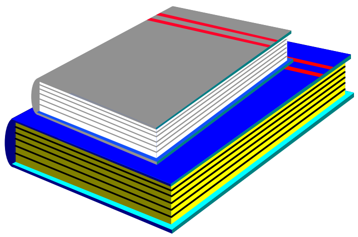
Engineering Safety Notes
and
Operational Safety Procedures
for
Pressure Vessels and Systems



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Engineering Safety Note

"A management-approved design document attesting every practicable precaution has been taken in the design of equipment to control all significant hazards"

---certifies mechanical integrity---

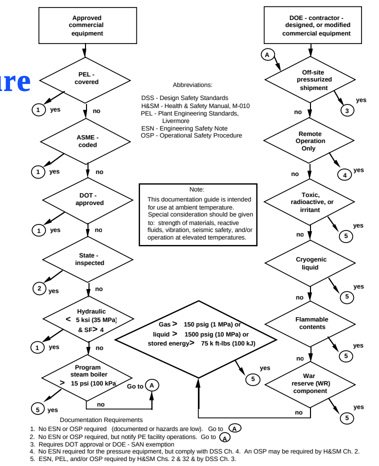
Operational Safety Procedure

An OSP assigns responsibility for safe operations, describes the work to be done, identifies the hazards and environmental concerns, and should describe maintenance and quality assurance of safety-related systems and equipment.

HS-5060-5

LLNL Documentation Guide for Pressure Equipment

LLNL Example



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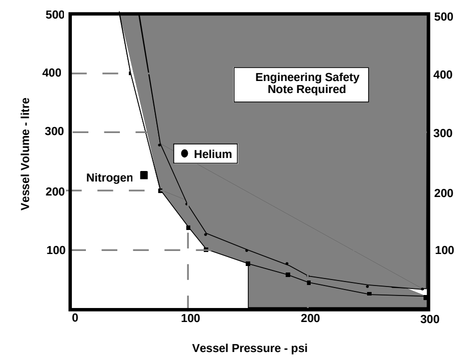
Engineering Safety Note Requirements for a Vessel or System Containing 100 Kjoules of Stored Energy



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An Engineering Safety Note is required for all manned-area pressure vessels and systems that:

- **Operate above 150 psig gas or 1,500 psig liquid**

~or~

- **Contain over 100 kilojoules of stored energy**

Contents of an Engineering Safety Note

A. Description
B. Hazards
C. Calculations
D. Pressure Testing
E. Labeling
F. Associated Procedures
G. References
H. Signature Authority
I. Distribution

A. Description

What is it?

What is its physical size?

What will it be used for?

What is its pressure rating?**

Is it is a manned or remote area?

Is it an ASME coded vessel?

Is it a D.O.T. coded vessel?

Are there drawing numbers or sketches you can reference?

****M.A.W.P.** Relief device setting.
M.O.P. Operating pressure 10 to 20% below M.A.W.P

Description, continued

Where will it be located?

Building ________ Room __________

Responsible experimenter or user

From your description could you find this vessel or system 3 years from now?

B. Hazards

- **Manned area or remote operation?**
- **Any radioactives, toxics, corrosives, explosives?**
- **If toxics in hood – what about power failure?**
- **How do you eliminate or lessen the hazard?**
  - **Hoods**
  - **Barricades**
  - **Protective clothing**
  - **Special Operating procedures**

Hazards, continued

Define and evaluate the associated hazards, i.e.

- **Stored energy in a confined liquid?**

$$E = \frac{1}{2}\left(\frac{P_1^{2}V}{B}\right)$$

- **Stored energy in a confined gas?**

$$E = \frac{P_1 V_1}{K-1}\left[1-\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}\right]$$

C. Calculations

For commercial components:

- **All components rated at or above M.A.W.P., therefore, no calculations are required.**
- **Reference manufacturer's ratings, stores catalog ratings.**
- **List of materials or part numbers.**

Calculations, continued

<u>For vessels/structures</u>

Include calculations on:

- **Weld shear stress**
- **Tensile stress on bolts, plates**
- **End closures**
- **Hoop stress**
- **Thread shear**
- **Safety factor**
- **Remote operation only - calculations on the barricading or shielding used.**

D. Pressure Testing

All pressure testing requires a test procedure. Use this section to write the test procedure. Specify: test sequence, test pressure, test fluid, hold time, acceptable leak rate.

Retest

You may also want to include the retest procedure. It may be different than the original procedure. You may want to change the frequency of inspection or retest.

Pressure Testing, continued

Special Pressure Test Situations

- **Low yield strength material, i.e., <55% of ultimate strength . . . . check that 150% test won't yield vessel.**
- **Test remote vessels @ 125% MAWP.**
- **To test high temp vessel at room temperature:**

$$\text{Test Pressure} = 1.5 \times \text{MAWP} \times \frac{\text{room temperature } S_a}{\text{high temperature } S_a}$$

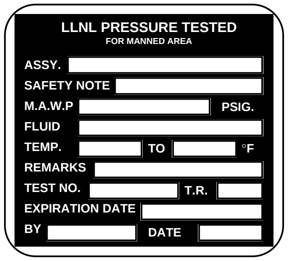
S_a = allowable stress

E. Labeling

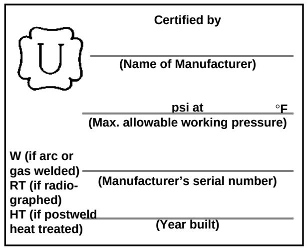
LLNL Example

The concept of labeling pressure vessels and systems is drawn from the ASME code stamping system.

Typical In-House Label



ASME Code Stamp



F. Associated Procedures

Building Procedure (FSP 231--)

Operating Procedure (OSP 231--)

Special Instructions (referenced)

G. References

Examples:

1. Marks Handbook, 7th Edition (Pg. 4-25)
2. Mechanics of Materials, Miller and Doeringfeld, Chapter 16
3. M.E. Safety Note ENS 78-954, L.L. Dibley
4. Health & Safety Manual Supplement 32.03, Pg. 13
5. Formulas For Stress and Strain, Roark, 3rd Ed.

Signature Authorization

Prepared by: ______________________
Responsible Designer

Reviewed by: ______________________
Pressure Consultant

Approved by: ______________________
Management

*Brittle materials or S.F. of less than 3

Recommended Distribution

Applicable management/supervision

Pressure Consultant

Industrial Safety Representative

Pressure Safety Representative

Responsible Designer

Central Library/Files

(Others concerned, including Building Coordinator)

There are two types of safety procedures:

- Facility Safety Procedure (FSP)
  - Basic ground rules for a facility
  - Reviewed every three years
- Operational Safety Procedure (OSP)
  - Specific
  - Limited in scope
  - For experimenters
  - Reviewed annually

An OSP is required for:

- Systems involving reactors, fission, criticality or radiation hazards.
- Systems involving high energy---electric, magnetic, or pressure.
- H.E. or radioactive material in a facility not approved for it.
- Activity involving carcinogens. (Reference LLNL Health & Safety Manual Chapter 2)

An OSP should include:

1. Reason for issue
2. Work to be done and location of the activity
3. Responsibilities
4. Hazard Analysis
5. Controls
6. Environmental concerns and controls
7. Training
8. Maintenance
9. Quality Assurance
10. Emergency Response Procedures
11. References
12. Review and approval

Before start of operations, the OSP is:

- Reviewed/signed by:
  - Person responsible
  - Safety Representative
- Read/Understood by:
  - All participants

Energy/Amagat

We will discuss

- Energy relationships and units.
- Real gas effects.
- Ideal gas and Real gas calculations using Amaget.
- When to apply Amagat number.

Compressed fluids store energy.... the more compressible the fluid, the more energy

Liquid: PdV mechanical work

$$E = \frac{P_1^2 V}{2B}$$

Gas: Isentropic expansion of a confined gas

$$E = \frac{P_1 V_1}{K-1}\left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{K-1}{K}}\right]$$

Where:

E = stored energy		K = ratio specific heats
P_1 = MAWP		V = volume
P_2 = atmospheric pressure		B = liquid bulk modules

Stored energy calculations require consistent units

$$E = C\left\{\frac{P_1 V_1}{K-1}\left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{K-1}{K}}\right]\right\}$$

E (Energy)	Joules	ft. lbs.	gms TNT	lbs. TNT
P (Pressure)	MPa	psia	psia	psia
V (Volume)	cc	in^3	cc	ft^3
C	1	8.33×10^{-2}	1.492×10^{-6}	9.22×10^{-5}

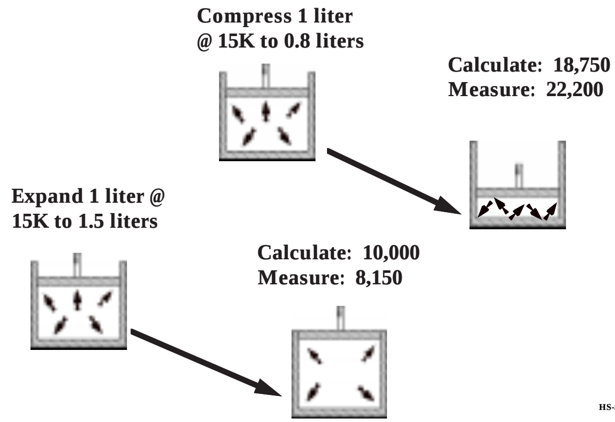
Real Gas Law

- Gases at higher pressures do not obey the Ideal Gas Law. . . PV = RT
- A correction Factor - <u>Compressibility</u> - must be used for real gases.
- A Real Gas Law would be ----- PV = ZRT

Where:

- Z = Compressibility and
  - is unique for every gas.
  - varies with temperature & pressure.
  - requires experimental measurements of P-V-T.

The REAL effect of a REAL gas is:



- Measured values of P-V-T may also be used to generate a more useful correlation factor . . .

Amagat Number

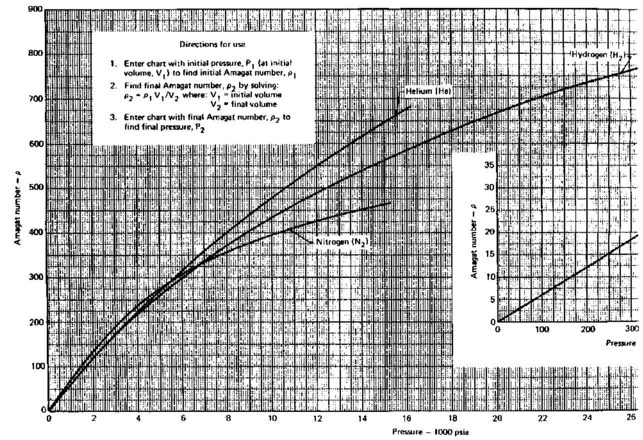
Amagat Number = $\dfrac{\text{Measured density}}{\text{Density per standard atmosphere}}$

$$\rho_a = \frac{\rho}{\rho_o}$$

- **Amagat Number still:**
  - — is unique for every gas
  - — varies with temperature and pressure

Amagat Number has some useful characteristics

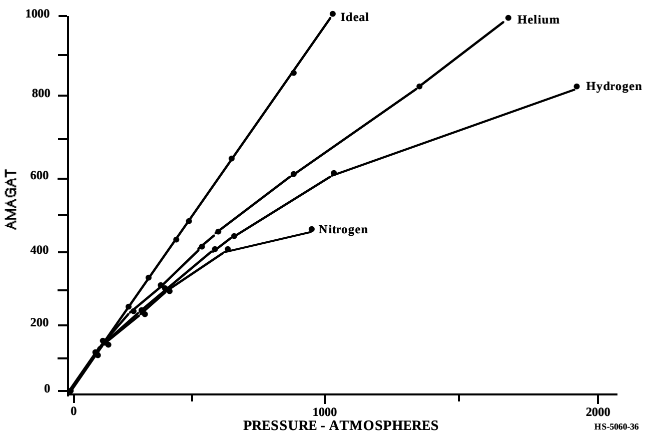
- Automatically corrects the ideal gas law for a real gas
- $PV=C_1$ relationship becomes $\rho_a V=C_2$
- Real gas calculations are greatly simplified
- Amagat data is available as:
  - — curves
  - — tables
  - — computerized data



Helium 4 Pressure vs. Amagat Number

AMAGAT	DENSITY G/CC	PRESSURE 0°C	25°C	50°C	PSI/DEG	PSI/AMAGAT
470	8.3895E-02	9014	9794	10,542	30.57	26.62
472	8.4252E-02	9063	9847	10,599	30.73	26.68
474	8.4609E-02	9112	9901	10,657	30.88	26.74
476	8.4966E-02	9162	9954	10,714	31.04	26.79
478	8.5323E-02	9211	10008	10,771	31.20	26.85

Amagat Number vs. Pressure



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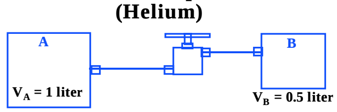
Gas transfer at high pressure

Constant temperature (Helium)



Initial	Ideal	Final
P_1 = 10,000 psia	T_1 = T_2 = 25°C	P_2 = ?
V_1 = V_A		V_2 = $V_A + V_B$
= 1L		= 1.5L

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}\left(T = C\right)$$

$$P_2 = \frac{P_1V_1}{V_2} = \frac{10{,}000x1}{1.5} = \underline{6667psia}$$

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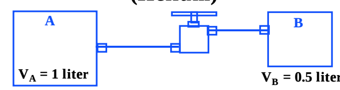
Gas transfer at high pressure

Constant temperature (Helium)



Initial	Actual	Final
P_1 = 10,000 psia	T_1 = T_2 = 25°C	P_2 = ?
V_1 = V_A		V_2 = $V_A + V_B$
= 1L		= 1+0.5 = 1.5L

$$\rho_1 V_1 = P_2 V_2 \left(T = C\right)$$

$$\rho_2 = \frac{\rho_1 V_1}{V_2} \to \rho_1 = 478$$

$$\rho_2 = \frac{478x1}{1.5} = 319 \to P_2 = \underline{6100\ psia}$$

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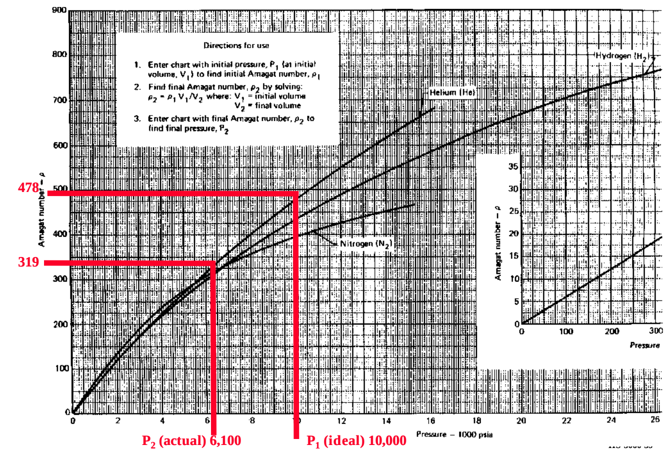


Ideal vs. real gas calculations: Helium

P_1	P_2 (ideal gas)	P_2 (real gas - Amagat)	% error
20,000	13,333	11,389	17.1
*10,000	6,667	6,100	9.3
5,000	3,333	3,174	5.0
3,000	2,000	1,939	3.1
1,500	1,000	980	2.0
500	333	331.6	0.4
200	133.3	133.15	0.1

** From example problem, pg HS-5060-23*

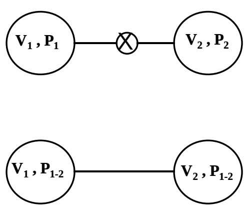
For equilibrium gas transfer problems:

- Think of gas quantities as PV products (in atm CCs)
- Initial gas quantity = final gas quantity
- Write a mass balance:

$$\rho_1 \mathbf{V}_1 + \rho_2 \mathbf{V}_2 = \rho_{1\text{-}2}\left(\mathbf{V}_1 + \mathbf{V}_2\right)$$

$$\rho_{1\text{-}2} = \frac{\rho_1 \mathbf{V}_1 + \rho_2 \mathbf{V}_2}{\mathbf{V}_1 + \mathbf{V}_2}$$

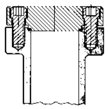
$$\text{For } \rho_2 = 0, \rho_{1\text{-}2} = \frac{\rho_1 \mathbf{V}_1}{\mathbf{V}_1 + \mathbf{V}_2}$$



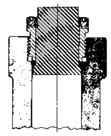
Summary Points

- Compressed liquids store significant energy
- Gases store much more energy than liquids
- Pressure-test with liquids whenever possible
- Gas calculations involve relationships between pressure, temperature, and volume
- Real gases do not obey the Ideal Gas Law above a few thousand psia
- Depending on the accuracy required:
  - — Use the Ideal Gas Law for pressures between 0 and 2000 psia, approximately
  - — Use Amagat data for higher pressures

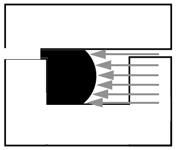
Pressure Vessel Closures



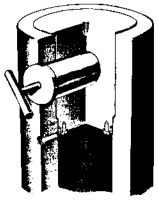
Flat end



Bridgeman



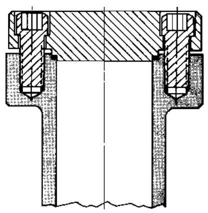
Axial O-ring



Other

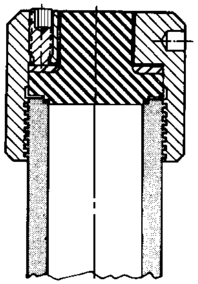
Bolted (Flat) Closure

- **High end loads can require heavy, massive parts.**
- **High bolt loadings can cause bending, part distortion, non-flat seal surfaces.**
- **O-ring or metal gaskets (metal for high temp).**
- **Usual applications < 5 ksi.**



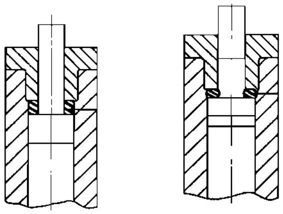
High Pressure Flat Closure

- **Relies on set screw loaded hold-down cap.**
- **Cover loads SST flat gasket against body.**
- **Clamping load carried by body OD threads and thrust washer/set screw system.**
- **Available to 30 ksi ranges.**



Bridgeman Unsupported Area Seal

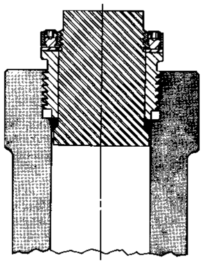
- **Internal pressure causes upward seal force across vessel ID.**
- **Unsupported stem subtracts from plug area resisting this force.**
- **Seal pressure thus greater than internal pressure as:**



$$P_{seal} = P_{initial}\left(\frac{D_1^2}{D_1^2 - D_2^2}\right)$$

Modified Bridgeman Seal

- Original Seal
  - —Requires careful design not to yield or overpressure seal area.
  - —Can be difficult to open after use.
  - —Requires relatively tight tolerances.
- Modification
  - —Uses a metal seal ring between body and cover.
  - —Sealing surfaces are at different angles to give line contact.



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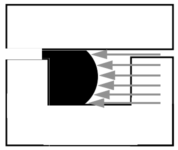
Axial O-ring Seals

- Major problem is o-ring extrusion through assembly clearance gaps.
- Extrusion effects can be minimized by:
  - —High hardness material, i.e., 90 durometer
  - —Use of anti-extrusion back-up rings
- Most commercial designs now use back-up rings successfully to near 100 ksi.
- With gas seals, permeation should also be considered.



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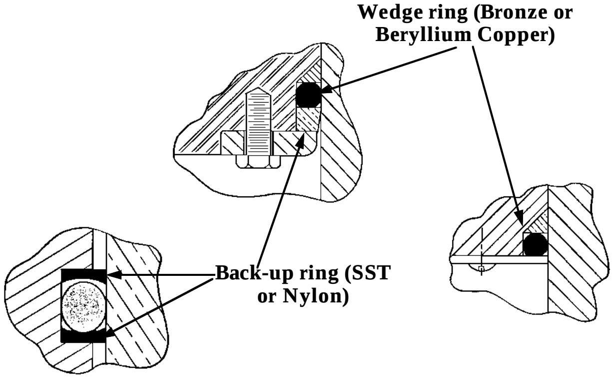
Some Typical High Pressure O-ring Designs



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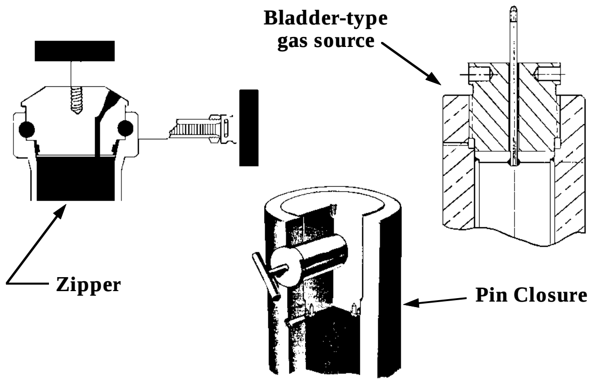
Some Other Types of Closures



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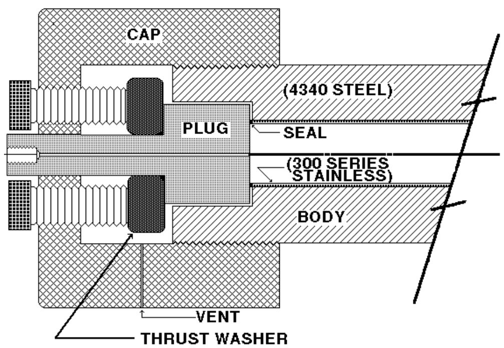
"Lined" Vessels are Sometimes Used to Store Hydrogen

- **Inner liner of hydrogen-compatible material - 304/316 SST, etc.**
- **High strength outer vessel wall of hydrogen non-compatible material - 4340, etc.**
- **Spiral phonograph grooving required between composite interface to insure no hydrogen buildup.**
- **Exit ports for grooving should be periodically tested for flow-through.**
- **Liner configurations include:**
  - **Fully welded inner can.**
  - **Inner sleeve only with compatible end plugs.**

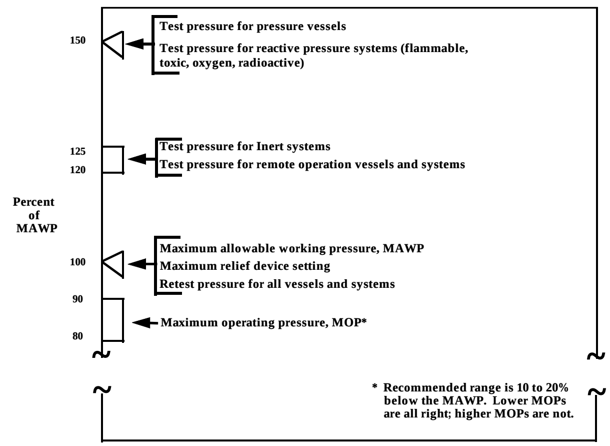
Hydrogen Storage Vessel



Pressure Vessel Design

We will discuss:

- **Basic design definitions.**
- **Vessel materials, fracture toughness.**
- **Welding, hydrogen embrittlement.**
- **Stress in thin and thick wall vessels.**
- **End closures.**
- **Yield criteria for pressure testing.**
- **SF-3 (super certified) vessels.**
- **"PC" solutions for design calculations.**



Design Definitions

- Safety Factor

Failure pressure/MAWP

Ultimate strength/stress @ MAWP = SF_u

Yield strength/stress @ MAWP = SF_y

SF_u = 4 : LLNL/ASME

= 3.75 : ASME-Section 8, Division II (SST)

= 3 : w/special documentation, testing material certification

< 3 : Management approval

Design definitions, continued

Vessel:

–Cross-sectional area > pipe or tube

–Concentrated isentropic energy source

System:

–Hardware, fittings, piping

–Low concentrated energy source

Manned Area :

More rigorous design safety and testing requirements to allow operation ***with people present***. Must establish mechanical integrity for primary vessel.

Remote Area :

Less rigorous design safety and testing requirements require operation ***without people present***. Must establish mechanical integrity for sheilding or barricade.

Material Selection

- Ductile/brittle/creep properties
- Heat treat effects
- Material identity
- Commercial considerations
- Hydrogen compatibility
- Fracture analysis

Exposure to hydrogen or hydrogen compounds requires considerations of HYDROGEN EMBRITTLEMENT

- Hydrogen
  - Dissolves in steel, forms an interstitial solution.
  - Solubility increases with temperature and pressure.
- Embrittlement
  - Is a general loss in ductility (sometimes dramatic).

    Embrittlement effects:

    increase with higher strength steels

    increase in yielded or highly stressed areas

    decrease with higher strain rates

    differs from normal failure :

    » slow crack growth

    » delayed failure

Chemistry, foundry practice and forming history all effect a material's resistance to hydrogen embrittlement.

- **Basic 18-8 stainless steel (Cr-Ni 304) in low chemistry (< .02 C,N) grades can be susceptable to embrittlement.**
  - —Initially of unstable austenite; after forming, transforms to alphaprime martensite.
  - —Is magnetic, will embrittle as maraging steel.
  - —No C,N minimums in basic chemistry; 8% nickel is ragged edge.
  - —Careful control of carbon, nitrogen and nickel content will stabilize the austenite structure, increase resistance to hydrogen.

To enhance austenitic stability in 316 SST, the tolerance of key elements in the alloy's chemistry can be reduced.

Element	Cr	Ni	C	N
Specification				
SA-240	16-18	10-14	.08 Max.	.10 Max.
QQ-S-783	16-18	10-14	.08 Max.	---
LLNL-1168	17-18	13-14	.04-.06	.04-.09

Controlled foundry practice allows more exact chemistry.

- **Vacuum processing**
  - VIM — Vacuum induction melting
  - VAR — Vacuum arc remelting
  - — Inexact nitrogen control by addition
- **Air processing***
  - AOD — Argon oxygen decarbonization
  - — Ar, O, N injection
  - ESR — Electroslag remelting
  - — Slag removal

* *Current*

Some actions to minimize hydrogen embrittlement

- **Correct materials:**
  - Proven specification
  - Metallographic certification for grain size and cleanliness
- **Controlled welds:**
  - By established, reviewed procedures
  - Certified personnel
- **Hydrogen exposure:**
  - Always test below previous max test pressure
  - Pressure cycle test
- **Proper design:**
  - Avoid sharp radii, other stress concentrations

Other concerns

- Stress corrosion cracking
  - Failure in presence of corrosive medium and applied stress
  - Faster failure than by either individual effect
  - Bad actors = Fluorine, chlorine compounds
    = H_2S + Water
- Inclusions
  - Slag inclusions (pipes)
  - Manganese sulphides
  - Control by ASTM E45 - Plate 3 callout

The good, the bad and the ugly of hydrogen resistant materials:

The good *	The bad and the ugly
304	416
316	17-4 PH
21-6-9	4130 **
Be CU	4340
A-286	Inconel X
JBK-75	A-723

** Chemistry, grain size controlled by inspection.*
*** At high strength heat treat conditions.*

Fracture analysis concerns the effects of material flaws that are resident in the structure.

- Assumes that all structures are flawed.
- Under load, will the flaw act as a stress riser?
- Will the flaw "run", i.e., catastrophic fail?
- Defines a material property . . . fracture toughness . . . a function of environment and material condition.

Fracture critical designs require the preparation of a fracture control plan. The plan accesses potential hazards of resident flaws and outlines controls to be applied.

Such a plan:

- Accesses flaw size:
  - expected (material quality)
  - detectable (non-destruct testing)
  - calculated (fracture toughness, geometry)
- Compares resulting values to insure leak-before-break ($T_f >> T$).
- Defines environmental controls, i.e., temperature, cycles, corrosives, NDT, reinspections, etc.

Fracture analysis:

- May require "expert" assistance.
- May require fracture toughness measurements.
- Can be costly.
- Might be avoided by a different material selection.

Typical pressure vessel materials

Material	Hardness	Yield	Ultimate	Elongation	
316	$80R_B$	30	75	40	Annealed
	$25R_C$	80	110	25	Condition B
21-6-9	$100R_B$	55	90	40	Annealed
		130	150	25	HERF
JBK-75	$32R_C$	110	160	30	Heat treat
A-286	$30R_C$	85	130	15	Heat treat
4340	$30R_C$		125	145	Mill anneal
	$40R_C$		150	170	Quench-temperature

Design Considerations

- Seamless vessels - no longitudinal welds.
- Stress concentrations - thread relief/corners.
- Environmental conditions - vibration/shock, corrosion, etc.
- Non-destruct testing - dye penetrant, mag particle, x-ray, ultrasonic inspection.
- Fracture analysis.
- Operation at elevated temperature.

Welding Considerations

Heat affected zone:
- Annealing effects embrittlement (hydrogen)

Joint efficiency:
- Per ASME, Division I
- "E" value from UW-12

Certified welds:
- Per ASME
- Purchase Fabrication - ASME shop

In-House Weld Certification*

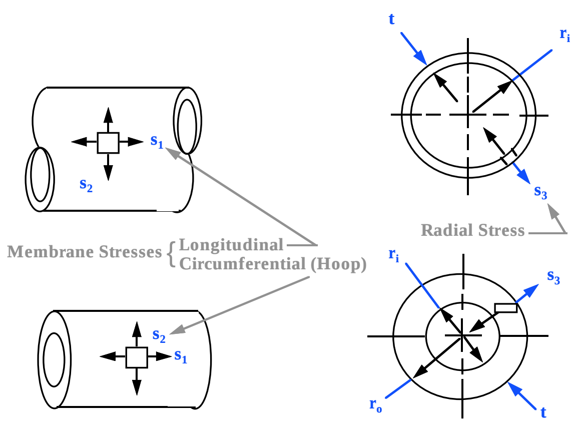
- Develop/document weld parameters.
- Certify the operator - Samples / DT.
- Define NDT requirements.
- Document all production welds.

*Expensive - justify for { radioactive, flammable, toxic }

Typical vessel design features that should be analyzed

- Hoop stress in vessel wall.
- Thickness of end closures.
- Shear stress in threads.
- Tensile strength of bolt cross-sections.
- Strength of welds.
- Yield criteria for pressure testing.

Thin wall vs. thick wall



The state of stress in the vessel wall depends upon the wall thickness

- Thin wall:
  - Barlow equation
  - Assumes uniform wall stress
  - Hoop σ = 2 x longitudinal stress
- Thick wall
  - Non-uniform wall stress
  - Maximum at I.D.
  - Minimum at O.D.
- Function of ratio of radii
  - $R = \frac{r_0}{r_i}$

The wall thickness determines the design equation

For cylinders:

$$P = \frac{\sigma_u E t}{SF_u r_i}$$ **Barlow: Thin wall (R < 1.1)**

$$P = \frac{\sigma_u E t}{SF_u (r_i + 0.6t)}$$ **ASME: Medium Wall (1.1 < R < 1.5)**

$$P = \frac{\sigma_u (r_o^2 - r_i^2)}{SF_u (r_o^2 + r_i^2)}$$ **Lame:**

$$P = \frac{2\sigma_u}{\sqrt{3} SF_u}\left(2 - \frac{\sigma_y}{\sigma_u}\right)\ln R$$ **Faupel:**

Thick wall (1.5 < R < 2.0) (Lame and Faupel)

$$P = \frac{\sigma_u (r_o^2 - r_i^2)}{SF_u (r_o^2 + r_i^2)}$$ **Lame: X thick wall (R > 2.0)**

Symbols for Stress can be Stressful!

σ = Greek letter sigma
S = English letter
σ_u = Ultimate tensile stress or strength
σ_a = Allowable stress (for design)
σ_a = Sa = SE (ASME designator for allowable stress)

Regardless — REMEMBER

$$\text{Allowable Stress} = \frac{\text{Ultimate Tensile Strength}}{\text{Safety Factor}}$$

ASME - ANSI Equivalency

The ASME medium wall equation

$$P = \frac{\sigma_u E t}{SF_u(r_i + 0.6t)}$$

is equivalent to the ANSI B31.1 equation

$$P = \frac{2SE(t_m - A)}{D_o - 2Y(t_m - A)}$$

When Y = 0.4 and (t_m-A) is an equivalent wall reduced by the thread depth.

An ANSI calculation for threaded and unthreaded pipe

Given: *1" schedule 40 UNS Alloy C23000 brass pipe @ 120°*

SE (ANSI) = 8 ksi *A = 0.070 in.*
t_m = 0.119 in. *D_o = 1.315 in.*
Y = 0.4

Determine: MAWP

Threaded

$$P = \frac{2SE(t_m - A)}{D_o - 2Y(t_m - A)}$$

$$P = \frac{2 \times 8{,}000 \times (0.119 - 0.070)}{1.315 - 2 \times 0.4(0.119 - 0.070)}$$

$$P = 615\text{psi}$$

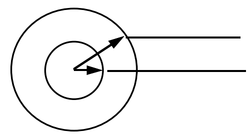
Unthreaded (A = O)

$$P = \frac{2SE(t_m - A)}{D_o - 2Y(t_m - A)}$$

$$P = \frac{2 \times 8{,}000 \times 0.119}{1.315 - 2 \times 0.4 \times 0.119}$$

$$P = 1{,}561\text{psi}$$

Faupel vs. Lame



$$\frac{r_o = 2.7}{r_i = 1.5} = R = 1.8$$

Material	s_y / s_u	Faupel	Lame	SFu
304SST	30/75	8,176	9,906	4
21-6-9	120/160	25,548	21,113	4

- **For low "yield to ultimate ratios" use Lame.**
- **For high "yield to ultimate ratios" use Faupel.**

End closures should be designed per ASME rules --- reference Section 8, Division 1, UG-34, where:

- **For no bending, i.e., welded, integral, etc.**

(Cases a ⟶ i , m ⟶ s)

$$t = d\sqrt{\frac{C_p}{S_a E}}$$

- **For bending, i. e., flanged, bolted, etc.**

(Cases j,k)

$$t = d\sqrt{\frac{C_p}{S_a E} + \frac{1.9 W h_G}{S_a E d^3}}$$

Maximum Energy of Distortion Analysis

For pressure vessels made of low yield strength materials, i.e. annealled SST, a 1.5 x MAWP test pressure may plasticly deform the vessel. To check:

- **Determine the safety factor based on yield . . . at test pressure**

$$SF_y = \frac{\text{S yield}}{\text{S test pressure}} = \text{Von Mises Number}$$

Where:

S test pressure = S combined (Von Mises)

—To insure no yielding, SF_y>1

The combined (Von Mises) stress is determined as:

$$S_{Von\ Mises} = \sqrt{\frac{1}{2}\left[(S_1 - S_2)^2 + (S_2 - S_3)^2 + (S_3 - S_1)^2\right]}$$

Where

S_1 = Longitudinal stress = $P\left(\frac{r_i^2}{r_o^2}\right) = \frac{P}{Z-1}$

S_2 = Hoop stress $= P\left(\frac{r_o^2 + r_i^2}{r_o^2 - r_i^2}\right) = P\left(\frac{Z+1}{Z-1}\right)$

S_3 = Radial stress = -P

Where Z $= \left(\frac{r_o}{r_i}\right)^2$

SF-3 pressure vessels are allowed if:

- Documented chemistry/media compatibility.
- Fracture toughness criteria per ME design standards.
- Documented mechanical properties.
  - RA ≥ 40%, e ≥ 15%
  - 3 tensiles, 1 fracture toughness
- Certified welding
  - TIG/EB only
  - Welds tested
  - Burst 1 vessel
- 100% Non-destruct testing.

Safe design also applies to purchased vessels

- Require a formal design analysis . . . safety factors, maximum stresses, etc.
- Submit this analysis to technical in-house review.
- Consider and specify applicable non-destruct testing performed by the manufacturer.
- If critical, require materials certifications — chemistry, mechanical properties, proof of heat treat.

Safe design of purchased vessels, continued

- When applicable, specify and require acceptance pressure testing - might include user involvement.
- Provide the option to witness any "at-manufacturer" testing.
- Consider your needs for drawings, spare parts, disassembly/assembly and maintenance procedures.
- All of the above best addressed in the procurement action or specification.

For design analysis of complex vessels . . .

GET HELP!

Help =

Stress Analysis ⟶ Applied Mechanics

Fracture Mechanics ⟶ Nondestructive Evaluation

Materials ⟶ Metallurgist

ASME PRESSURE VESSEL CODE GUIDE

The following list may be helpful in locating some of the generally-used information in the ASME Boiler and Pressure Vessel Code, Section VIII, Pressure Vessels, Division I (1992 edition):

Section	Subject	Page
UG-23	Maximum Allowable Stress Values (Subsection C starts on page 153)	20
UG-27	Thickness of Shells under Internal Pressure	23
UG-32	Formed Heads, Pressure on Concave Side	33
UG-34	Unstayed Flat Heads and Covers (See Figure UG-34 on page 37)	36
UG-101	Proof Tests to Establish Maximum Allowable Working Pressure	77
UG-125 UG-136	Pressure Relief Devices through	87 through 100
UW-9	Design of Welded Joints	107
App. 1	Supplementary Design Formulas (Mandatory)	291
App. 6	Methods for Magnetic Particle Examination (MT)	343
App. G	Suggested Good Practice Regarding Design of Supports	477
App. L	Examples Illustrating the Application of Code Formulas and Rules	481

HP CALCS computer disk

- **An Apple/Macintosh or IBM computer diskette is available to perform the types of calculations described in this course.**
- **This software, developed for HS-506, involves stored energy, amagat, gas transfer, and vessel/piping design.**
- **The basis for and description of these programs is contained in LLNL document END 91-030.**

HP CALCS, continued

1. **PR-AMG-STD**

   Converts pressure to or from amagat, for the following gases: helium 4, deuterium, nitrogen, argon, hydrogen. Usable up to about 30 ksi.

2. **TUBE**

   Calculates MAWP for tubing (or cylindrical shapes) given material properties, dimensions, and safety factor. Basis is hoop stress calculations as defined in Health & Safety Manual, chapter 32, supplement 32-03.

3. **ENERGY-GAS**

   Calculates the energy in a gas charged vessel, assuming isentropic expansion. Reference is Health & Safety Manual, Chapter 32, supplement 32-03.

4. **EQUILIB-STD Apl**

   Calculates equilibrium pressure and gas distribution in a gas system where the source and receiver are at different (or the same) temperatures. Gases may be single components or mixtures of helium 4, deuterium, nitrogen, argon, hydrogen. Gives a print-out.

HP CALCS, continued

5. **VOLUME Calc**

   Calculates the volume of a sphere or right cylinder, given dimensions.

6. **PIPE**

   Calculates MAWP for tubing and threaded or unthreaded pipe per ANSI Code for Power Piping, B31.1.

7. **BOTLCALC-N Apl**

   Calculates

   1) equilibrium gas transfers between two or more volumes.

   2) minimum vessel volume required for a given gas transfer process.

   Gases are helium 4, nitrogen, argon, or hydrogen. Will give a print-out.

8. **ENERGY-LIQ**

   Calculates the energy in a liquid (water) charged vessel by approximating the pdv work done on the liquid. References END 88-039.

Summary Points

- Vessel <u>design</u> is determined by MAWP and SF.
- Vessel <u>use</u> is determined by MOP, test pressure, manned/remote operation.
- Mechanical properties, fracture/embrittlement behavior, and certification are important material considerations.
- Design should consider stress concentrations, non-destruct testing, environment.
- Address these welding issues: heat effects, material weldability, in-house or ASME certification.

Summary Points, continued

- Consider section thickness and yield/ultimate properties in determining wall stress.
- Design end closures per ASME Section 8, Division I.
- Evaluate test pressure effects on vessel yielding.
- SF-3 vessels are allowed, subject to extensive certification and testing.
- Complex vessels may require outside help.
- Pressure calculation disk is available upon request.