

Equivalent Safety Study Highlights 1992 vs 2015 American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME BPVC)

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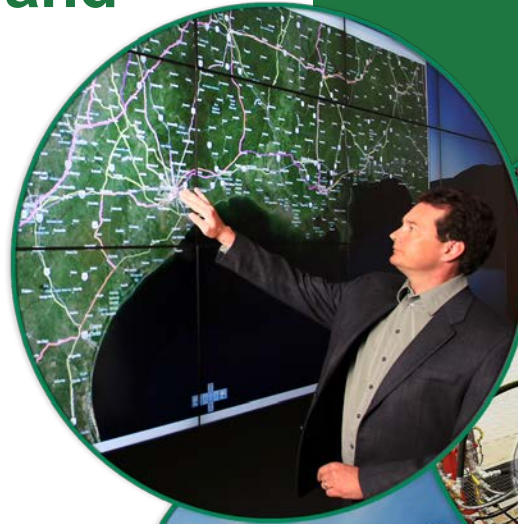
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Background on Equivalent Safety Study

- 49 CFR 193 prescribes DOT PHMSA Federal safety standards for Liquefied Natural Gas (LNG) facilities
- Rules in NFPA 59A-2001 further state boilers and pressure vessels must be Code stamped
- This presentation provides preliminary highlights from the ongoing study and includes comparison of rules governing materials, design, fabrication, inspection, pressure testing, and overpressure protection in 1992 and 2015 editions of Section I, Section VIII, Division 1, and Section VIII, Division 2 of the ASME BPVC

49 CFR 193—LNG Facilities: Federal Safety Standards

- 49 CFR 193 Incorporated by Reference (IBR) **NFPA – 59A – 2001 and 2006 editions**

- ✓ NFPA 59A-2001, Paragraph 1.2 – Equivalency
- ✓ NFPA 59A-2006, Paragraph 1.3 – Equivalency

*“Nothing in this standard is intended to prevent the use of systems, methods, or devices of **equivalent or superior** quality, strength, fire resistance, effectiveness, durability, and **safety** over those prescribed by this standard.”*

- ✓ NFPA 59A-2001, Chapter 12 – Referenced Publications
- ✓ NFPA 59A-2006, Paragraph 6.4.2 – ASME Publications.

*“Boilers shall be designed and fabricated in accordance with the ASME Boiler and Pressure Vessel Code . . . and shall be **Code stamped.**”*

- ✓ NFPA 59A-2001 IBR **ASME BPVC – 1992 edition**
- ✓ NFPA 59A-2006, IBR **ASME BPVC – 2004 edition**

- IBR codes and standards have the full force of law.

Equivalent Safety Study

- PHMSA requested assistance from ORNL to evaluate **equivalent safety** between 1992 and 2015 editions of ASME BPVC
 - ✓ Section I – Boilers
 - ✓ Section VIII, Division 1 – Pressure Vessels
 - ✓ Section VIII, Division 2 – Alternative Rules
- Equivalent safety evaluation report:
 - ✓ Title: ASME Boiler and Pressure Vessel Code Evaluation and Equivalence Study for Liquefied Natural Gas Facilities
 - ✓ Draft submittal date: December 31, 2016
- Key subjects areas:
 - Materials**
 - Design**
 - Fabrication**
 - Inspection**
 - Pressure Testing**
 - Overpressure Protection**

Materials

- Materials for boiler and pressure vessel construction are provided in Section II of ASME BPVC
 - ✓ Part A – Ferrous Material Specifications
 - ✓ Part B – Nonferrous Material Specifications
 - ✓ Part C – Specifications for Welding Rods, Electrodes, and Filler Metals
 - ✓ Part D – Properties
- Material specification changes:
 - ✓ Part A – 7 materials removed, 42 materials added
 - ✓ Part B – 1 material removed, 15 materials added
 - ✓ Part C – 1 material removed, 5 materials added
- Allowable design stress changes – Part D:
 - ✓ Allowable design stresses for Section I and Section VIII, Division 1
1992 - lesser of $S_T/4$ or $2/3 S_y$ – 2015 - lesser of $S_T/3.5$ or $2/3 S_y$
 - ✓ Allowable design stresses for Section VIII, Division 2
1992 - lesser of $S_T/3$ or $2/3 S_y$ – 2015 - lesser of $S_T/2.4$ or $2/3 S_y$

Fabrication and Inspection

- Forming and tolerance rules are unchanged.
- 2015 edition permits
 - ✓ Cold stretching (Section VIII, Division 1 only)
 - ✓ Diffusion Welding (DFW)
 - ✓ Friction Stir Welding (FSW)
- Weld examination rules are more stringent in the 2015 edition.
 - ✓ ultrasonic examination (UT) permitted
 - ✓ digital radiography (DR) permitted
- Additional NDE personnel qualifications are required for:
 - ✓ computed radiography (CR)
 - ✓ digital radiography (DR)
 - ✓ Phased Array Ultrasonic Technology (PAUT)
 - ✓ ultrasonic Time of Flight Diffraction (TOFD)
- Flaw acceptance criteria are unchanged

Design Basis

- The Foreword to 2015 edition of Section I of ASME BPVC states:
The objective of the rules is to afford reasonably certain protection of life and property, and to provide a margin for deterioration in service to give a reasonably long, safe period of usefulness.
- The various possible modes of failure which confront a boiler or pressure vessel designer are:
 1. Excessive elastic deformation including elastic instability
 2. Excessive plastic deformation (ductile rupture)
 3. Brittle fracture
 4. Stress rupture / creep deformation (inelastic)
 5. Plastic instability – incremental collapse
 6. High strain – low-cycle fatigue
 7. Stress corrosion
 8. Corrosion fatigue

1. Excessive Elastic Deformation Including Elastic Instability

- Section I and Section VIII, Division 1 - Use **charts and tables for determining shell thickness of components under external pressure** provided in Subpart 3 in 1992 and 2015 editions of Section II, Part D, of ASME BPVC.
- Section VIII, Division 2 – **1992** - Uses **charts and tables for determining shell thickness of components under external pressure** provided in Subpart 3 in 1992 edition of Section II, Part D, of ASME BPVC.
- Section VIII, Division 2 – **2015** - Provides **rules for three alternative types of buckling analysis** to evaluate structural stability from compressive stress fields.

2. Excessive Plastic Deformation – Ductile Rupture

- Rules in 1992 and 2015 editions of ASME BPVC provide a **minimum design margin against plastic collapse equal to or greater than 1.5**.
 - ✓ Section I
 - ✓ Section VIII, Division 1
 - ✓ Section VIII, Division 2
- The minimum design margin against plastic collapse is based on principles of **limit design theory** which is used to establish:
 - ✓ Plastic Collapse Stress Limits
 - ✓ Design Stress Limits
- The basis for these stress limits is discussed later in this presentation.

3. Brittle Fracture

- Section I - Boilers operate at elevated temperatures where brittle fracture is very unlikely mode of failure. Therefore, **no fracture toughness requirements** are specified in either 1992 or 2015 edition of Section I of ASME BPVC.
- Section VIII, Division 1 - Material toughness requirements in 2015 edition are **more stringent and comprehensive** than corresponding material toughness requirements in 1992 edition.
- Section VIII, Division 2 - Material toughness requirements in 2015 edition are **significantly more stringent and comprehensive** than corresponding material toughness requirements in 1992 edition.
- The required stress intensity factor, K_I , increases with an increase in the maximum allowable design stress from $S_T/4$ to $S_T/3.5$ and increases even further from $S_T/3$ to $S_T/2.4$ (Welding Research Council (WRC) Bulletin 435).

3. Brittle Fracture (cont'd)

- According to Linear Elastic Fracture Mechanics (LEFM) theory, allowable stress in the presence of a given crack size is directly proportional to the fracture toughness.
- Critical flaw size, a_c , times allowable stress, σ , squared is proportional to toughness, K_{Ic} , squared.

$$\sigma^2 \pi a_c \propto K_{Ic}^2$$

- Flaw size acceptance criteria remain unchanged from 1992 to 2015.
- **To maintain an equivalent or greater level of safety against brittle fracture resulting from increase in allowable stresses, fracture toughness rules in 2015 edition of Section VIII, Division 2 were significantly changed from corresponding rules in 1992 edition of Section VIII, Division 2.**

4. Stress Rupture and Creep Deformation

- Stress rupture and creep are high-temperature phenomena.
- Allowable stresses specified in 1992 and 2015 editions of Section II, Part D of ASME BPVC at temperatures in the range where creep and stress rupture strength govern are the **same** in:
 - ✓ Section I
 - ✓ Section VIII, Division 1
 - ✓ Section VIII, Division 2

5. Plastic Instability – Incremental Collapse

- Section I - Boilers are generally not subjected to cyclic loading. Therefore, **no plastic instability and incremental collapse requirements associated with ratcheting** are specified in either the 1992 or 2015 edition of Section I of ASME BPVC.
- Section VIII, Division 1 - **No plastic instability and incremental collapse requirements associated with ratcheting** are specified in either 1992 or 2015 edition of Section VIII, Division 1 of ASME BPVC.
- Section VIII, Division 2 - The **elastic analysis method** provided in 2015 edition of Section VIII, Division 2 of ASME BPVC to evaluate ratcheting in accordance with rules specified in Part 5, paragraph 5.5.6 is **same** as method provided in 1992 edition of Section VIII, Division 2 of ASME BPVC.
- Section VIII, Division 2, **2015 edition - Includes elastic-plastic stress analysis criteria not included in 1992 edition.**

6. Fatigue

- Section I - Boilers are generally not subjected to cyclic loading. Therefore, **no fatigue requirements** are specified in either 1992 or 2015 edition of Section I of ASME BPVC.
- Section VIII, Division 1 - **No plastic instability and incremental collapse requirements** are specified in either 1992 or 2015 edition of Section VIII, Division 1 of ASME BPVC.
- Section VIII, Division 2, 1992 edition - **Prevents fatigue failure by limiting peak stresses.**
- Section VIII, Division 2, 2015 edition - **Includes rules for three types of fatigue assessments.**

7 and 8. Stress Corrosion and Corrosion Fatigue

- Section I - **Does not include rules** in either 1992 or 2015 editions **that specifically govern corrosion allowances.**
- Section VIII, Division 1 - Rules in 1992 and 2015 edition state that the **user or his/her designated agent must specify corrosion allowances** other than those required by rules of this Division.
- Section VIII, Division 2 - Rules in 1992 and 2015 edition state that vessels or parts thereof subject to loss of metal by corrosion, erosion, mechanical abrasion, or other environmental effects **must have provisions made** for such of the same thickness for all parts of the vessel.

Strength Theory

- Design-by-Rule equations specified in 1992 and 2015 editions of Section I and Section VIII, Division 1 of ASME BPVC for determining wall thickness are, by implication, consistent with the **maximum stress theory**.
- Design-by-Rule and Design-by-Analysis requirements specified in 1992 edition and Design-by-Rule requirements specified in Part 4 in 2015 edition of Section VIII, Division 2 are based on the **maximum shear stress theory** – also known as the **Tresca yield criterion**.
- Design-by-Analysis requirements specified in Part 5 in 2015 edition of Section VIII, Division 2 are based on the **distortion energy theory** using the **von Mises yield criterion**.

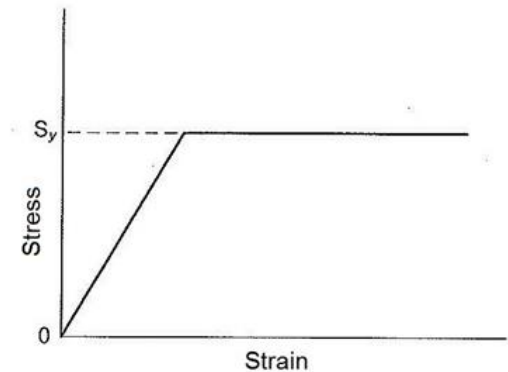
Plastic Collapse Stress Limits

- Section I - Adequate safety against plastic collapse based on rules specified in 1992 and 2015 editions is achieved by limiting design membrane stress, P_m , to two-thirds of the yield strength to be consistent with the maximum stress theory. Based on the **principles of limit design theory**, the minimum design margin against plastic collapse is at least 1.5.
- Section VIII, Division 1 - Adequate safety against plastic collapse based on rules specified in 1992 and 2015 editions is achieved by limiting design membrane stress, P_m , to two-thirds of the yield strength and primary bending stresses, P_b , to the yield strength to be consistent with the maximum stress theory. Based on the **principles of limit design theory**, the minimum design margin against plastic collapse is at least 1.5.
- Section VIII, Division 2 - The limits on local membrane stress intensity and primary membrane plus primary bending stress intensity of $1.5S_m$ have been placed at a level in 1992 and 2015 editions which conservatively assures prevention of collapse as determined by **principles of limit analysis** and a minimum design margin against plastic collapse equal to or greater than 1.5.

Principles of Limit Design Theory

- Assumptions:

- ✓ Materials are assumed to exhibit an elastic perfectly plastic stress-strain relationship with no strain hardening.
- ✓ The actual strain-hardening properties of specific materials will give them an increase margin above this floor.



- ✓ **Allowable stresses based on perfect plasticity and limit design theory are considered by ASME to be a floor below which a boiler or pressure vessel constructed from any sufficiently ductile material will be safe.**

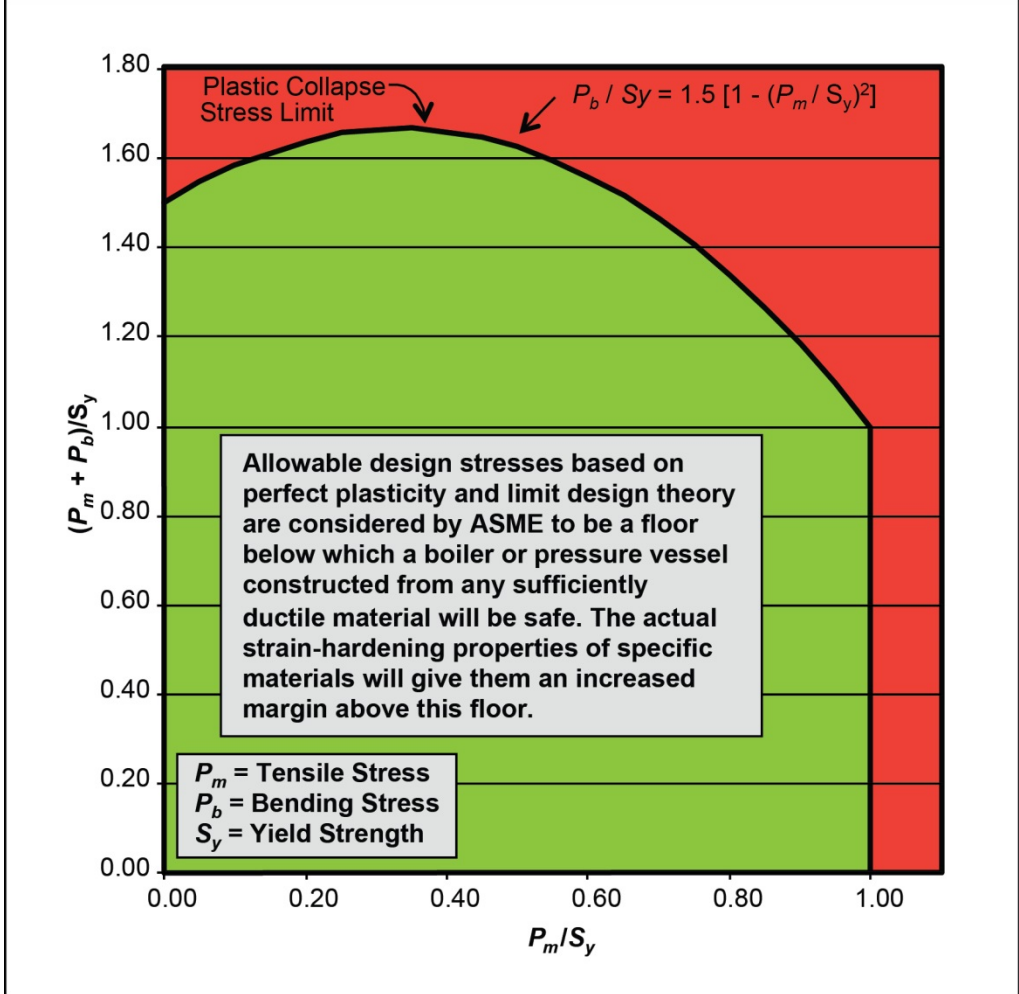
- Collapse occurs whenever:

- ✓ the membrane stress, P_m , equals the yield strength, S_y . When expressed as an equation, collapse occurs when **$P_m = S_y$** .
- ✓ a bending stress, P_b , equals the yield strength, S_y , times a shape factor equal to 1.5. When expressed as an equation, collapse occurs when **$P_b = 1.5S_y$** .

Plastic Collapse Stress Limit

- The plastic collapse stress limit is defined by the following equation.

$$P_b / S_y = 1.5 [1 - (P_m / S_y)^2] \quad \text{for } 0 \leq P_m / S_y \leq 1.0$$



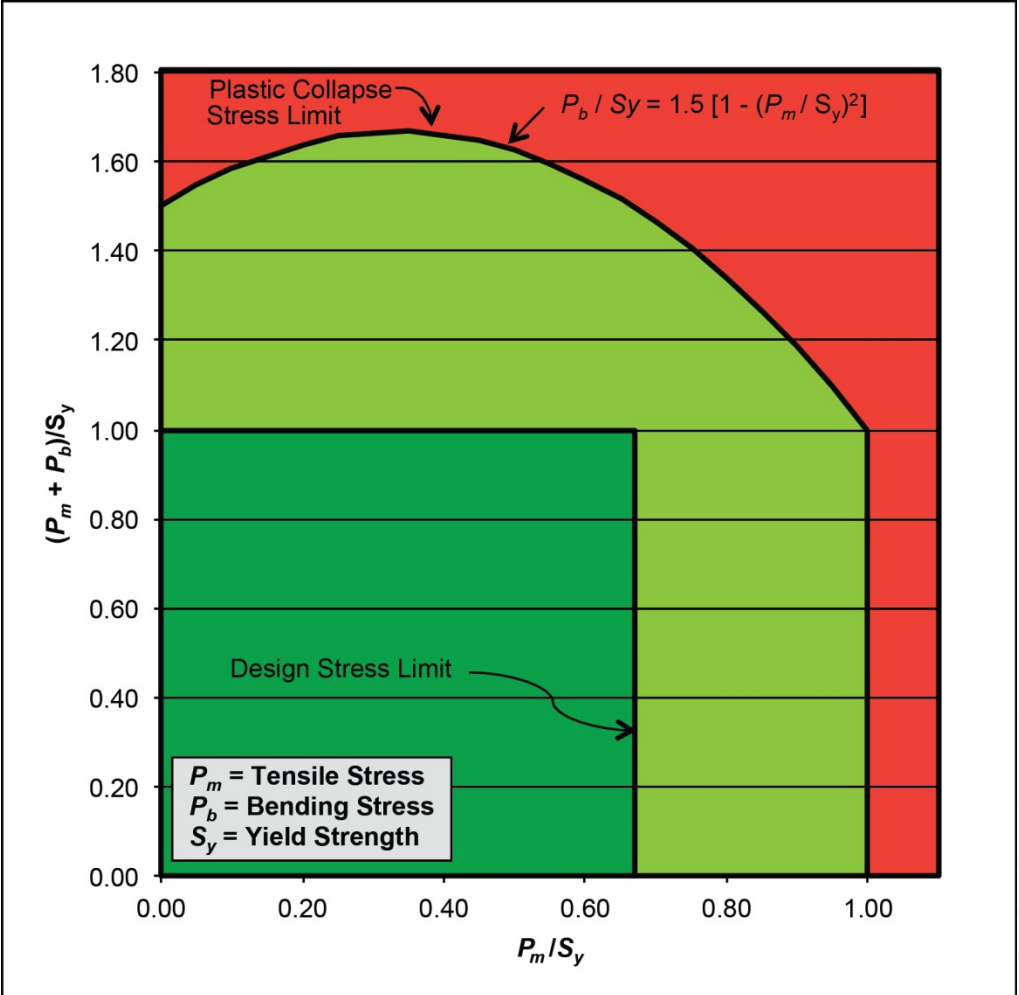
Plastic collapse stress limits:

$$P_m \leq 1.0 S_y$$

$$P_m + P_b \leq 1.5 S_y$$

Design Stress Limit

- Adequate safety against plastic collapse is achieved by limiting design stresses to 2/3 of the plastic collapse stress limits.

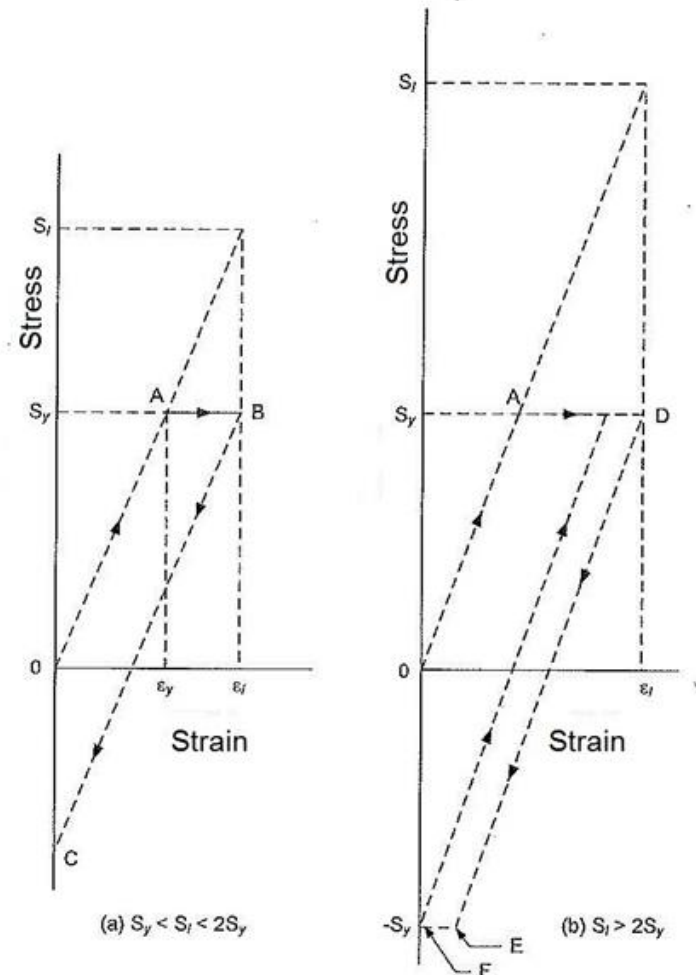


Design stress limits:

$$P_m \leq 0.67 S_y$$
$$P_m + P_b \leq 1.0 S_y$$

Stress Range for Repetitively Applied Loads

- Section I does not provide rules for fatigue. Therefore, **Section I does not include rules for the 'shakedown' phenomenon** represented by Fig. (a).
- Section VIII, Division 1 and Division 2 limit localized discontinuity stresses to 3.0 times the maximum allowable stress value in tension or 2.0 times the minimum specified tensile yield stress, S_y , of the material (i.e., **$2 S_y$**) to avoid the ratcheting phenomenon represented by Fig. (b).



Hydrostatic and Pneumatic Pressure Test Objectives

- A pressure test is performed after fabrication is completed primarily to verify the leak tight integrity of the pressure vessel, but also to identify gross deformations or anomalies that may indicate design errors, material deficiencies, or weld defects.
- Pressure test limits are established to maintain primary membrane and bending stresses within the elastic range so the pressure vessel does not permanently deform.
- **Pressure tests are not intended to verify the pressure-resisting (burst) capacity of a pressure vessel.**

Hydrostatic Pressure Test Limits

- Section I
 - 1992 – minimum hydrostatic test pressure – 1.5 MAWP to 1.59 MAWP
 - 1992 – maximum general membrane stress limit – $P_m \leq 0.90 S_y$
 - 2015 – minimum hydrostatic test pressure – 1.5 MAWP
 - 2015 – maximum general membrane stress limit – $P_m \leq 0.90 S_y$
- Section VIII, Division 1
 - 1992 – minimum hydrostatic test pressure – 1.5 MAWP
 - 1992 – If the pressure vessel is subjected to visible permanent distortion, the Inspector shall reserve the right to reject the vessel.
 - 2015 – minimum hydrostatic test pressure – 1.3 MAWP
 - 2015 – If the pressure vessel is subjected to visible permanent distortion, the Inspector shall reserve the right to reject the vessel.
- Section VIII, Division 2
 - 1992 – minimum hydrostatic test pressure – 1.25 MAWP
 - 1992 – maximum general membrane stress limit – $P_m \leq 0.90 S_y$
 - 2015 – minimum hydrostatic test pressure – 1.43 MAWP or 1.25 MAWP (S_T/S)
 - 2015 – maximum general membrane stress limit – $P_m \leq 0.95 S_y$

Pneumatic Pressure Test Limits

- Section I - The 1992 and 2015 editions do not include pneumatic pressure testing requirements
- Section VIII, Division 1
 - 1992 – minimum pneumatic test pressure – 1.25 MAWP
 - 1992 – maximum general membrane stress limit not specified
 - 2015 – minimum pneumatic test pressure – 1.1 MAWP
 - 2015 – maximum general membrane stress limit not specified
- Section VIII, Division 2
 - 1992 – minimum pneumatic test pressure – 1.15 MAWP
 - 1992 – maximum general membrane stress limit – $P_m \leq 0.80 S_y$
 - 2015 – minimum pneumatic test pressure – 1.15 MAWP (S_T/S)
 - 2015 – maximum general membrane stress limit – $P_m \leq 0.80 S_y$

Overpressure Protection by Pressure Relief Device

- Section I - 1992 and 2015 editions
 - ✓ Overpressure protection rules limit the pressure to **1.20 MAWP** or less.
 - ✓ This ensures the primary membrane stress, P_m , does not exceed **0.80 S_y** (i.e., $1.20/1.50 S_y$).
- Section VIII, Division 1 and Division 2 - 1992 and 2015 editions
 - ✓ Overpressure protection rules state that when a pressure vessel can be exposed to fire or other unexpected sources of external heat, the pressure relief device(s) must be capable of preventing the pressure from rising more than 21% above the MAWP. (i.e., **1.21 MAWP**).
 - ✓ This overpressure protection limit ensures that the primary membrane stress, P_m , does not exceed **0.81 S_y** (i.e., $1.21/1.50 S_y$).
- Note: Pressure vessels that comply with Section VIII, Division 2 could experience overpressure beyond the maximum permitted pneumatic test pressure when controlled by $P_m \leq 0.80 S_y$.

Overpressure Protection by System Design

- Overpressure protection by system design does not rely on pressure relief devices for overpressure protection.
- Overpressure protection by system design is not permitted in:
 - ✓ Section I – 1992 and 2015 editions
 - ✓ Section VIII, Division 1 – 1992 edition
 - ✓ Section VIII, Division 2 – 1992 and 2015 editions
- The 2015 edition of Section VIII, Division 1 provides rules for overpressure protection by system design.
 - ✓ For pressure vessels in which the pressure is not self-limiting there must be no credible overpressure scenario in which the pressure exceeds 116% of MAWP times the ratio of the allowable stress value at the temperature of the overpressure scenario to the allowable stress value at the design temperature. (i.e., **1.16 MAWP**)
 - ✓ This overpressure protection limit ensures that the primary membrane stress, P_m , does not exceed **0.77 S_y** (i.e., $1.16/1.50 S_y$).
 - ✓ **The overpressure limit shall not exceed the test pressure.**

Requirements Summary – Section I and Section VIII, Division 1

- Rules specified in 1992 and 2015 editions of Section I and Section VIII, Division 1 of ASME BPVC:
 - ✓ provide for Design-by-Rule – based on the maximum stress theory
 - ✓ provide equations for minimum allowable wall thickness
 - ✓ do not require calculation of thermal stresses and do not provide allowable values for them
 - ✓ do not require detailed calculation and classification of all stresses and application of different stress limits to different classes of stress
 - ✓ do not provide rules for fatigue
 - ✓ do not provide for Design-by-Analysis

Requirements Summary – Section VIII, Division 2

- Rules specified in 1992 edition of Section VIII, Division 2 of ASME BPVC provide for:
 - ✓ Design-by-Rule – based on the maximum shear stress theory which is also known as the Tresca yield criterion
 - ✓ Design-by-Analysis – based on the maximum shear stress theory which is also known as the Tresca yield criterion
- Rules specified in 2015 edition of Section VIII, Division 2 of ASME BPVC provide for:
 - ✓ Design-by-Rule – based on the maximum shear stress theory which is also known as the Tresca yield criterion
 - ✓ Design-by-Analysis – based on the distortion energy theory using the von Mises yield criterion
- Rules specified in 1992 and 2015 editions of Section VIII, Division 2 of ASME BPVC require detailed calculation and classification of all stresses and application of different stress limits to different classes of stress.

Requirements Summary – Section VIII, Division 2 (cont'd)

- Rules specified in 1992 edition of Section VIII, Division 2 of ASME BPVC prevent fatigue failure by limiting peak stresses.
 - ✓ Cyclic loading design procedures that apply when principal stress direction does not change are specified in paragraph 5-110.3(a).
 - ✓ Cyclic loading design procedures that apply when principal stress direction change are specified in paragraph 5-110.3(b).
- Rules for performing a fatigue evaluation are specified in the following paragraphs in 2015 edition of Section VIII, Division 2 of ASME BPVC.
 - ✓ Paragraph 5.5.3 – Fatigue Assessment – Elastic Stress Analysis and Equivalent Stresses
 - ✓ Paragraph 5.5.4 – Fatigue Assessment – Elastic Plastic Stress Analysis and Equivalent Strains
 - ✓ Paragraph 5.5.5 – Fatigue Assessment of Welds – Elastic Analysis and Structural Stress

QUESTIONS?

