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Title:	Implementing Code Case 2564: Impulsively Loaded Pressure Vessels ASME Section VIII., Division 3
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Implementing Code Case 2564: Impulsively Loaded Pressure Vessels ASME Section VIII, Division 3

Focused Exchange Meeting on Confinement & Containment Vessels JOWOG 32HDT

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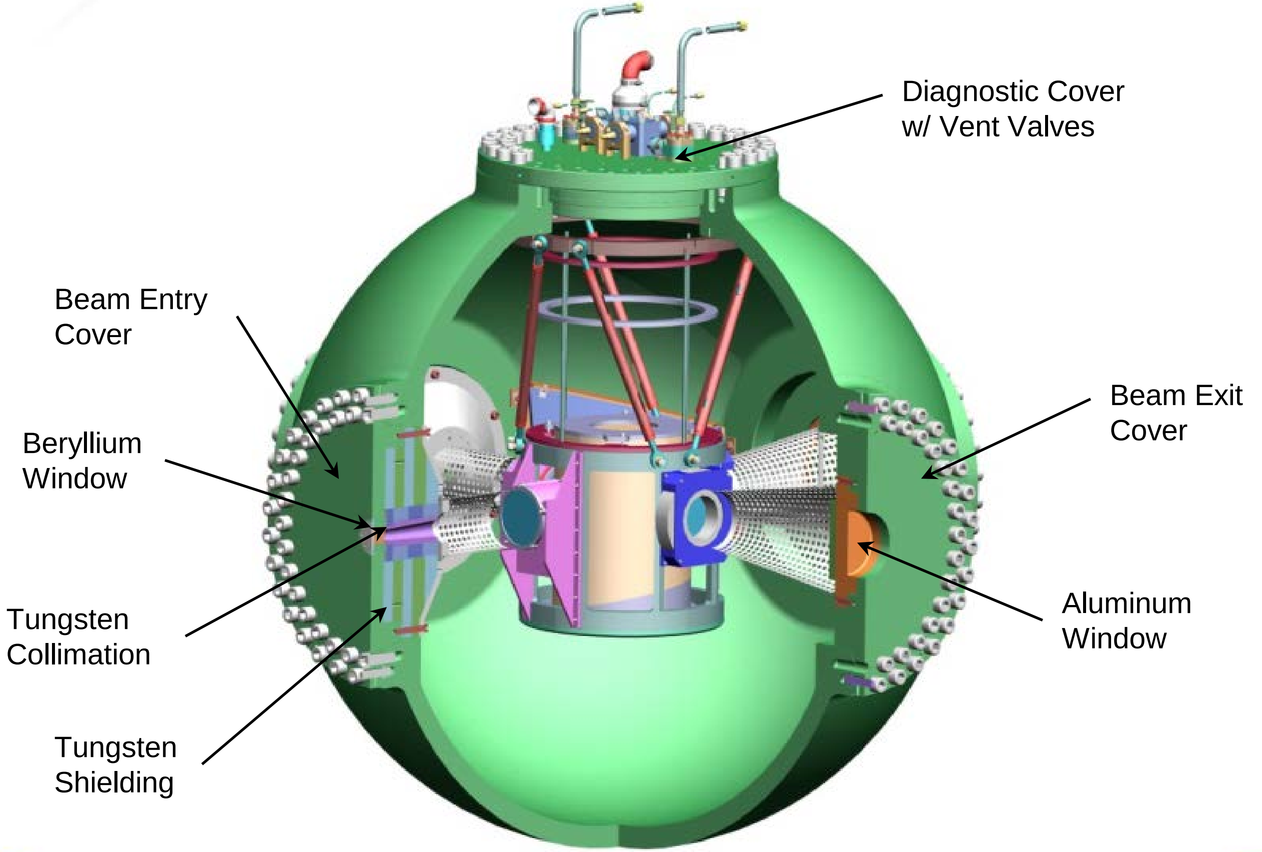
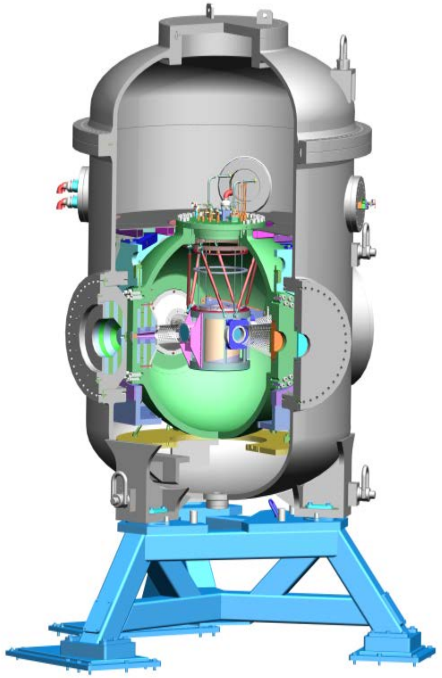
Introduction

- Present design guidance for impulsively loaded vessels in accordance with ASME Code Sec. VIII, Div. 3 and Code Case 2564.
- Differentiate between Code Case 2564 and basic rules of Sec. VIII, Div. 3
- Describe noteworthy design/analysis qualification successes with Code Case 2564
- Present brief Gemini analysis results

Background

- In 2001, LANL staff met with ASME B&PV Code Executive Committee to address explosively loaded vessel design in support of DynEx Program execution





Dual-Axis Containment System (DACS)

Background

- Working with the Pressure Vessel Research Council (PVRC) in developing the design guidance, LANL staff authored two seminal papers published as WRC Bulletins,
  - Ductile Failure Design (WRC 477, Dec. 2002)
  - Fracture Safe Design (WRC 494, Aug. 2004)
- January 2008 ASME TG-ILV, with ASME Sec VIII, Div. 3 approval, publishes Code Case 2564
  - Addresses design rules for impulsively-loaded pressure vessels
    - High-explosives (HE)
    - Gaseous detonations
  - All other construction rules (e.g., fabrication and inspection) adopted from ASME B&PVC Code Section VIII, Div. 3

Background

- The Gemini Series (Castor Confirmatory & Pollux Subcritical Experiment) was 1st LANL vessel design qualified to the ***intent of*** ASME B&PV Code and CC-2564:
  - 1500 g TNT-equivalent loading
- The Gemini Series vessels were also the 3rd vessel design qualified to ASME CC-2564
  - Sandia National Laboratories (SNL) Explosive Destruction System (EDS) supporting US Army Chemical Weapon Demilitarization (CWD)
  - Kobe Steel “DaVinch DV-60 Vessel” (CWD)
- Deep Well Fracturing
  - Fluid pressures of 50,000 psi
  - Surgical high-explosive detonations
  - Various petro customers

Background

- SNL's EDS-2 Vessel

  - Design = 4.8-lb TNT Eq.
  - Test = 6.0 lb
  - SA-182 316 SS shell
    - o Sy = 36 ksi
    - o Su = 70 ksi

- Kobe Steel "DaVinch 60"

  - Design = 60 kg TNT Eq.
  - Test = 75 kg
  - SA-350 LF3 shell
    - o Sy = 36 ksi
    - o Su = 70 ksi

ASME Code Sec. VIII, Div. 3

- Primarily for high-pressure design
  - Thick-shell vessel wall
  - Only specific high-strength materials allowed (Table KM-400)
  - Static design pressure exceeding 10,000 psi
    - Deep well exploration pressures exceed 50,000 psi
    - HMX charges fissure rock formation
- Methodology based on utilizing computational modeling throughout
  - Elastic-plastic analysis techniques preferred
  - Linear-elastic design methodology may still be used
    - Criteria relegated to Appendices
- KD-3 fatigue analysis requires use of ground or machined welds and Structural Stress method employed for weld stress analysis
    - Only if leak-before-burst (LBB) is demonstrated per KD-141
- KD-4 fatigue crack-growth fracture mechanics assessment is endorsed

Design Methodology for Impulsively Loaded Vessels

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- Design Methodology for Impulsive Loading
  - Develop dynamic model and forcing functions
    - Simplified approach per UFC 3-340-02 (successor to TM 5-1300)
      - Common geometries and point symmetric solutions
    - Computational hydrodynamics
      - EOS for HE and steel
  - Develop structural response computational model
    - Explicit dynamics
      - Non-symmetric spatial and temporal pressure history
    - Material models
      - Elastic-plastic stress-strain curve
      - Rate dependent preferred
  - Perform CC 2564 analyses
    - Global Plastic Instability
      - 175% of design basis impulse
      - No unbounded deformations

Code Case 2564

- Design Methodology for Impulsive Loading (cont'd)
  - Perform CC 2564 analyses (cont'd)
    - Local Tearing failure
      - 100% of design basis impulse
      - Accumulated plastic strains remain below limits
    - Dynamic Proof Test
      - 125% of design basis impulse
      - Strain history must be included in overall assessment
    - Multiple-detonation event design
      - Determine Strain Ratcheting
      - Elastic Shakedown
      - Successive detonation event strain-history (strain accumulation)
        - Demonstrate shakedown or
        - Limit vessel life

Code Case 2564

- Design Methodology for Impulsive Loading (cont'd)
  - Perform CC 2564 analyses (cont'd)
    - Perform static pressure analysis per KD-230
      - Residual quasi-static pressure is a sustained load
        - Global Collapse @ 1.80 x peak pressure
      - Ductility exhaustion methodology applies
        - Local Failure @ 1.28 x peak pressure
      - Include hydrostatic test @ 125% of residual pressure
    - Perform fatigue crack-growth analysis
      - Fitness for Service (FSS) methodology per API-579/ASME-FFS
        - Material fracture toughness data
        - Develop failure assessment diagram (FAD)
        - Determine Kr-Lr for vibration cycles/detonation cycles
        - Determine number of detonation events

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Dynamic Pressure Design Criteria

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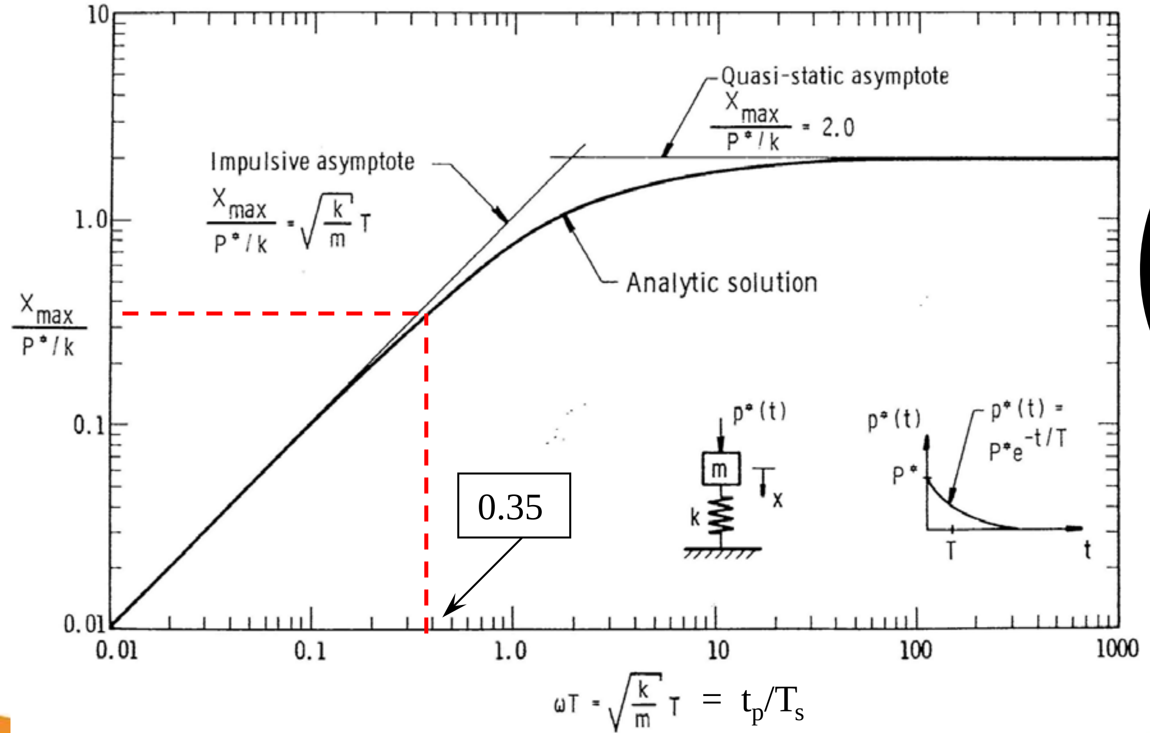
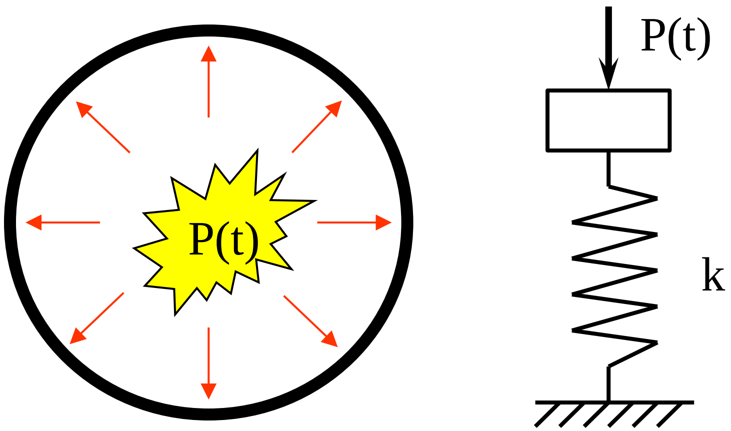
- Impulsive regime
  - Impulsive loads are energy-controlled events
    - Finite amount of energy delivered over a limited period of time
    - Impulse regime is defined as: $\frac{t_p}{T_s} \leq 0.35$





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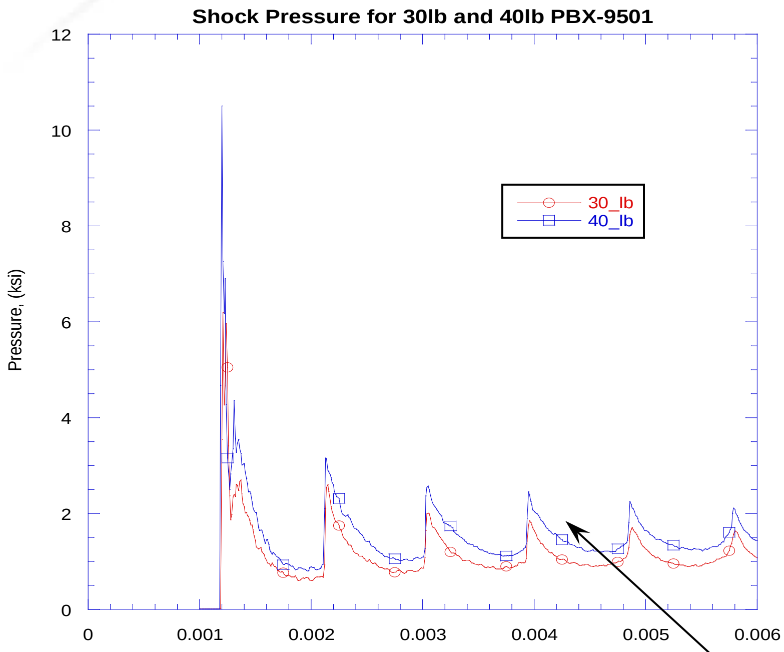
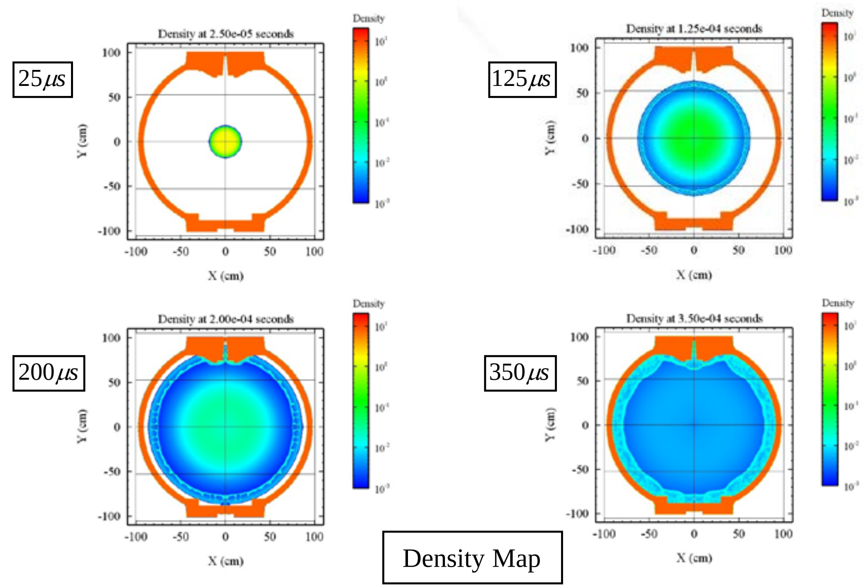
- Pulse-period to structural-period of vibration
  - Fundamental breathing-mode response



t_p

Quasi-static residual pressure



Fundamental Structural Period

$$T_s = 2\pi\sqrt{\frac{m}{k}}$$

Code Case 2564

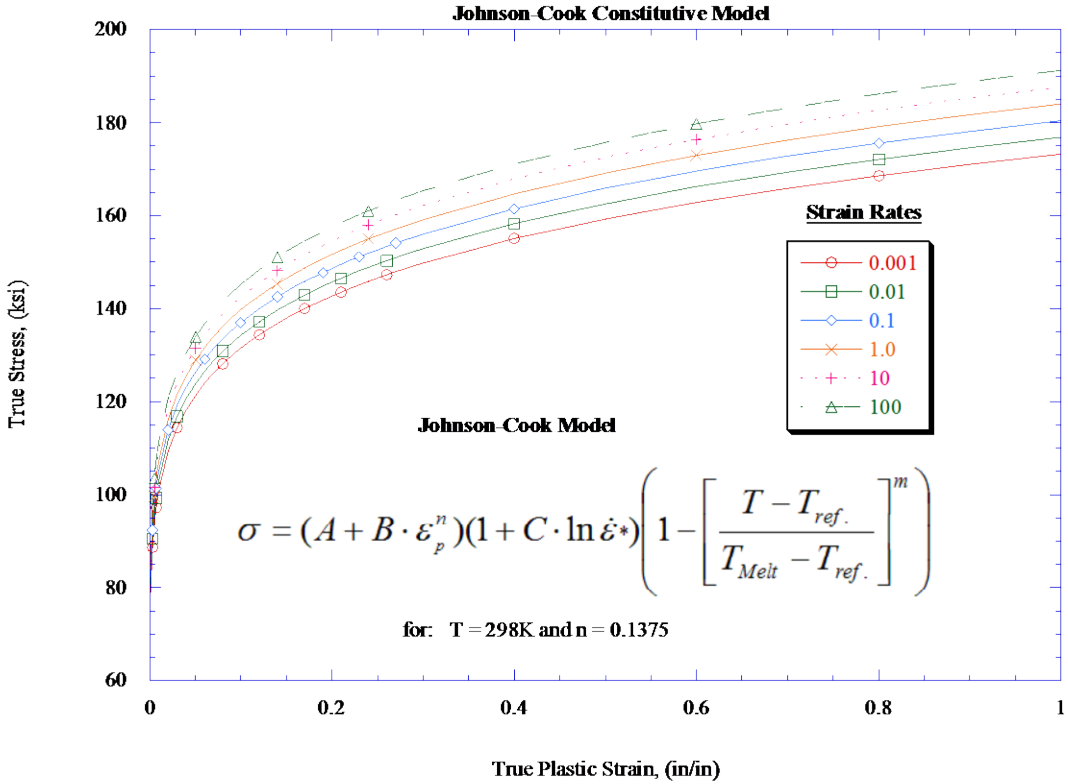
- Material Models
  - von Mises yield function and associated flow rule preferred (vice Tresca)
  - Elastic-plastic stress-strain with temperature dependent hardening behavior model may be developed per guidance in KD-231.4
    - Actual strain-rate dependent data is preferred (i.e., Johnson-Cook Model)

$$\sigma = (A + B \cdot \varepsilon_p^n)(1 + C \cdot \ln \dot{\varepsilon}*)\left(1 - \left[\frac{T - T_{ref.}}{T_{Melt} - T_{ref.}}\right]^m\right)$$

    - Temperature dependence may or may not be important
    - Otherwise, static stress-strain curve shall be used, i.e., $\dot{\varepsilon} = 0.001 \ \sec^{-1}$
    - Quasi-static pressure analysis portion requires
      - Elongation (%e) and
      - Reduction of Area (%RA)

Code Case 2564

- Material Models
  - HSLA-100 (Gemini Vessel)



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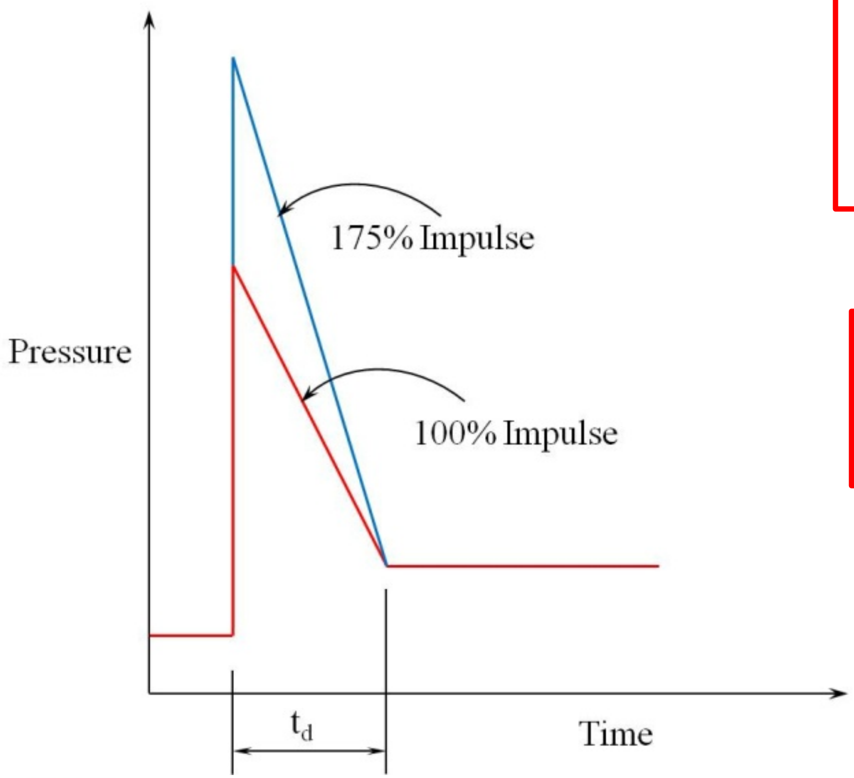
- Global Plastic Instability
  - Analysis conducted at 175% of DB impulse
    - Ensure numerical convergence
    - Plastic strains are not limited

Global Plastic Instability Load

- The plastic instability load for members under predominantly tensile or compressive loading is defined as that load at which unbounded plastic deformation can occur without an increase in load.
- At the plastic tensile instability load, the true stress in the material increases faster than strain hardening can accommodate.



Instability for a complete spherical shell under deformation control occurs when the circumferential strain is equal to the strain at necking in the tensile test.
(T. Duffey, JPVT, Vol. 133, 2011)

Total Specific Impulse: $I_S = \int P dt$

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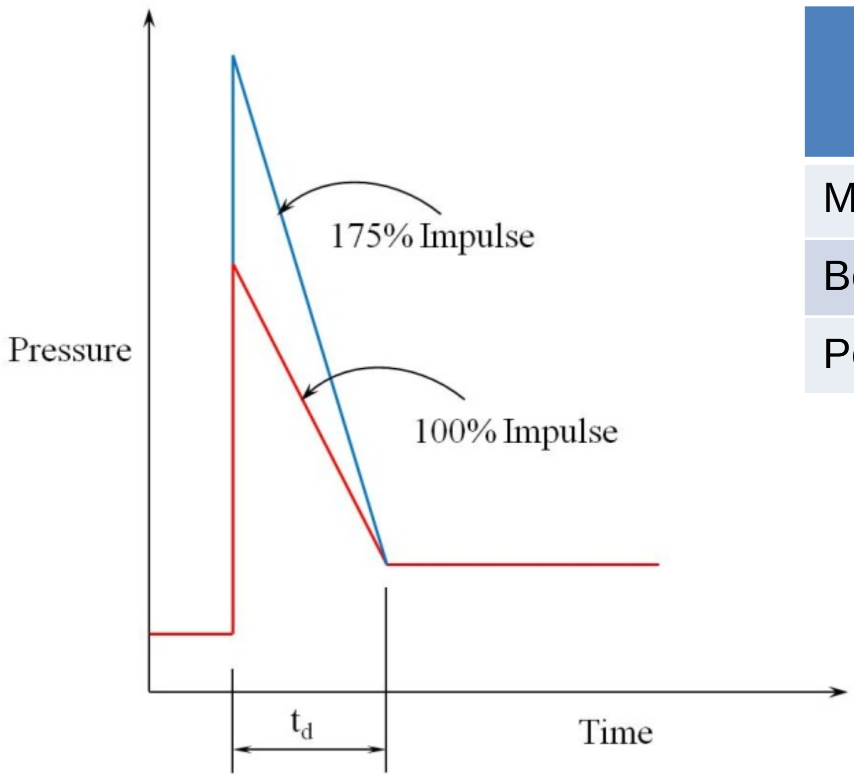
- Local Tearing Failure
  - Analysis conducted at 100% of DB impulse.
  - Accumulated equivalent plastic strain limits for parent metal and welds.

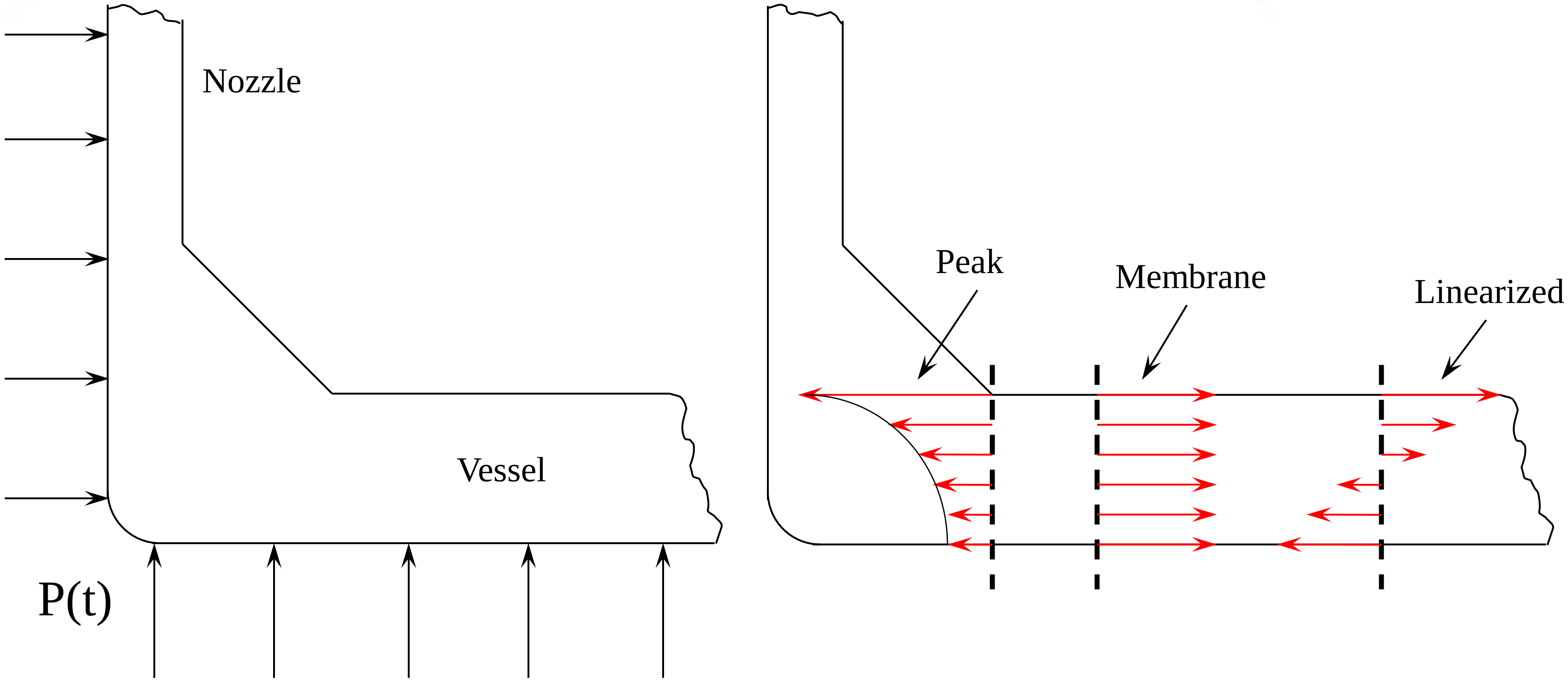


Plastic Strain Component	Strain Limits (%)	
	Parent Metal	Weld
Membrane	0.2	0.2
Bending	2.0	1.0
Peak	5.0	2.5

- Limits are much lower than current KD-230 ductility exhaustion criteria.
- Use of KD-230 ductility exhaustion methodology <u>for impulsive events</u> is not endorsed by Code Case 2564.
  - o Ferritic and austenitic steel parameters are non-conservative.
  - o Use of this methodology is cautioned for impulsive loading

Code Case 2564

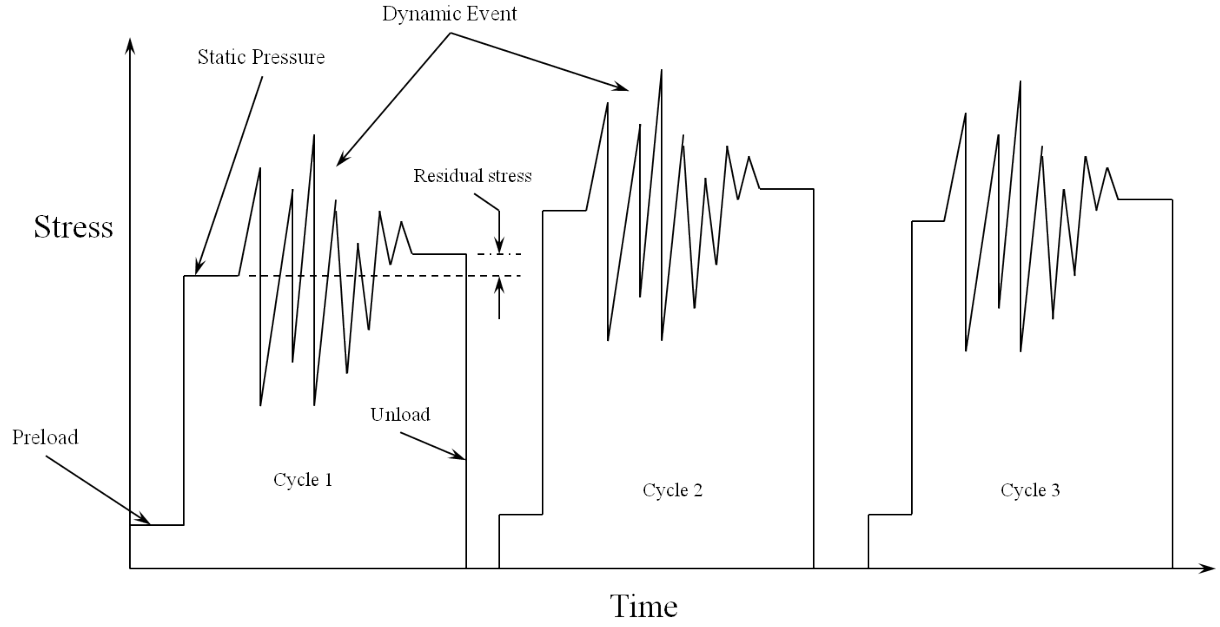
- Plastic Strain Components



Strain Ratcheting / Elastic Shakedown

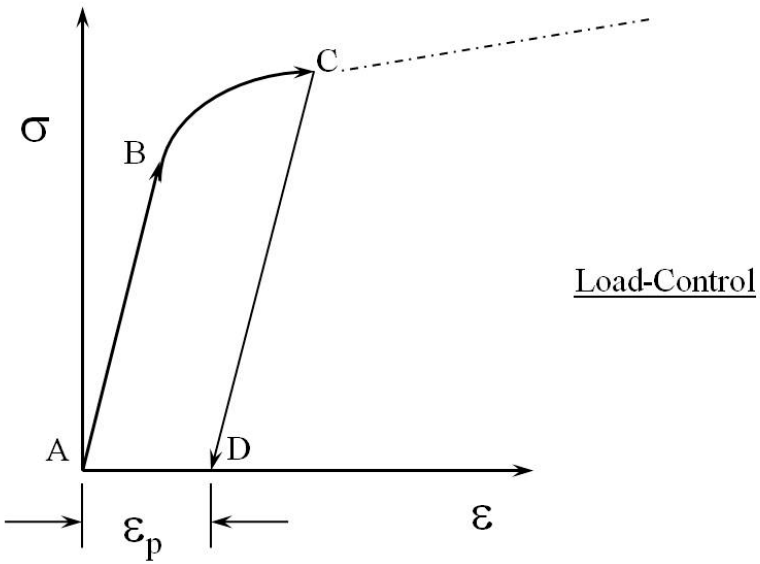
Code Case 2564

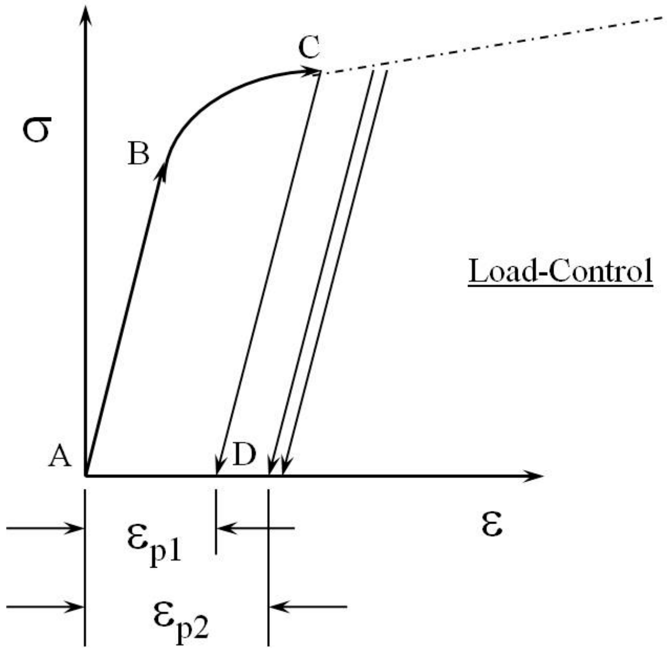
- Strain Ratcheting / Elastic Shakedown
  - Demonstrate that subsequent application of DB impulse will not result in strain ratcheting (i.e., progressive incremental plastic straining).
    - Computationally inexpensive to re-run model with existing history
  - If strain limits are exceeded, the vessel design can only be certified for a certain number of detonation cycles.



Code Case 2564

- Strain Ratcheting / Elastic Shakedown





- But impulsive loadings are NOT load controlled!
- Impulse loads are energy-controlled which are akin to strain- or deformation-controlled.

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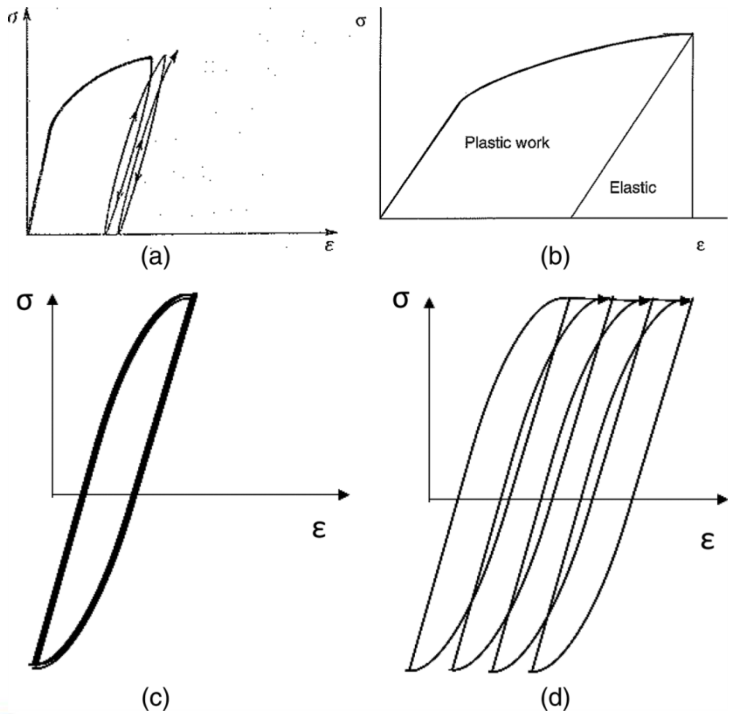
- Strain Ratcheting / Elastic Shakedown
  - Ratcheting is produced by a sustained load acting over the full cross section of a component, in combination with a strain-controlled cyclic load.
    - Impulsively loaded vessels: (1) are subject primarily to deformation or strain-controlled cyclic loads, and (2) have a small percentage of sustained loading; i.e., quasi-static residual pressure.



(a) Ideal load-controlled hysteresis becoming narrower, resulting in shakedown
(b) Plastic work and elastic strain energy
(c) Deformation-controlled hysteresis loop stable in-time; resulting in shakedown
(d) Deformation-controlled hysteresis loop incrementally increasing; resulting in strain ratcheting

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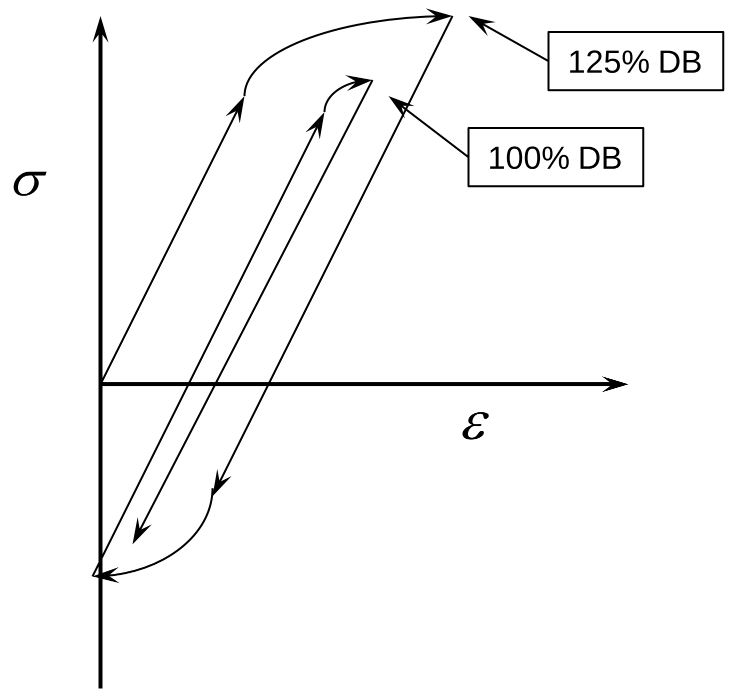
- Strain Ratcheting / Elastic Shakedown
  - Dynamic proof test at 125% of the DB loading results in local regions beyond elastic limits
  - Additional reduced loading events (i.e., 100% DB load) will cycle elastically
    - Shakedown demonstrated



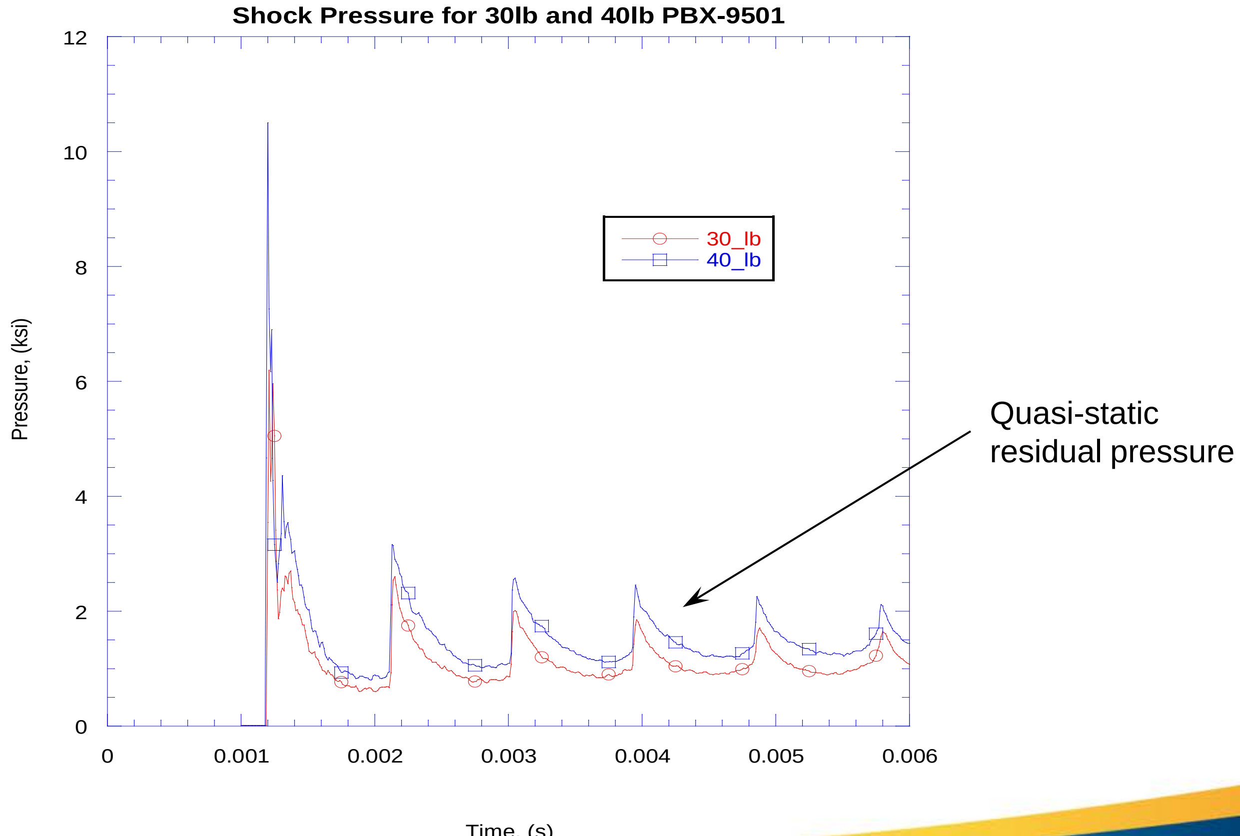
Test No.	Charge (kg)	Cylinder Strains (μs)			
		T3-L	T3-L Delta	T7-L	T7-L Delta
Calibration	40.5	2455	2455	1043	1043
1	75	7966	5511	9832	8789
2	40.5	8041	75	9877	45
3	60	8053	12	10027	150

Kobe Steel

Static Pressure Design Criteria

Code Case 2564

- Design Criteria of KD-230 for Static Pressure
- For impulsive loading design, rules of KD-230 are ONLY applied to the long-term, quasi-static, residual gas pressure remaining in vessel.



Code Case 2564

- Design Criteria of KD-230 for Static Pressure
  - Static pressure loading uses Ductility Exhaustion methodology of KD-231; Elastic-Plastic Analysis
    - Global Collapse Criteria*: The plastic collapse load is taken as the load that causes structural instability using the following

      Loading Function $1.80\left(P_D + P_S + D\right)$

    - Local Failure Criteria: Meet the following plastic strain allowable to capture triaxilaity effects.

$$\varepsilon_{L,k} = \left(\varepsilon_{Lu}\right)\exp\left[\frac{-m_5}{m_2+1}\left(\frac{\sigma_{1,k}+\sigma_{2,k}+\sigma_{3,k}}{3\sigma_{e,k}}-\frac{1}{3}\right)\right]$$

Local tearing damage

      Loading Function $1.28\left(P_D + P_S + D\right)$

* Global collapse is indicated by the inability to achieve an equilibrium solution for a small increase in load (i.e., the solution will not converge); unbounded deformations.

Code Case 2564

- Design Criteria of KD-230 for Static Pressure
  - Local Failure Criteria (Triaxiality Effects)

Tabular Values for Coefficients in Ductility Exhaustion Calculations (Reproduction of ASME VIII-3, Table KD-230.5)

Material	Maximum Temperature	m_2	m_3	m_4	m_5	ε_p
Ferritic Steel (Note 1)	480°C (900°F)	$0.60(1-R)$	$2\ln\left[1+\frac{El}{100}\right]$	$\ln\left[\frac{100}{100-RA}\right]$	2.2	2.0E-5
Austenitic stainless steel and nickel-based alloys	480°C (900°F)	$0.75(1-R)$	$3\ln\left[1+\frac{El}{100}\right]$	$\ln\left[\frac{100}{100-RA}\right]$	0.6	2.0E-5
Duplex stainless steels	480°C (900°F)	$0.70(0.95-R)$	$2\ln\left[1+\frac{El}{100}\right]$	$\ln\left[\frac{100}{100-RA}\right]$	2.2	2.0E-5
Precipitation hardening, nickel based	540°C (1000°F)	$1.90(0.93-R)$	$\ln\left[1+\frac{El}{100}\right]$	$\ln\left[\frac{100}{100-RA}\right]$	2.2	2.0E-5
Aluminum	120°C (250°F)	$0.52(0.98-R)$	$1.3\ln\left[1+\frac{El}{100}\right]$	$\ln\left[\frac{100}{100-RA}\right]$	2.2	5.0E-6
Copper	65°C (150°F)	$0.50(1-R)$	$2\ln\left[1+\frac{El}{100}\right]$	$\ln\left[\frac{100}{100-RA}\right]$	2.2	5.0E-6
Titanium and Zirconium	260°C (500°F)	$0.50(0.98-R)$	$1.3\ln\left[1+\frac{El}{100}\right]$	$\ln\left[\frac{100}{100-RA}\right]$	2.2	2.0E-5

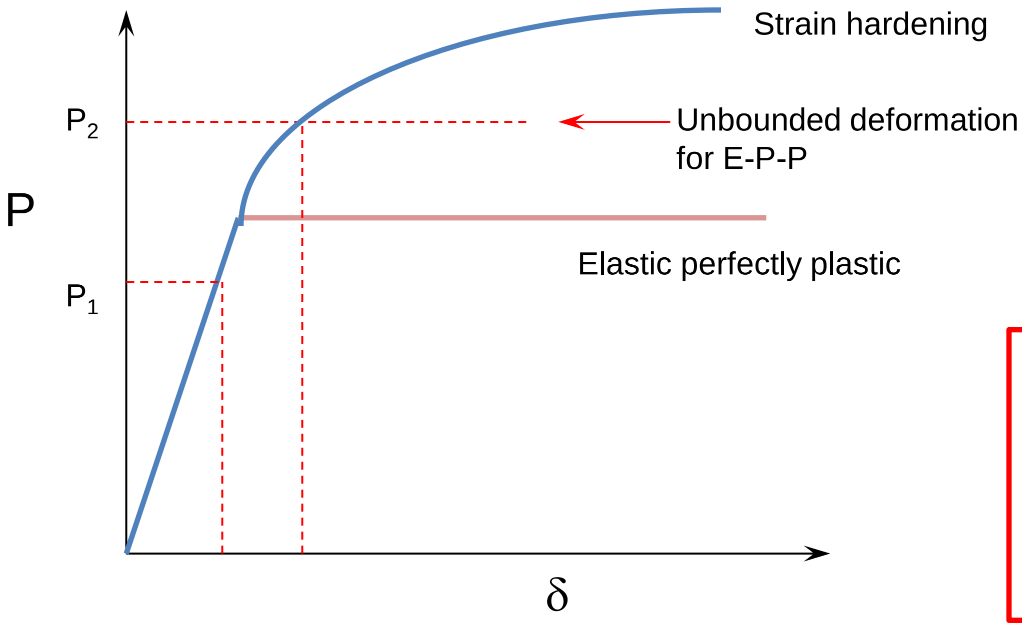
NOTE:

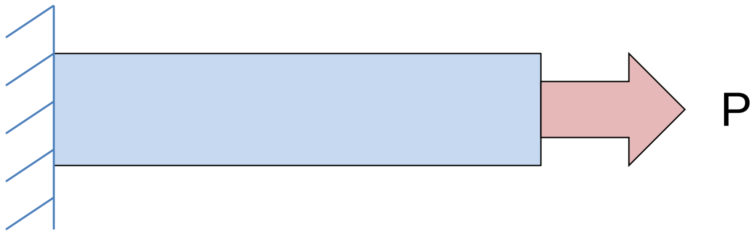
(1) Ferritic steel includes carbon, low alloy, alloy steels, ferritic, martensitic, and iron-based age-hardening stainless steels.

(2) m_5 is also α_{sL}.

Code Case 2564

- Mitigating global collapse under static (i.e., sustained) pressure requires “Primary” loads be maintained below failure limit
  - Primary Load





Collapse Load

- The methods of limit analysis are used to compute the maximum load, which a structure comprised of ideally plastic material can carry.
- The deformations of an ideally plastic structure increase without bound at this load, which is termed collapse load.

Code Case 2564

- Mitigating local failure entails ensuring plastic strains are below the triaxial plastic strain limit $\varepsilon_{L,k}$
  - This limit is based on the uniaxial test specimen data, strain hardening exponent, n, %Elong, %RA.

$$\varepsilon_{L,k} = (\varepsilon_{Lu})\exp\left[\frac{-m_5}{m_2+1}\left(\frac{\sigma_{1,k}+\sigma_{2,k}+\sigma_{3,k}}{3\sigma_{e,k}} - \frac{1}{3}\right)\right] \qquad T_r = \frac{\sigma_1+\sigma_2+\sigma_3}{3\sigma_e}$$

$m_2 =$ Maximum uniaxial plastic strain limits using strain-hardening measure

$m_3 =$ Maximum uniaxial plastic strain limits using logarithmic strain

$m_4 =$ Maximum uniaxial plastic strain limits using RA measure

$m_5 =$ Notch effect factor.

$T_r =$ Triaxiality factor

$\varepsilon_{L,u} =$ Uniaxial strain limit; maximum of m_2 m_3 m_4

Fatigue Crack-Growth Analysis

Code Case 2564

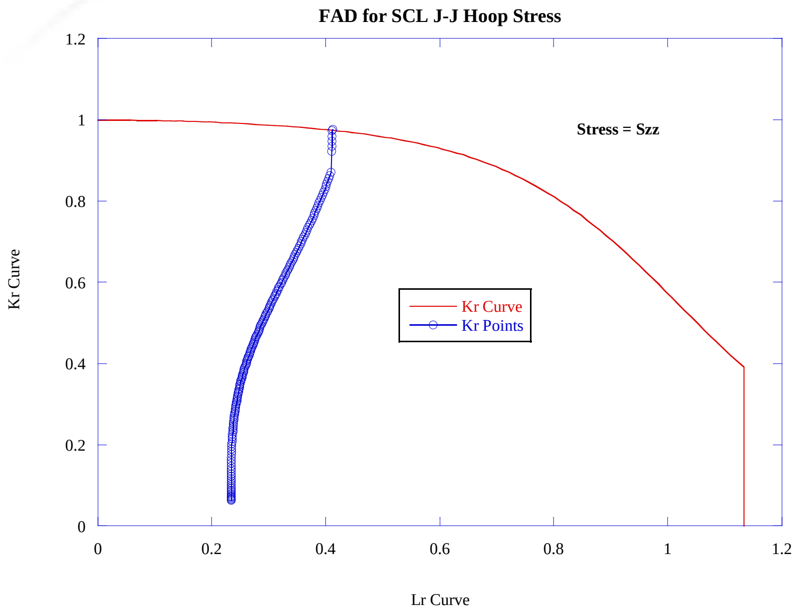
- Fatigue Crack-Growth Analysis
  - Use non-mandatory guidance in CC 2564, Sec. 3.3 or
  - API-579/ASME-FFS
- Each vibration cycle within a single detonation event may result in crack-growth
- Each detonation event results in multiple vibration cycles.
- Failure assessment diagram (FAD) utilizes an interaction between the toughness ratio, K_r , and primary load ratio, L_r^P

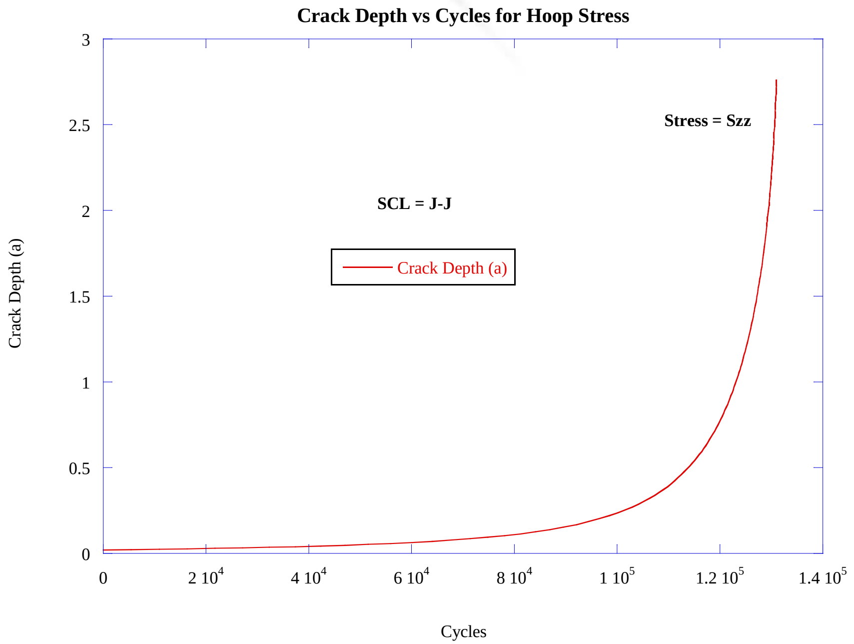
$$K_r = \frac{K_I^P + \Phi K_I^{SR}}{K_{mat}} \qquad L_r^P = \frac{\sigma_{ref}^P}{\sigma_{ys}}$$

NOTE:	As mentioned earlier, primary stresses are minimal and therefore K_I^P is negligible. This implies that secondary stresses, i.e., deformation-controlled stresses are predominant; K_I^{SR} is the significant quantity correlating fracture.

Code Case 2564

- Fatigue Crack-Growth





Failure Assessment Diagram (FAD) per API-579/ASME-FFS

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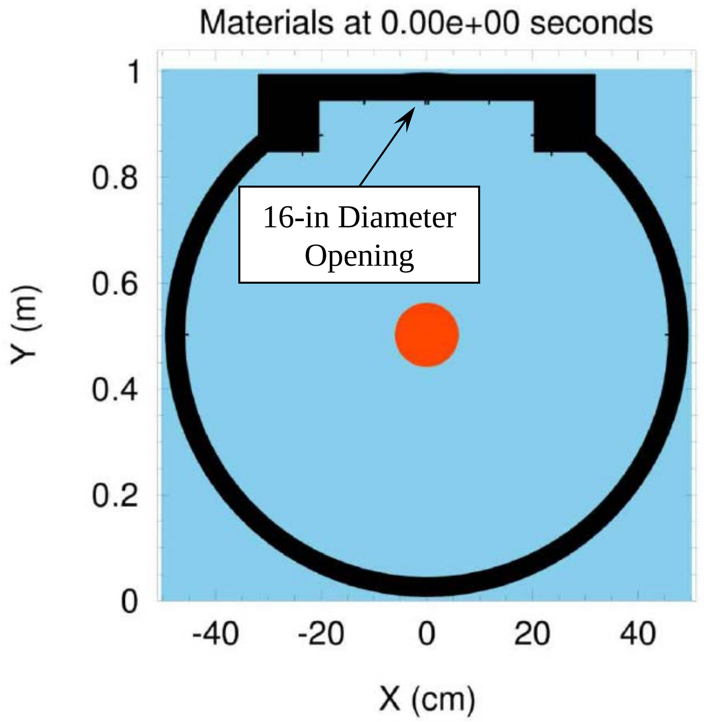
Gemini Series Vessel Design

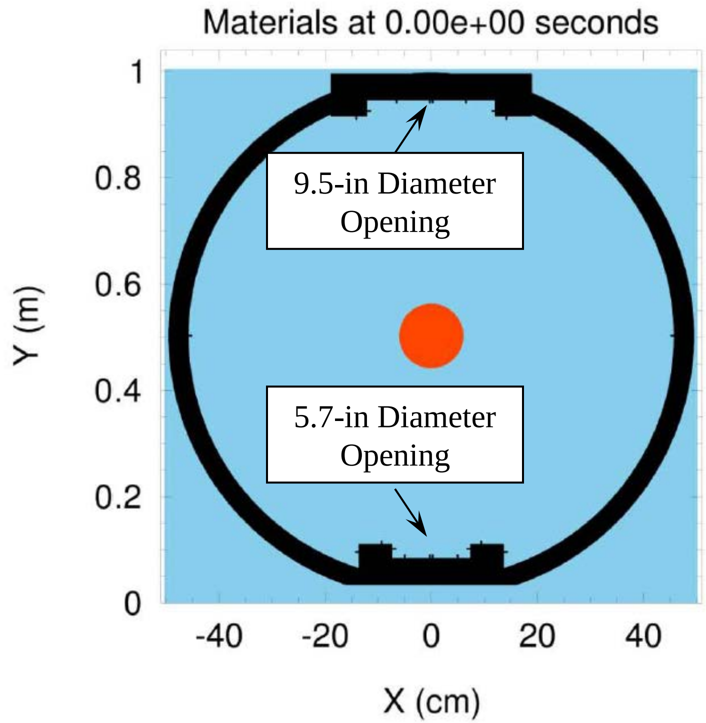
Gemini Vessel Analysis

- Gemini was the 1st LANL design certified to ASME Code Case 2564
- The 3-ft diameter HSLA-100 steel vessel design is analyzed in accordance with the rules and regulations of ASME Sec. VIII, Div. 3 and Code Case 2564-2.
- Analysis is subdivided into three separate entities:
  - Vessel weldment
  - Radiographic windows
  - Top cover
- Structural design is analyzed for:
  - Detonation induced impulsive loading
  - Quasi-static, long-term, residual pressure
  - Fatigue crack-growth

Gemini Vessel Analysis

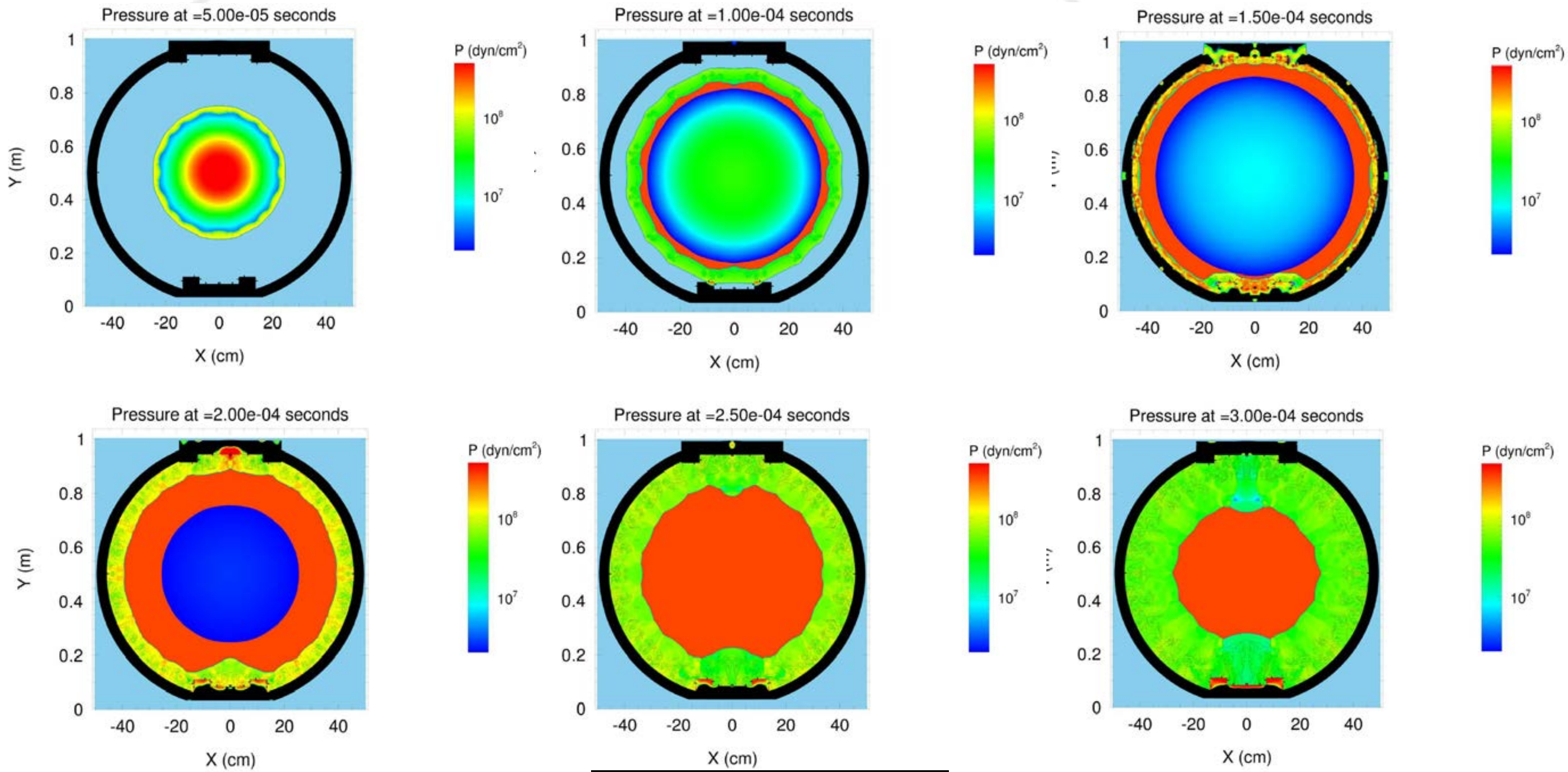
- Loading Function
- Hydrodynamic Analysis
  - Performed with CTH code (SNL)
  - Dual axisymmetric models





Gemini Vessel Analysis

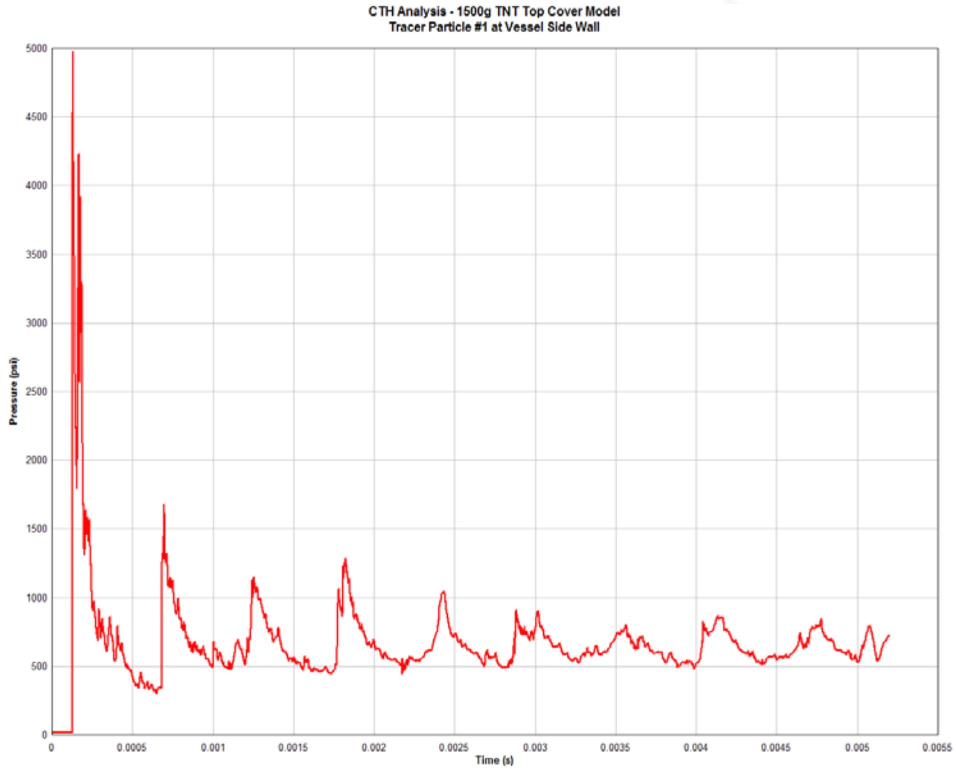
- CTH Blast Pressure



Pressure in dyn/cm^2

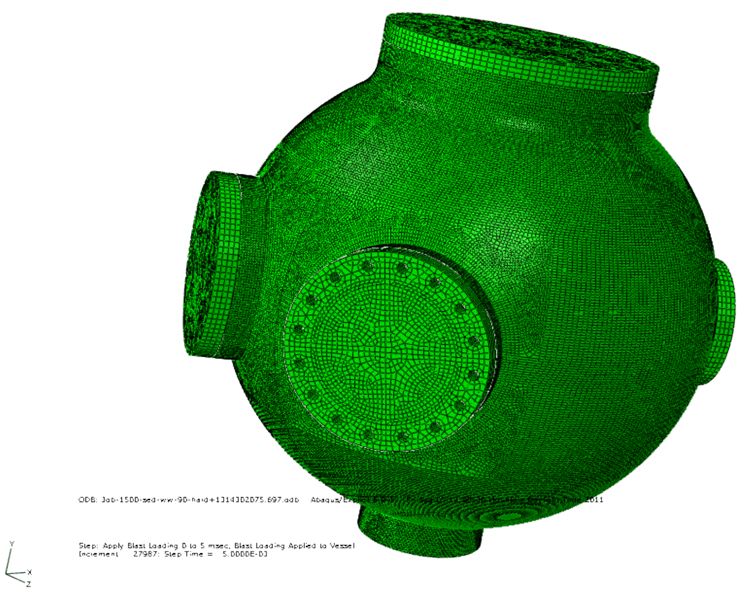
Gemini Vessel Analysis

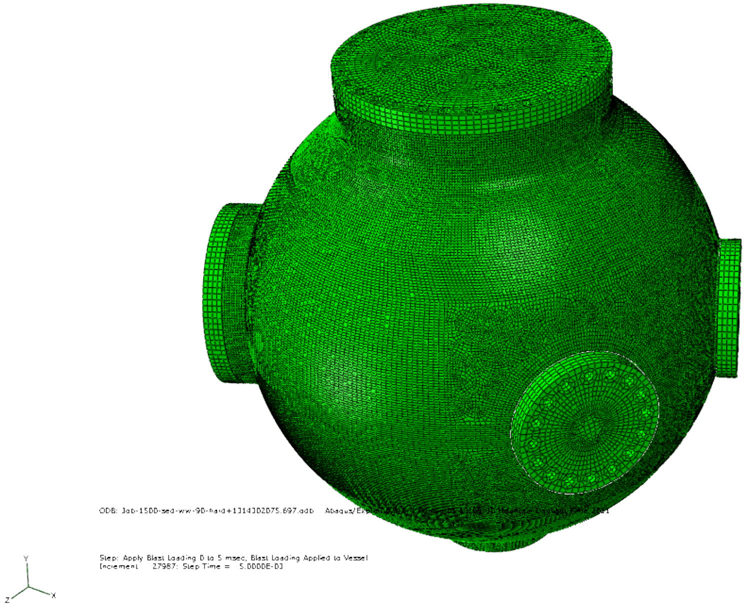
- Hydrodynamic Analysis
  - CTH model using a bare, spherical, HE charge.
  - 1500 g TNT
  - Center detonation
  - JWL EOS for TNT
  - System is air-filled
    - 1-atm
  - P_{gas} = 615 psi



Gemini Vessel Analysis

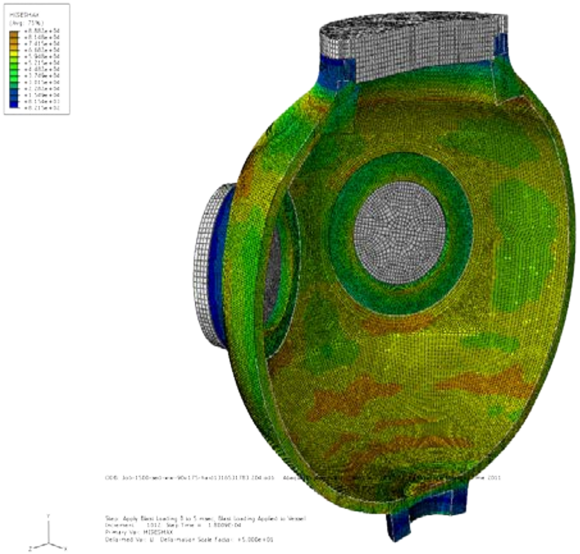
- Structural Response Analysis
  - Vessel Weldment
    - High-fidelity, full 360°, 3D model
    - ABAQUS/Explicit solution scheme
    - Bolts are explicitly modeled



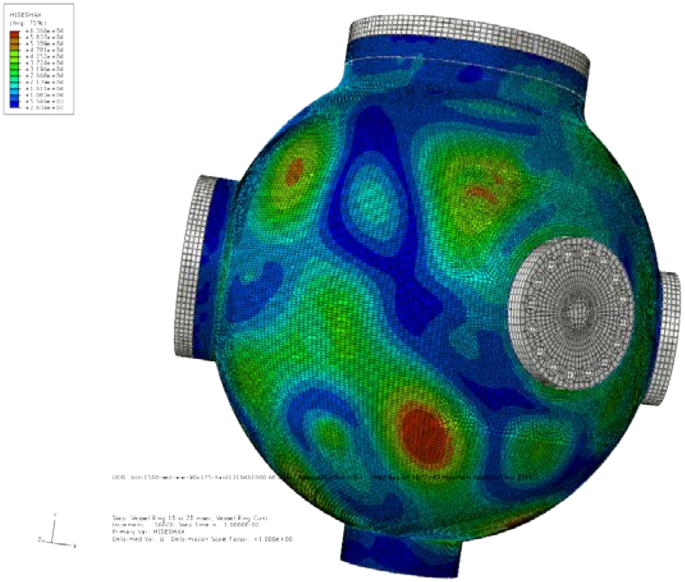


Gemini Vessel Analysis

- Vessel Weldment
  - Structural response is subdivided into 2-regimes:
    - Early-time (i.e., breathing-mode response)
    - Late-time (i.e., higher-order bending modes)



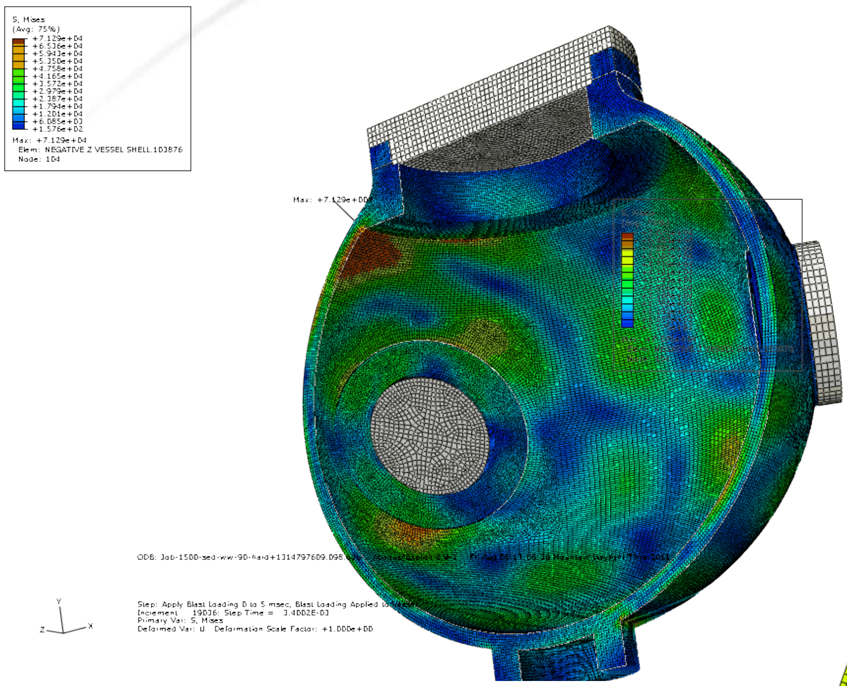
Early-Time

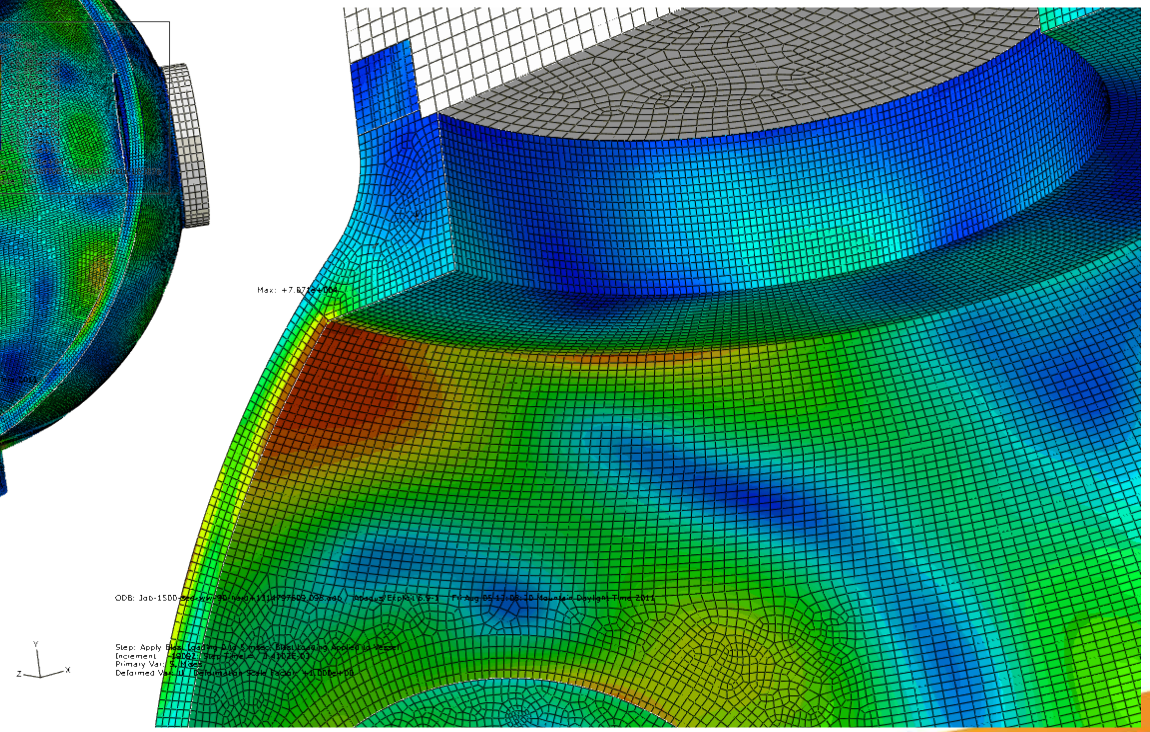


Late-Time

Gemini Vessel Analysis

- Vessel Weldment

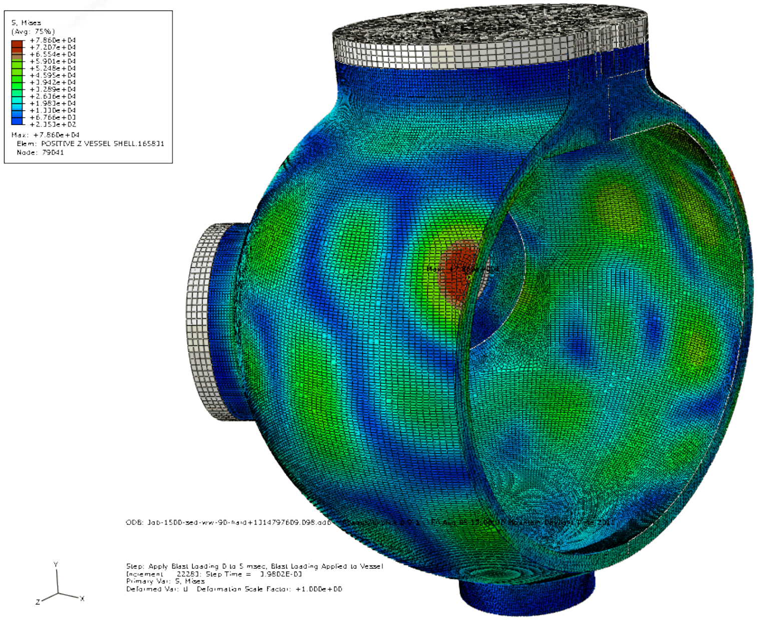


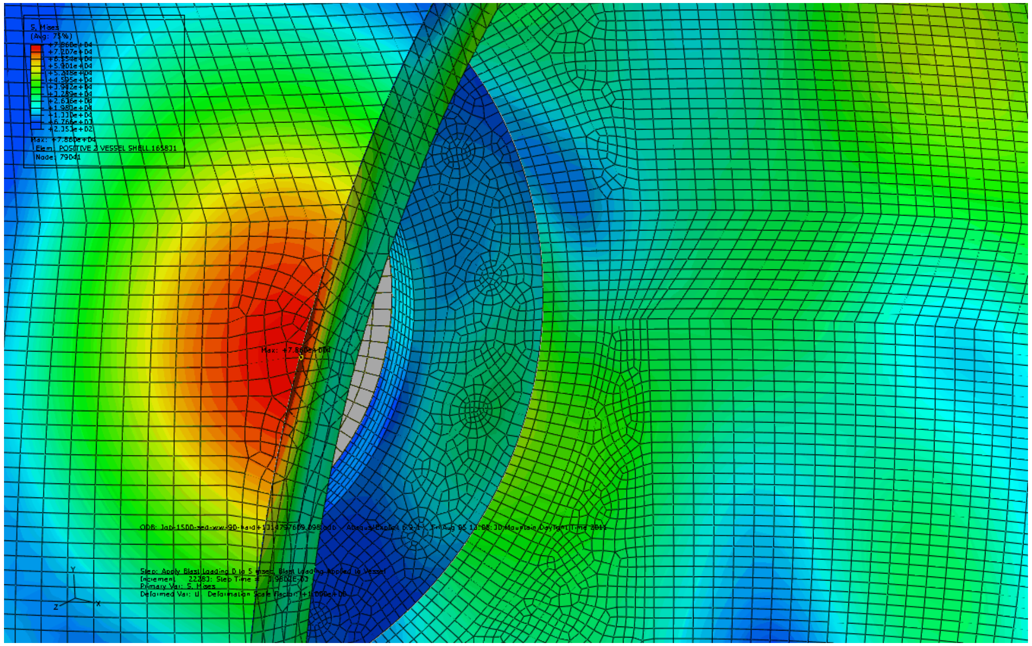


Late-Time response
t = 3.4 ms

Gemini Vessel Analysis

- Vessel Weldment



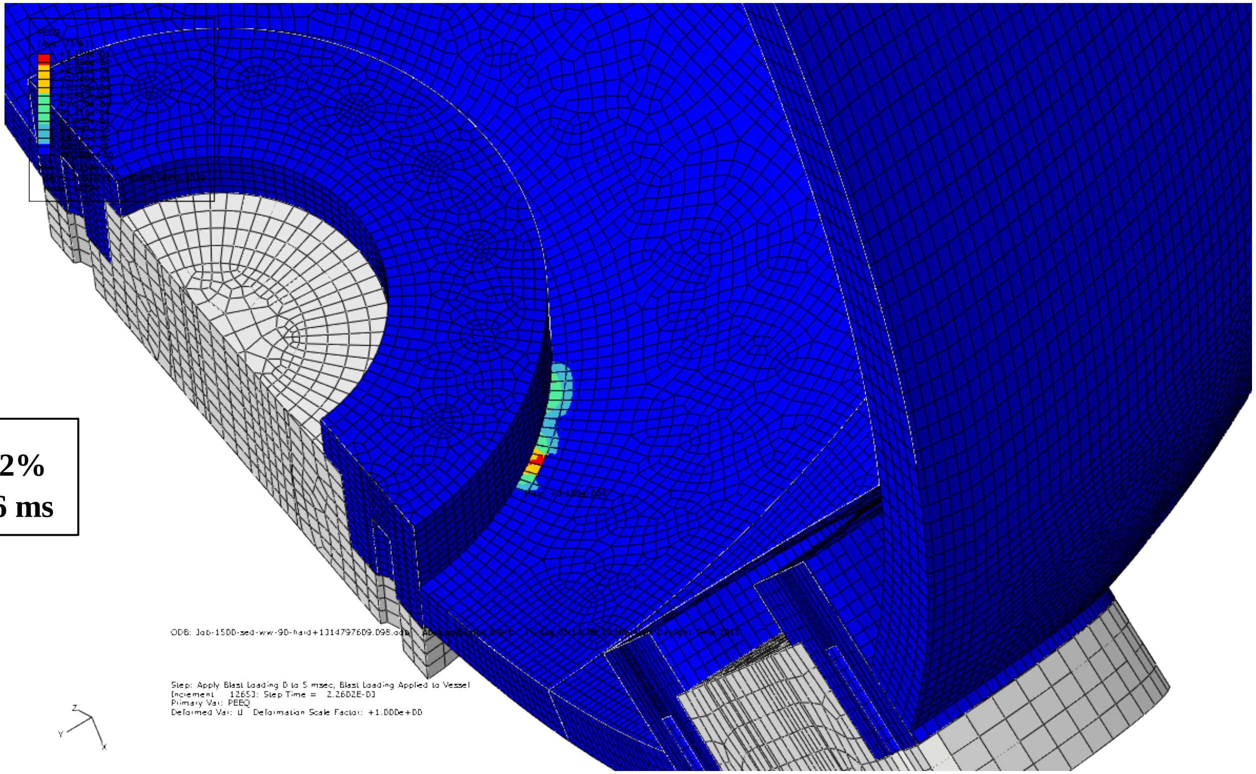


Late-Time response
t = 3.98 ms

Gemini Vessel Analysis

- Vessel Weldment
  - Maximum equivalent plastic strain @ weld

ε_p = 0.032%
@ t = 2.26 ms



Gemini Vessel Analysis

- Vessel Weldment
  - Shell is responding in a gross linear-elastic fashion
  - Few locations with vibration cycles above yield surface
  - Vessel meets ASME Code & CC-2564 rules

Failure Criteria	Accumulated Equivalent Plastic Strain (%)				
	Allowable Plastic Strain	Shell	Nozzle	Allowable Plastic Strain	Weld
Membrane	0.2	0.0	0.0	0.2	0.0
Linearized	2.0	0.0	0.0	1.0	0.0
Peak	5.0	0.0	0.0	2.5	0.032

"Linearized" – Implies through-thickness bending distribution.

Summary

- Provided a brief presentation on the genesis of Code Case 2564
  - Identified successful applications of Code Case design guidance
- Outlined important features from ASME Section VIII, Div. 3
- Presented Code Case 2564 methodology identifying required ductile failure and fatigue crack-growth analyses
- Brief overview of the Gemini series design analysis