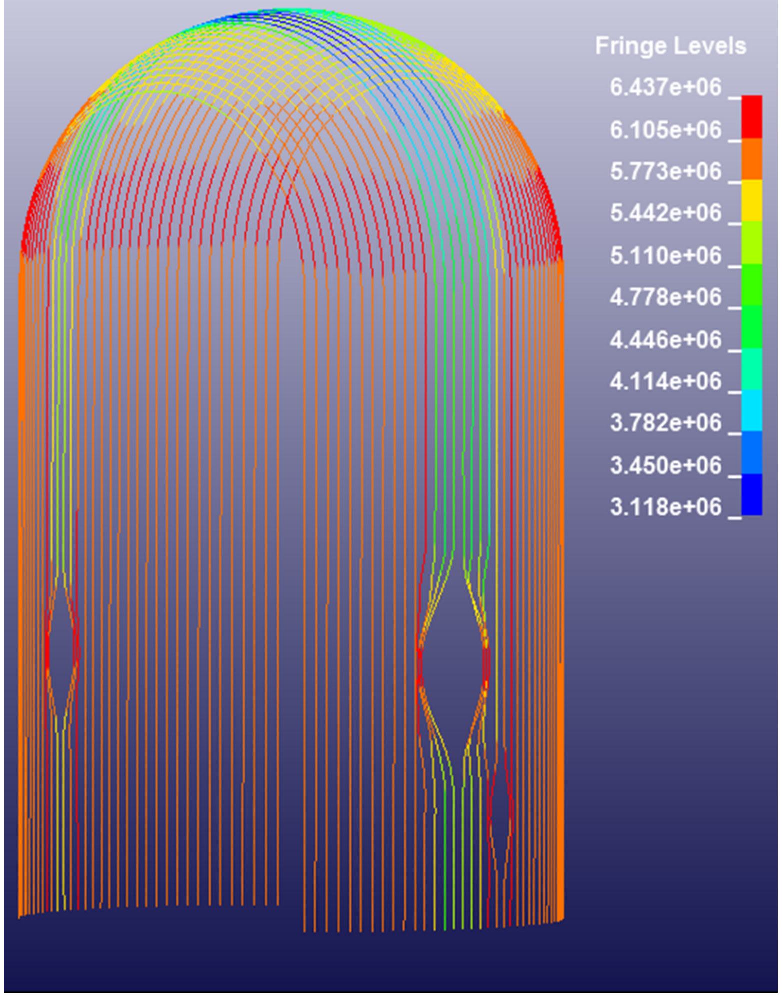
Yield stress	1790MPa	(Yield strain ~ 0.01)
Post-yield modulus	4825MPa	
Failure strain	3.6%	

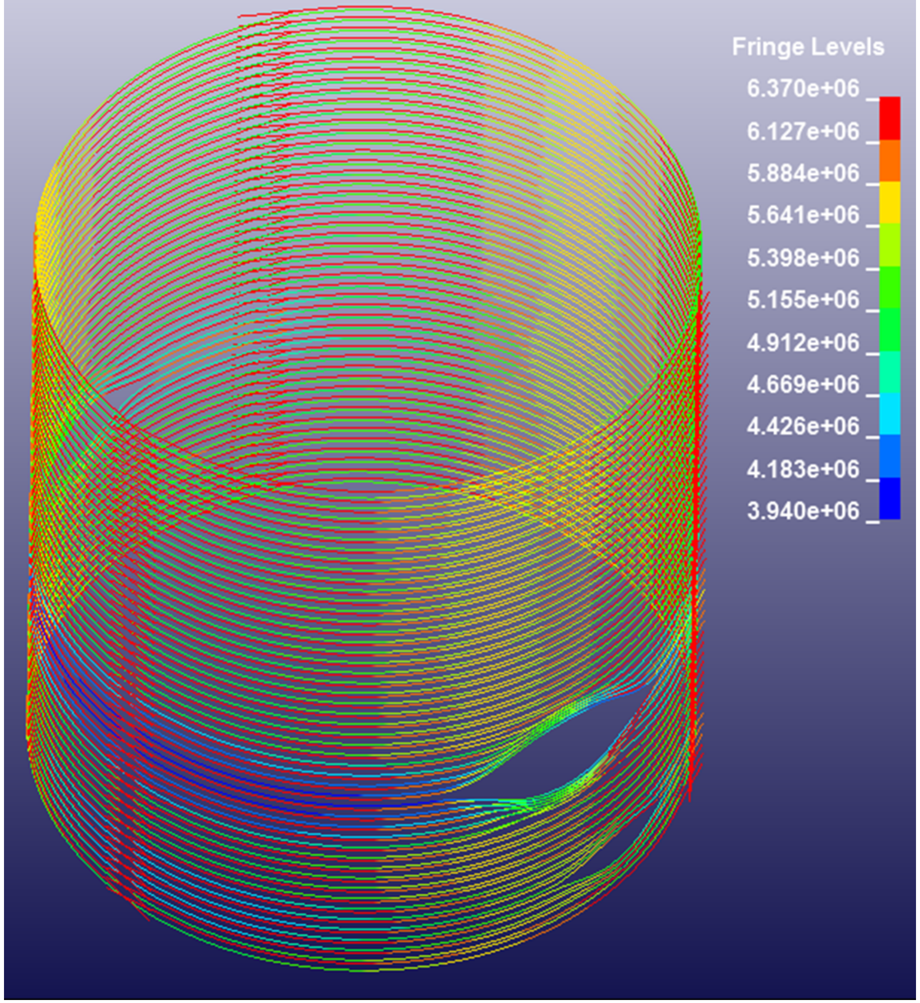
- Concrete (compressive and tensile strength)

Containment	53MPa and 4.5MPa
Basemat	43MPa and 4.1MPa

Analysis

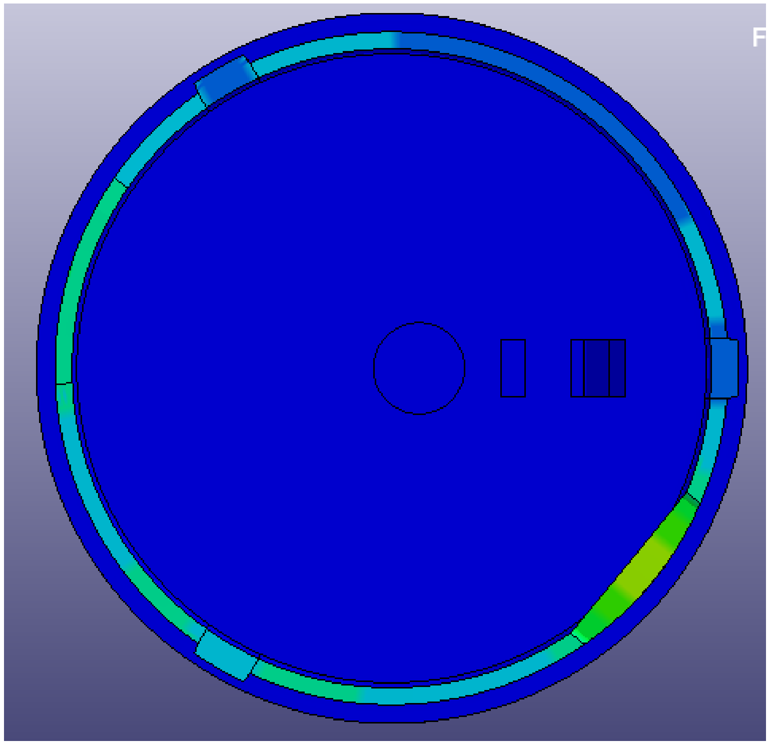
- Dynamic relaxation – Initial stresses including prestress
- Step-by-step for internal pressurization with mass scaling (small)



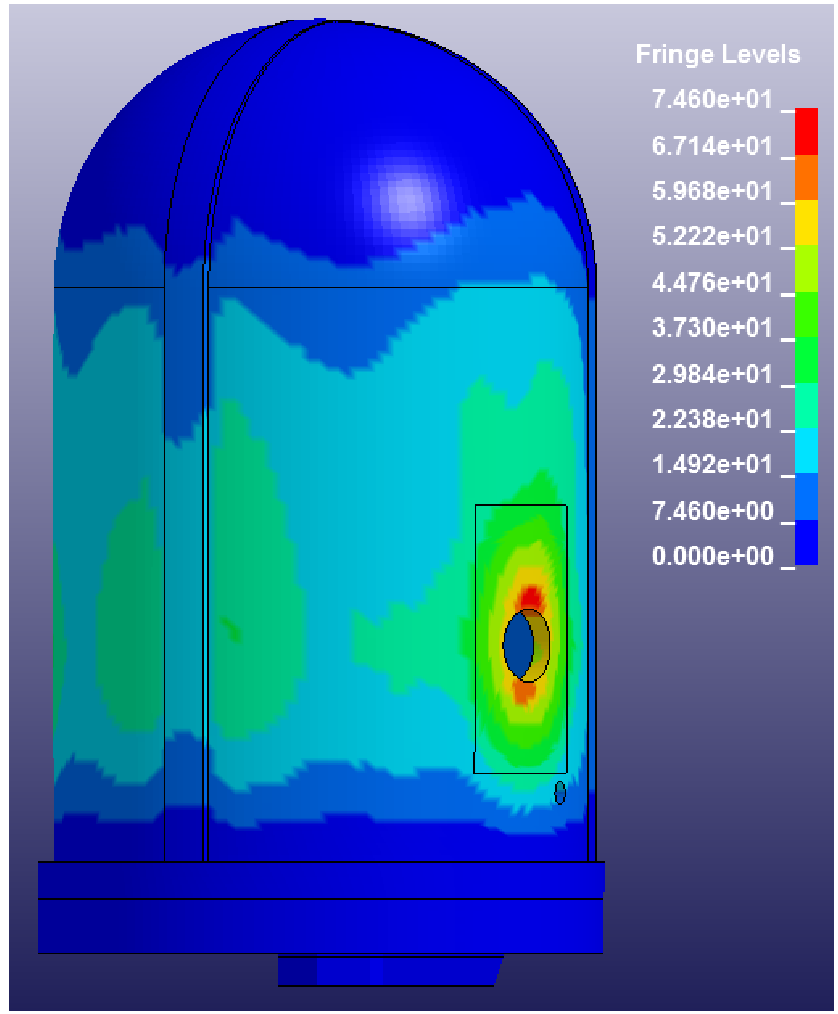


Analysis

- Slow increase of internal pressurization (0.83 MPa/s)



Total displacements at 0.83MPa (120psig)



Total running time of entire analysis on a 12-processor PC ~ 14.5 hours

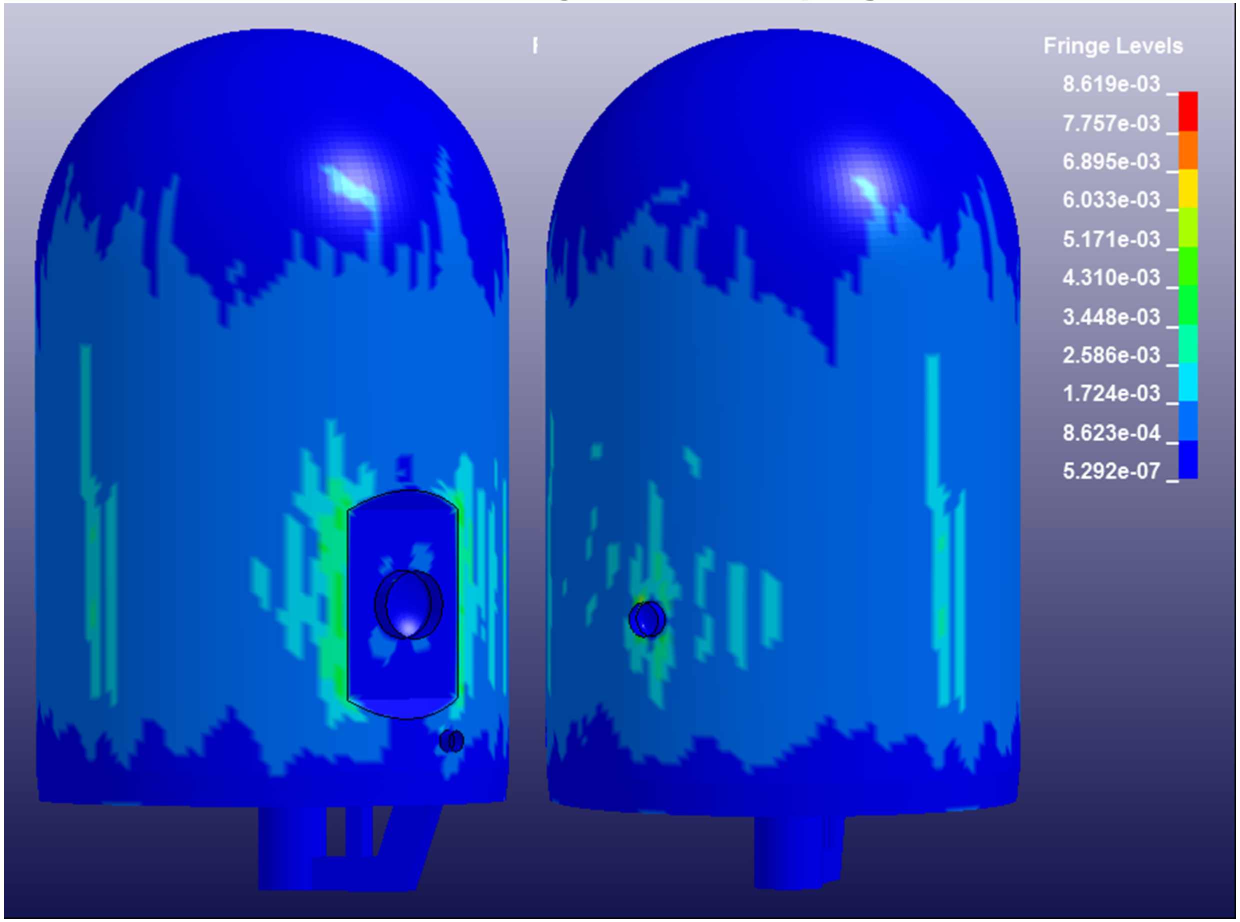
U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Analysis

- Functional (leakage) limit states
  - Onset of liner tearing
  - Leakage 0.1ft^2 (93cm^2)
  - Functional rupture 0.3 – 1.0ft^2 (280 – 930cm^2)
- Structural limit states
  - Hoop tendon strains of about 1%
  - Shear at wall-basemat junction
- Liner tearing
  - Results of the 3D containment finite element analysis with strain concentration factors (Tang, Dameron, Rashid, 1995) and statistics of failure strain for liner's carbon steel (Cherry, 1996)
- Leakage area
  - Tear opening ~ (wall strain)x(anchorage spacing)
  - Crack area (in an element) = (tear opening)x(element length)
  - Sum over elements

Results Summary

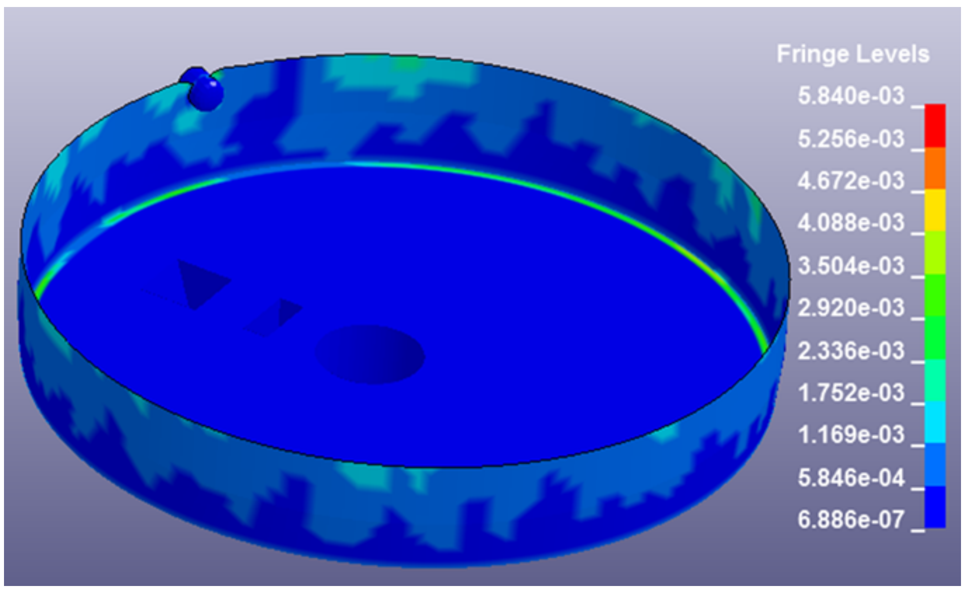
- Likely leakage locations
  - Near containment, emergency airlock and personnel hatch
  - Wall-basemat junction (high strain concentration factors)

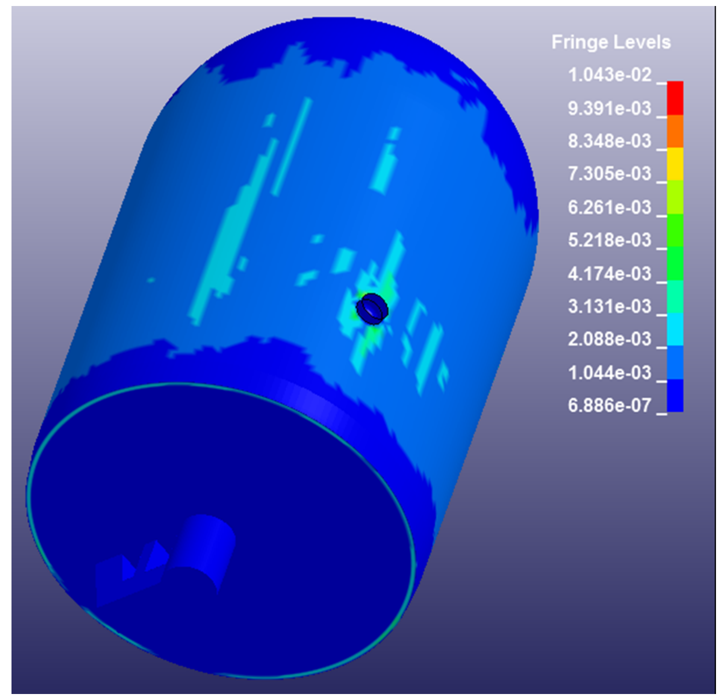


Maximum principal strains at 0.86MPa (124 psig)

Results Summary

- More likely leakage locations
  - Near containment, emergency airlock and personnel hatch
  - Wall-basemat junction (high strain concentration factors)



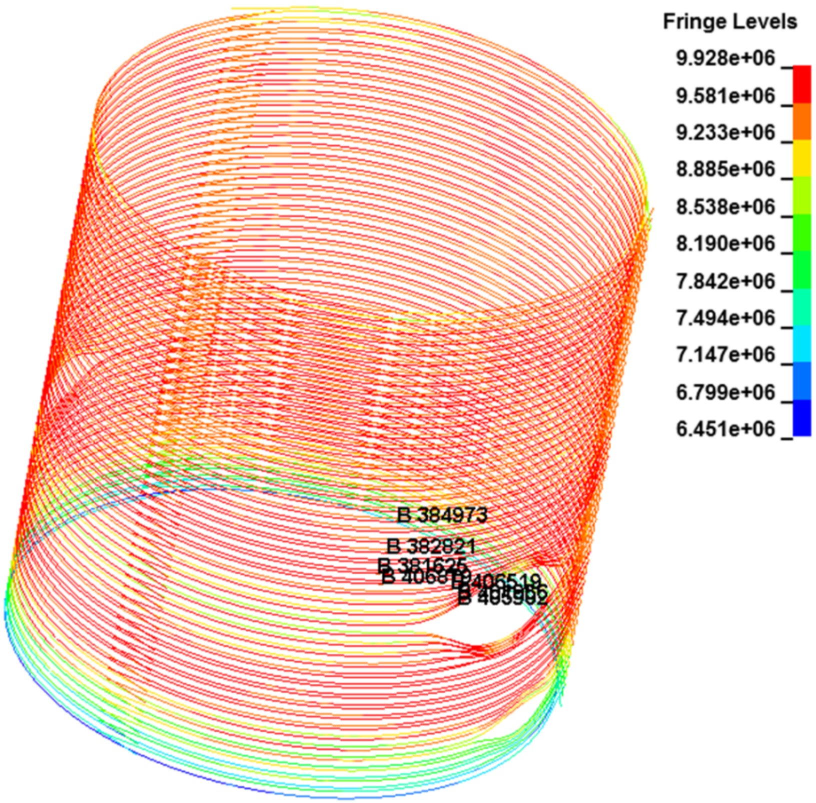


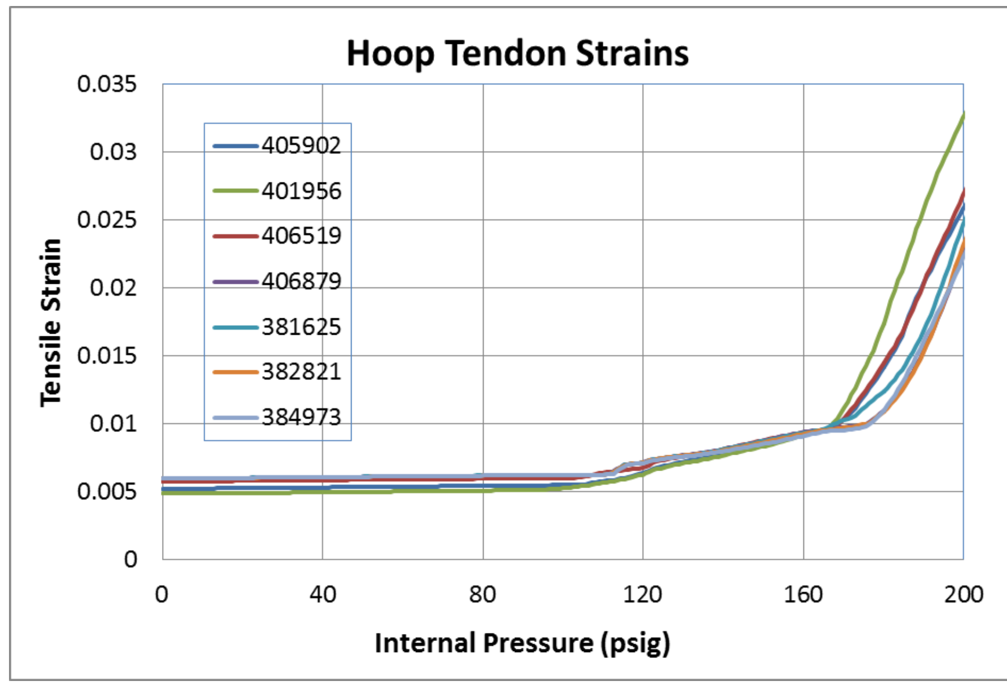
Maximum principal strains at 0.90MPa (131 psig)

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Results Summary

- Structural limit states – Tendon hoop strains (wall strains)



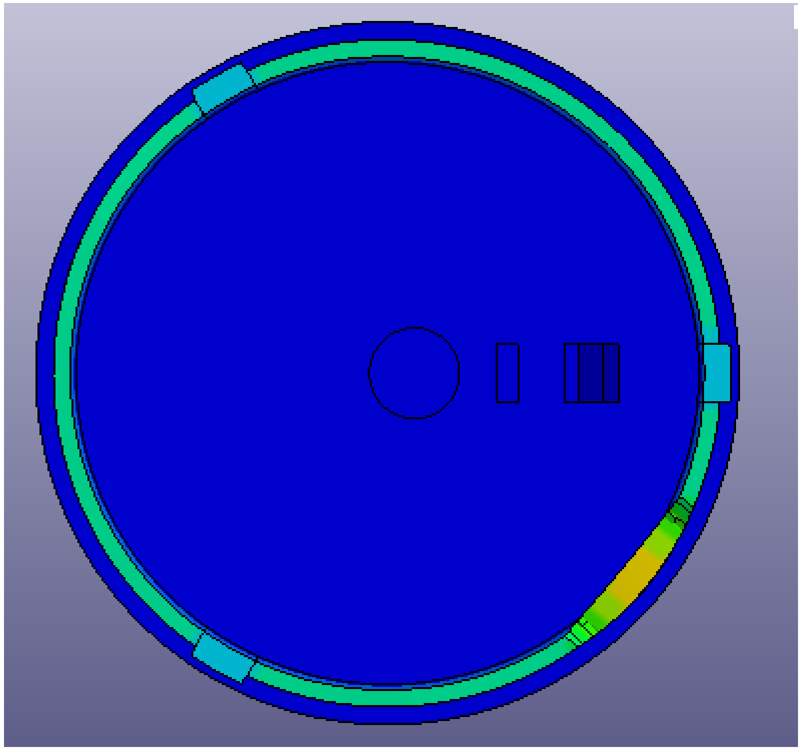


Tendon forces at 1.13MPa (164psig)

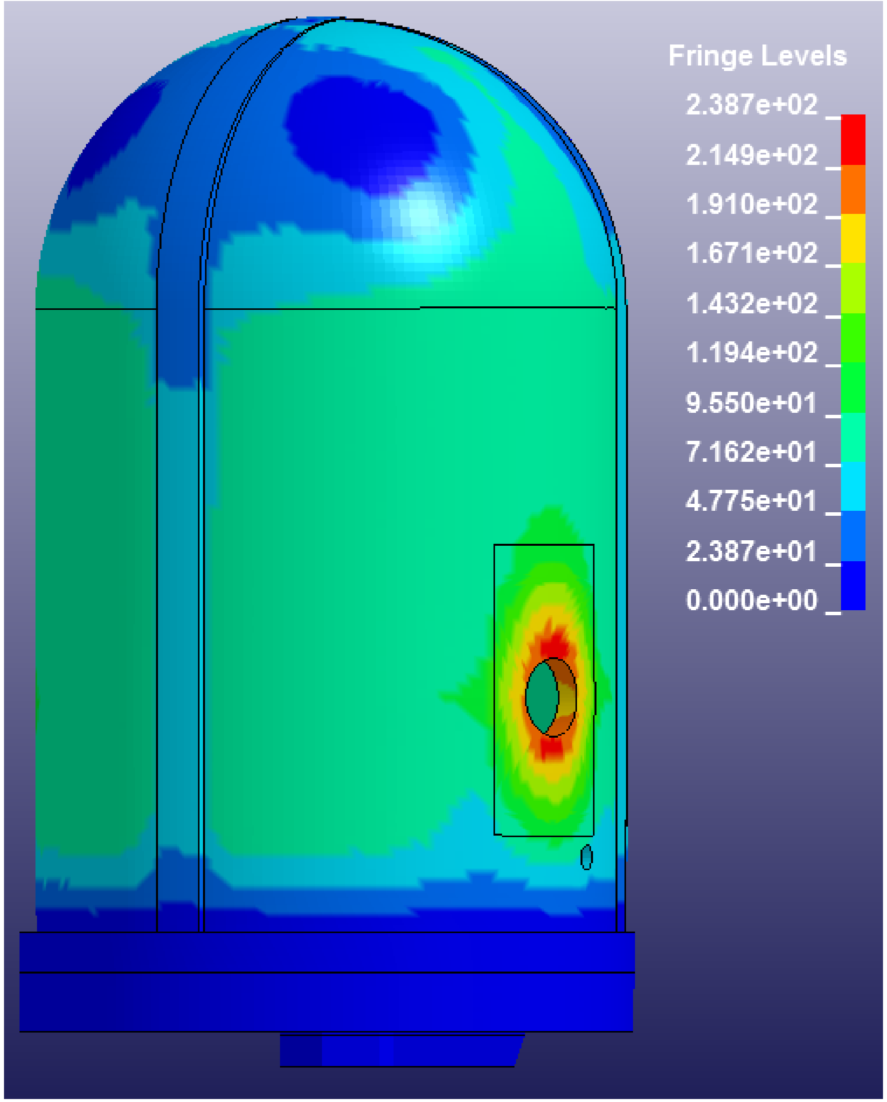
Tendon force at 1% strain ~ 9.7×10^6 newtons (2.2×10^6 lbf)

Results Summary

- Structural limit states – Tendon hoop strains

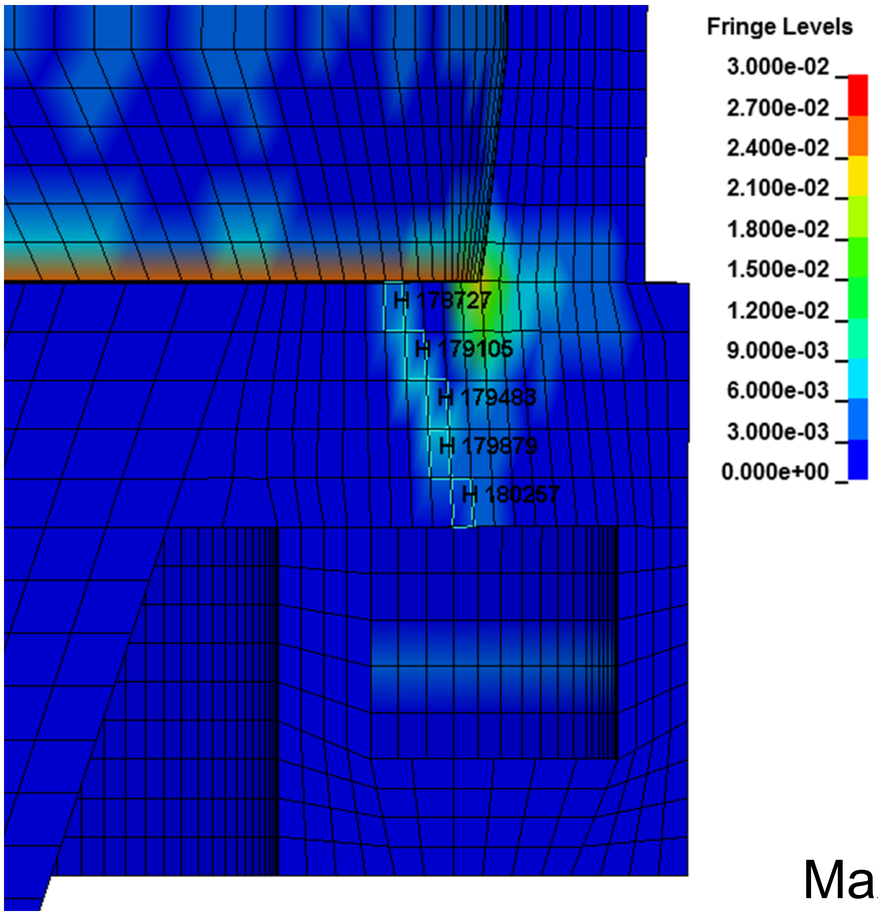


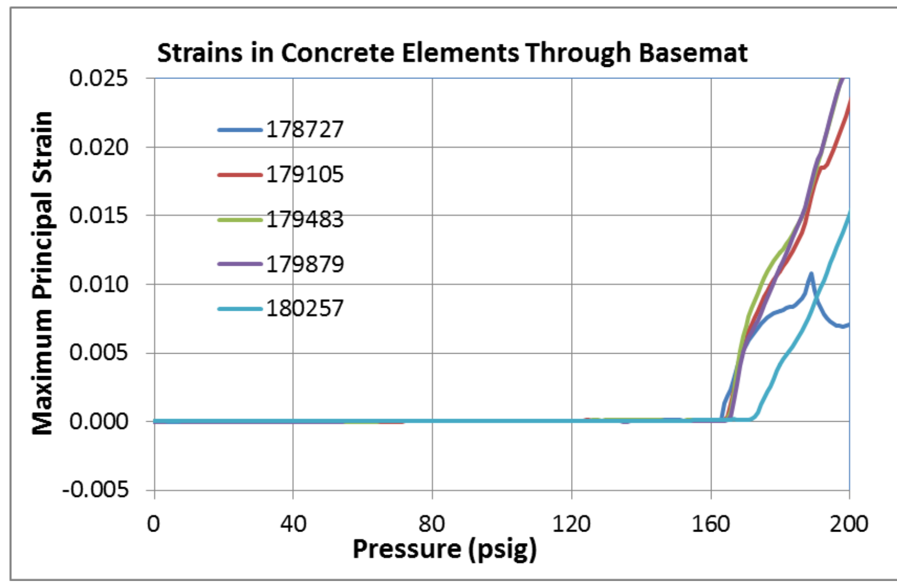
Displacements at 1.13MPa (164psig) (1% hoop strain)



Results Summary

- Structural limit states – Shear at wall-basemat junction





Maximum principal strains at 1.16MPa (168psig)

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Results Summary

- Cylinder wall (hatches)
  - Liner tearing 0.83MPa (120psig)
  - Leakage 0.86MPa (124psig)
  - Leakage Rupture 0.87-0.88MPa (126-128psig)
- Wall-basemat junction
  - Liner tearing 0.88MPa (128psig)
  - Leakage 0.90MPa (131psig)
  - Leakage Rupture 0.90-0.92MPa (131-134psig)
  - Likely to the tendon gallery
- Closeness of pressures makes both locations plausible
- Structural limit state
  - Tendon strains (1%) 1.10 – 1.16MPa (159-168psig)
  - Shear at wall-basemat 1.16 – 1.20MPa (168-174psig)
- Closeness of pressures makes both cases plausible

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

Summary/Conclusions

- The paper describes the modeling and results of a three-dimensional finite element analysis of a post-tensioned concrete containment with ungrouted tendons for beyond-design basis internal pressurization.
- Goals for the analysis include illustrating results that would inform Level 2 probabilistic risk assessments and assessing modern modeling and analysis techniques.
- The analysis provides results that are generally consistent with results that would be expected based on insights obtained from prior containment testing and analyses.
- The analysis provides pressures for various leakage damage states including a containment functional rupture state associated with uncontrollable leak rates as well as the associated leak locations both of which are relevant for the Level 2 PRA.

Summary/Conclusions

- The analysis also provides pressures corresponding to potential structural failure limit states corresponding to specified tendon hoop strains or shear at the wall-basemat junction.
- Calculated pressures for the leakage limit states are 2.4 to 2.5 times greater than the design pressure which is equal to 0.36 MPa (52 psig) and for the structural limit state more than 3 times grater than the design pressure.
- Containment structural failure is not expected to be catastrophic if the pressurization rate inside the containment is less than the depressurization from the leak rate.
- The calculations with this modeling and explicit analysis are sufficiently fast so that sensitivity analysis and uncertainty analysis with, for example, Latin Hypercube statistical simulation is feasible.