

proj: **XENON TPC**

Xenon Pressure Chamber

title: **Pressure Safety Note**

**DRAFT, for review,
not complete**

Prepared by: _____
Responsible Designer - Derek Shuman

Reviewed by: _____
EH&S Pressure Safety Subject Matter Expert - Joe Dionne

Approved by: _____
Engineering Division Director - Peter Denes

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1. Introduction

This Safety Note covers a pressure vessel and associated gas system for a physics research experiment involving neutrinoless double beta decay. The heart of the system is a pressure vessel recently acquired by LBNL from LLNL. There are new components both purchased, and LBNL designed, which will be attached to this pressure vessel, which are treated in this note.

The pressure vessel will enclose a small detector called a Time Projection Chamber (TPC) with Xenon gas used as both the electron drift volume and for electrical insulation. The vessel was designed by LLNL, and used at LLNL from 2000-2009 for a similar purpose, and has not been modified from the original design. LLNL Mechanical Engineering Safety Note MESN99-020-OA (1999) contains the vessel design calculations, performed in accordance with ASME Pressure Vessel code Section VIII (1995), and is included here in the Appendix. It includes pressure testing procedures. Also included is a copy of the original pressure test at LLNL for the vessel and head. The attached components consist of a 2" diameter high vacuum/high pressure valve, a Kimball physics octagonal vacuum chamber, a spool connecting the octagon to the vessel lid, assorted cabling feedthroughs, and a gas handling system composed of small diameter high pressure metal tubing, purifiers, valves, and pumps. The gas system includes a cryogenic Xenon reclamation cylinder, which was designed, built, and tested by Acme Cryogenics for LLNL, for 3000 psi MOP. We will be using it here at LBNL up to a pressure of 950 psi MOP. Its design calculations and test report are also included in the Appendix (LLNL M.E. Safety Note MESN99-038-OA). This note is to assure that the Vessel meets LBNL Safety requirements of PUB-3000. The pressure vessel is shown below:

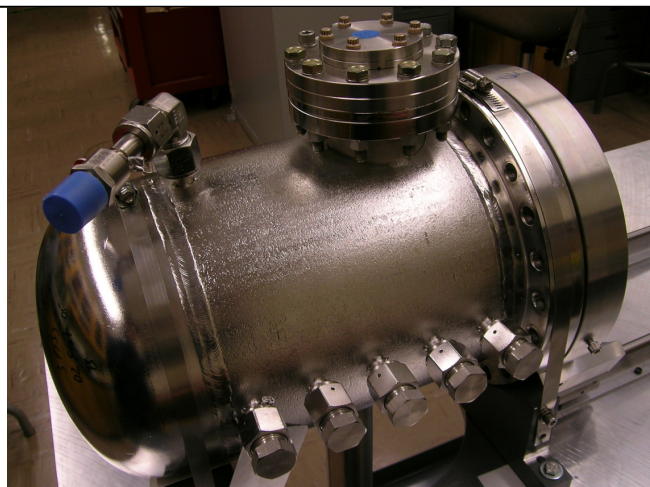


Fig. 1 Main pressure Vessel, 850 psig MOP

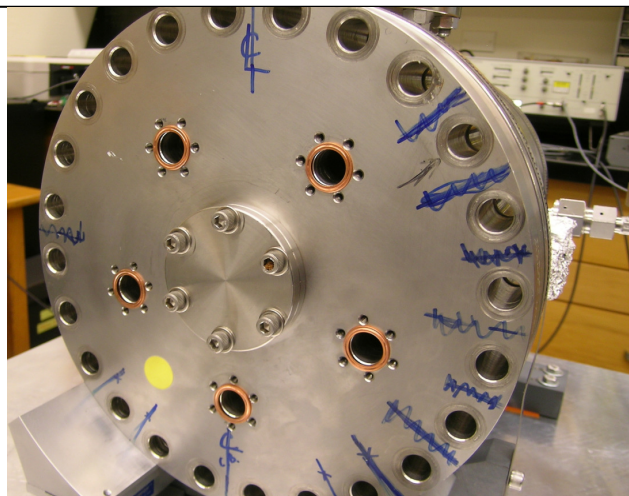


Fig. 2 Flat Heat for 350 psig MOP (CF seals)

Pressures for use at LBNL

Maximum Operating Pressure Maximum Allowable Working Pressure

$$P_{MOP} := 300\text{psi}$$

$$P_{MAWP} := 350\text{psi}$$

Initial Maximum Operating and Allowable Working Pressures

$$P_{MOP_i} := 225\text{psi}$$

$$P_{MAWP_i} := 250\text{psi}$$

(to be used initially with existing Ceramtec SHV-20 connectors (see below) until higher rated feedthroughs are obtained)

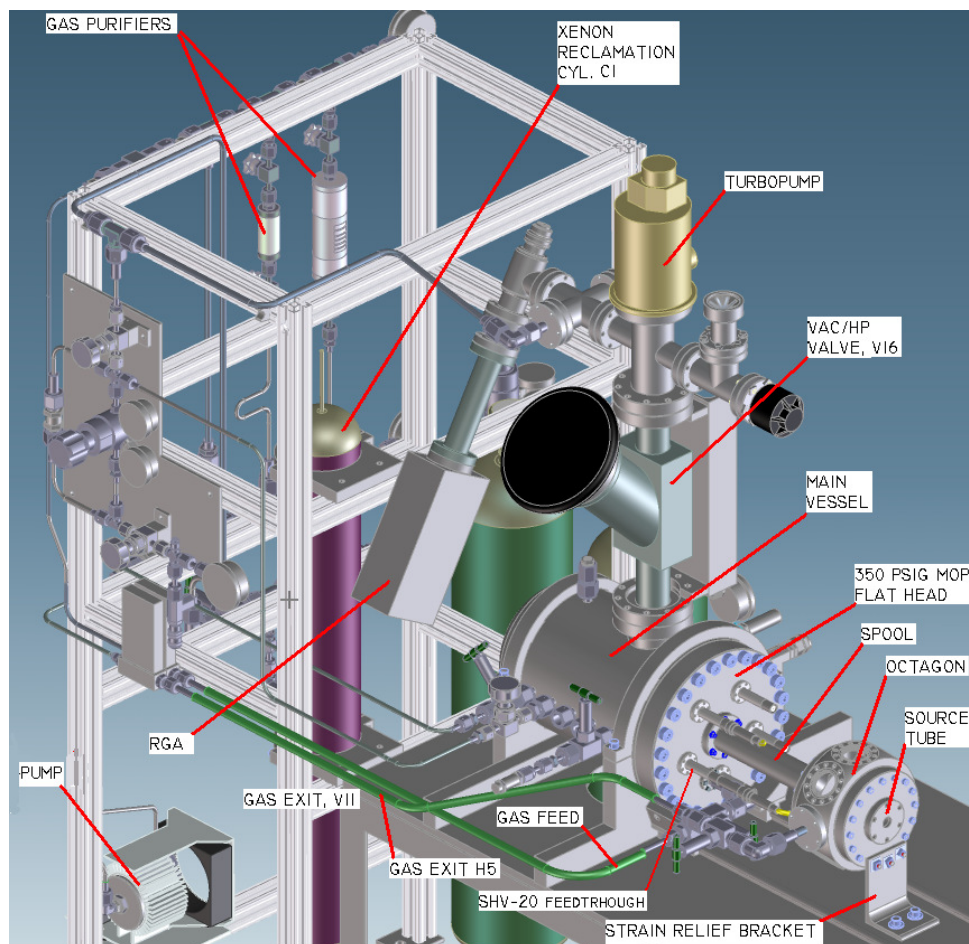


Fig. 3 LBNL configuration: pressure vessel with cabling extension spool, octagon vac. cham. & gas sys.

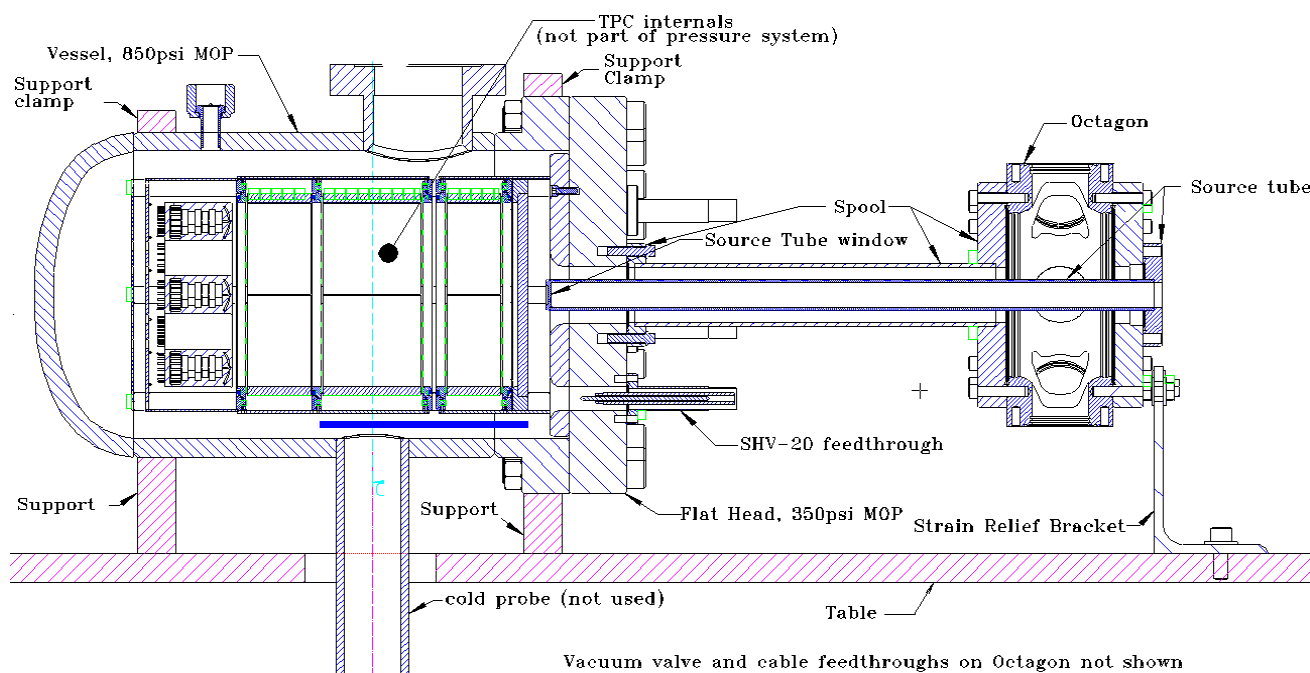


Fig. 4, Cross Section, longitudinal-vertical

2. System Description and Basic Operation

The main pressure vessel is approximately 8 inches in diameter and 14 inches long, (inside volume), and fabricated from 316L and 304 stainless steel. It will be operated at LBNL at a 300 psig maximum operating pressure (MOP), with a maximum allowable pressure (MAWP) of 350 psig. Minimum pressure is high vacuum. The main vessel was designed for operation up to 850 psig MOP, with a section of the chamber operated at LN₂ temperature. There are two flat heads for it, only one of which will be used at LBNL, this head has an MAWP of 406 psig. At LBNL, the chamber will be used with inert gases only, mainly Xenon and Argon, as well as high vacuum. It will be operated only in temperature range of room temperature to 50C; the cryogenic section will not be used, and it will be labeled as such to prohibit use. An associated gas system is used to supply gas to the chamber, to pressurize and depressurize the vessel, and to circulate Xenon continuously through the detector, primarily to purify the Xenon gas to a high purity state, but also to eliminate any thermal convection currents from electronics inside the vessel. Argon may be used for initial flushing of air, H₂O, etc. when the vessel is first assembled, and perhaps for leak checking under pressure. A 5.4L stainless steel Xenon reclamation cylinder is used to condense/ freeze out Xenon in order to open up the vessel without venting the Xenon. It will be left open during some operations, and so is considered part of the vessel volume. The total system stored energy is 54 kJ for either of these monatomic gasses @MAWP = 350 psig. A schematic is shown below:

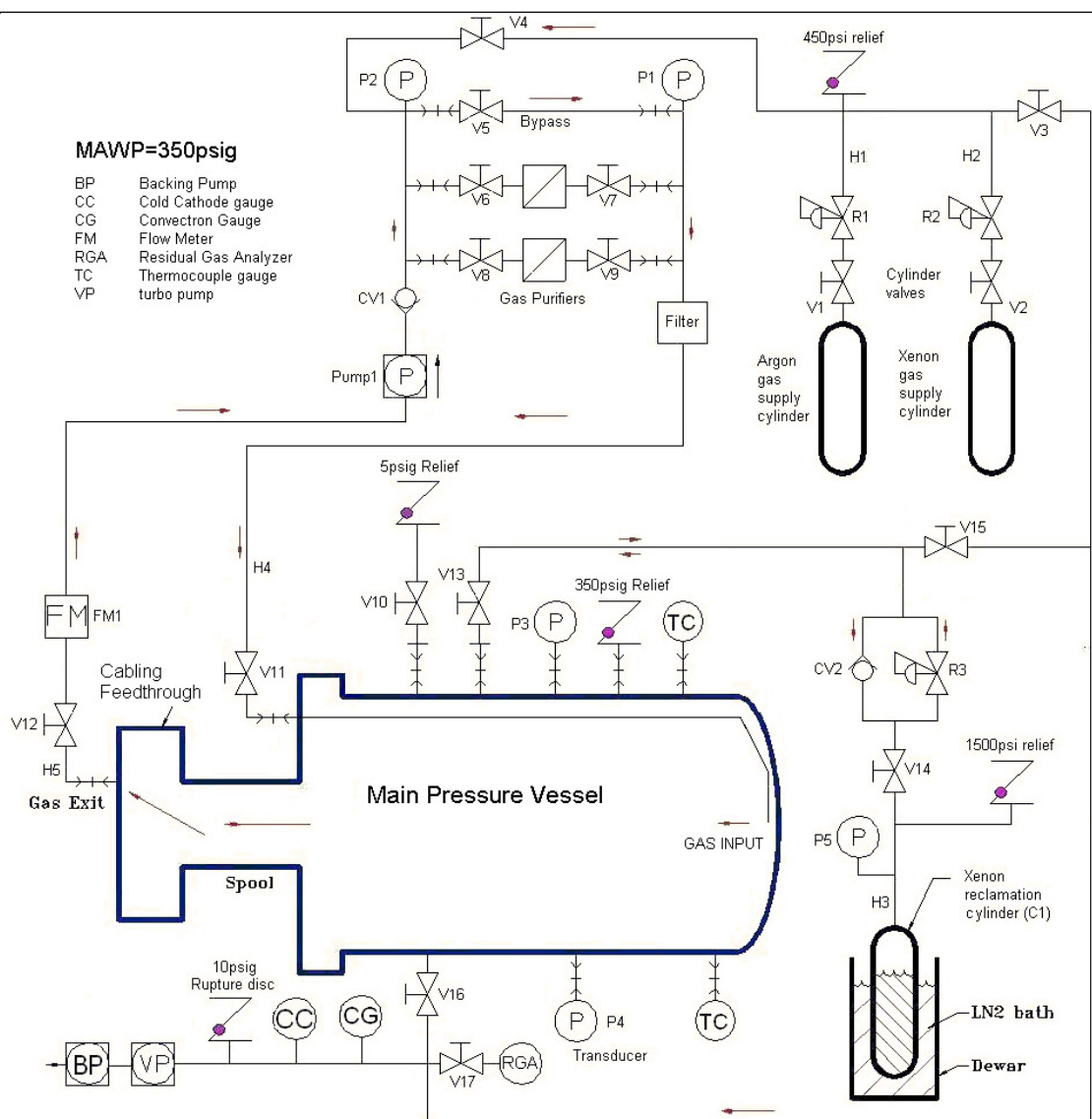


Fig. 5 Gas System Schematic

Operation of the system is treated in detail in section 8, Gas System below, and in the AHD (to be prepared). The basic sequence is essentially:

1. All valves, except the gas cylinder and vacuum purge valves, are opened (including the reclamation cylinder) and the system is pumped down to a high vacuum. Argon may be used for an initial flush, or to provide for a purge when the system is opened.
2. The vacuum valve is then shut and the system (including reclamation cylinder) is filled with Xenon to 300 psig (225 initially) at room temperature.
3. The dewar is filled with LN2; this freezes out the Xenon into the reclamation cylinder, which is then valved off.
4. The main system is refilled with Xenon to 50 psig, and step 3 is repeated. This step charges the reclamation cylinder with a small amount of extra Xenon to provide for quicker refilling of the main system.
5. To fill the main system at the desired pressure, the reclamation cylinder is opened and regulated flow is let back into the vessel until the desired pressure is reached. Heaters on the reclamation cylinder may be needed to warm the gas, as it will cool upon expansion; a maximum temp. of 50C is used. The gas will cool upon expanding

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through the regulator, and the pressure will be lower than 300 psig (225 psig initially) until the gas warms up to room temperature. Line heaters on the refill line may be needed to reduce the amount of time needed to come back to room temperature.

6. The pump is then operated to circulate the Xenon through the main pressure vessel and through the gas purifiers. The gas flow rate is varied as needed, using the pump controller, and only one gas purifier is used at a time. The reclamation cylinder valve is left open during operation.

4. To open the main pressure vessel for service (to TPC), step 3 is repeated.

5. After closing the main pressure vessel after TPC service and pumping it down to high vacuum, step 5 is repeated.

Pressure Safety Assurance There are five pressure zones in the system:

1. Main Vessel with attached components, 350 psig MAWP, protected by 350 psig relief valve on main vessel (a 250 psig relief valve will be installed initially until high pressure SHV-20 connectors are procured and installed).
2. Gas supply and purifier loops 1000 psig MAWP, protected by 450 psig relief valve.
3. Reclamation cylinder, 3000 psig MAWP, protected by 1500 psig relief valve.
4. The gas supply cylinders themselves have their burst disks behind their valves, per standard gas cylinder practice.
5. The vacuum system has a 10psig burst disk on the vacuum side.

Hazards Analysis

There are no toxic, flammable, biological, or radioactive gasses or materials inside the vessel with the possible exception of some small low intensity sealed gamma sources. The inside detector is composed of common metals, Teflon, Mylar, Kapton and PEEK polymers, glass, signal cabling and some semiconductor ICs. There will be high voltage components inside, operating as high as +/-20 kV, but at low stored energy, and there will be no organic liquids, gases, or aerosols, and no oxygen present when operating, so there is no explosion hazard. There are 19 photomultiplier tubes (PMTs) 1 inch diameter by 2 inches long which are known to withstand use at 20 bar; they have the possibility of imploding under excessive pressure, but this is not expected to create any hazard from excessive transient pressure, or other hazard since they are surrounded by a dense gas, not a liquid, as is the case in some neutrino detectors. These PMTs will be hydrostatically pressure tested before use at 125% MOP = 375 psig. There are no toxic or radioactive materials inside the PMT's. These PMTs are the limiting factor for the experiment, and set the MOP to 300psi. There are, initially two SHV-20 high voltage feedthrus that are rated for use at 250 psi; this is the lowest MAWP of the entire system and thus a 250 psig relief valve will be initially installed on the pressrue vessel until a high pressure (800 psig MAWP) version of this feedthrough is procured; at which time the MAWP will be changed to 350 psig.

There will be people present near the vessel when it is under full pressure. Under PUB3000, sec 7.6.1, it is classified as a High Hazard Pressure System, since there are gas pressures above 150 psig. An AHD is not required for the Xenon or Argon gases, nore any of the other materials inside, but there may be pressure and process hazards, so an AHD will be formulated.

Main Vessel Description

The chamber is constructed from Schedule 80 316L S.S. pipe and the flanges and heads are 304 S.S. (if not 304L). There are no brittle materials used. Welds were made by ASME certified welders according to the LLNL Note. Welds were designed with an efficiency factor of 0.7 to eliminate the need to radiograph welds.

As mentioned above, the main vessel has a Maximum Operating Pressure (MOP) of 850 psig when used with a specially made blank flat head which seals against the vessel flange with a C-type face gasket. Maximum allowable Pressure (MAWP) is 976 psig with this head. This vessel and head combination has been pressure tested to 1.5xMAWP=1467 psig. However there is no plan to operate the vessel at LBNL using this head.

It has an MOP of 350 psig when used with a different specially made flat head (labeled AAA- 99-104240-00) which has a number of openings for instrumentation, each of which seals with a CF-type (conflat) flange. This flat head is not a standard CF type flange but has increased thickness and uses double the number of clamping bolts.

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It seals using a standard CF gasket and knife edge design, however. Maximum allowable Pressure (MAWP) is 406 psig. It has been pressure tested to $1.5 \times \text{MAWP} = 609$ psig with this head (openings blanked off).

The Vessel can only, and will only be used at LBNL with the 350 psig MOP head. There are a number of valves, pipes and electrical feedthru's that will attach to the head and vessel; all will be either rated by the manufacturer for 350 psig operation (MAWP at min.), and, if not, will be analyzed for pressure safety and pressure tested, either in conjunction with this vessel or separately. The strength of this vessel and head have no dependency on any attached components, nor do any attached components rely on this vessel or head for strength.

As stated above, there are no toxic, flammable, biological, or radioactive gasses or materials used inside the vessel with the exception of some small low intensity sealed gamma sources. Argon gas will be used as a purge gas, most likely at low pressure but perhaps up to the MOP e.g. for leak checking. There is a cold probe welded to the main tank vessel which was used to condense Xenon inside the vessel, using a surrounding dewar of LN2, however, there are no plans at LBNL to use this feature, and it will be labeled to prohibit use.

As stated above, there are also some new components which will be attached to both the vessel and flat head, some of which are pressure rated by the manufacturer, some which are not rated by the manufacturer but which are suitable for safely holding pressure, and some which will be designed and built by LBNL. These latter two categories are analyzed in this note for sufficient strength and will be proof tested separately.

LLNL Safety Note MESN99-020-OA (1999) shows calculations performed in accordance with ASME Pressure Vessel Code Section VIII-1-1997. The analysis appears to be fairly complete and correct with respect to ASME Pressure Vessel Code Section VIII-1-2007, which this author has access to. There is an analysis of the 350 psi MOP head which uses a non-ASME method involving stress concentration factors, however there is also an analysis based on ASME methods. This document is reproduced in the Appendix. Also in the Appendix are the two pressure test reports from LLNL, plus two notes on pressure capacity of CF flanges, one from LLNL and one from ANL.

What follows are basic calculations for this experimental system and additional calculations for the added components:

3. Basic System Calculations**Stored Energy, U, @ 350 psig MAWP**

from PUB3000 , Chapter 7, Appendix E:

$$U = \frac{P_h V_h}{\gamma - 1} \left[1 - \left(\frac{P_1}{P_h} \right)^{\frac{\gamma - 1}{\gamma}} \right]$$

where:

$$P_h := P_{\text{MAWP}} + 14.7 \text{ psi} \quad P_h = 364.7 \text{ psi} \quad P_1 := 14.7 \text{ psi} \quad \gamma := 1.666 \quad (\text{for monatomic gases})$$

Volume includes vessel, cabling octagon, connection spool, valve and gas system tubing:

| | | |
|---------------------------------------|--------------------------------------|---|
| $d_{\text{ves}} := 7.63 \text{ in}$ | $l_{\text{ves}} := 13.5 \text{ in}$ | main vessel inner dimensions |
| $d_{\text{LNxt}} := 2 \text{ in}$ | $l_{\text{LNxt}} := 8 \text{ in}$ | LN2 extension (cold probe) |
| $d_{\text{oct}} := 8 \text{ in}$ | $l_{\text{oct}} := 3.0 \text{ in}$ | Kimball octagon for cabling |
| $d_{\text{spool}} := 2 \text{ in}$ | $l_{\text{spool}} := 10 \text{ in}$ | connection spool, flat head to octagon |
| $d_{\text{tubing}} := 0.5 \text{ in}$ | $l_{\text{tubing}} := 20 \text{ ft}$ | gas system tubing and purifiers (est.) |
| $d_{\text{valve}} := 2 \text{ in}$ | $l_{\text{valve}} := 4 \text{ in}$ | high pressure volume of closed vacuum valve and tank stub |
| $d_{\text{rc}} := 3.43 \text{ in}$ | $l_{\text{rc}} := 36 \text{ in}$ | reclamation cylinder |

$$V_h := \frac{\pi}{4} \cdot (d_{\text{ves}}^2 \cdot l_{\text{ves}} + d_{\text{LNxt}}^2 \cdot l_{\text{LNxt}} + d_{\text{spool}}^2 \cdot l_{\text{spool}} + d_{\text{oct}}^2 \cdot l_{\text{oct}} + d_{\text{tubing}}^2 \cdot l_{\text{tubing}} + d_{\text{valve}}^2 \cdot l_{\text{valve}} + d_{\text{rc}}^2 \cdot l_{\text{rc}})$$

$$V_h = 1.2 \times 10^3 \text{ in}^3 \quad V_h = 19.9 \text{ L}$$

Stored Energy @ 350 psig MAWP

$$U_v := \frac{P_h \cdot V_h}{\gamma - 1} \left[1 - \left(\frac{P_l}{P_h} \right)^{\frac{\gamma}{\gamma - 1}} \right] \quad U_v = 54 \text{ kJ}$$

Mass of Xenon in System at operating pressure

$$P_{MOP} = 300 \text{ psi} \quad R := 8.314 \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1} \quad T_{amb} := 300 \text{ K} \quad M_{a_Xe} := 131.3 \text{ gm} \cdot \text{mol}^{-1}$$

Critical Pressure, temperature of Xenon:

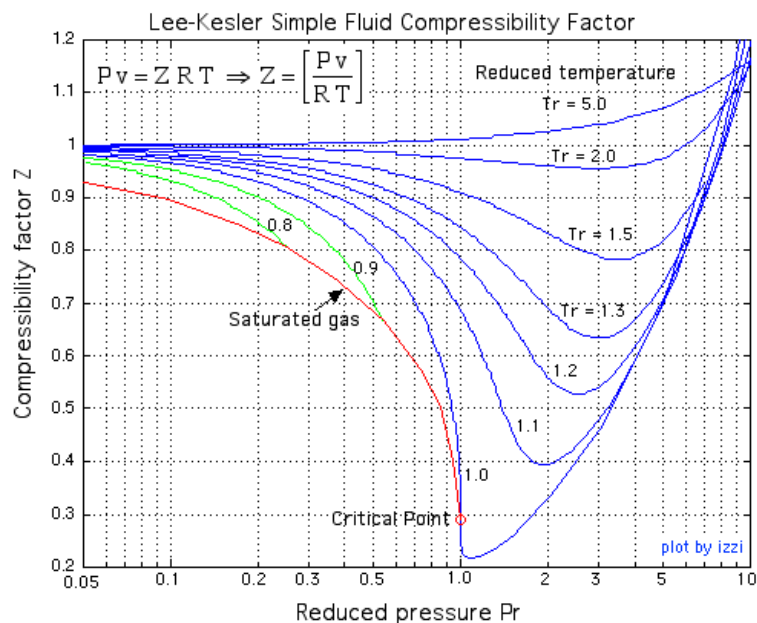
$$P_{c_Xe} := 58.40 \text{ bar} \quad T_{c_Xe} := 15.6 \text{ K} + 273 \text{ K}$$

reduced pressure:

$$P_r := \frac{315 \text{ psi}}{P_{c_Xe}} \quad P_r = 0.361 \quad T_r := \frac{T_{amb}}{T_{c_Xe}} \quad T_r = 1.04$$

Compressibility Factor:

$$Z_{Xe_20\text{bar}} := 0.88 \quad \text{from chart for pure gasses shown below}$$



ref: A Generalized Thermodynamic Correlation based on Three-Parameter Corresponding States, B.I.Lee & M.G.Kesler, AIChE Journal, Volume 21, Issue 3, 1975, pp. 510-527' (secondary ref. from: <http://www.ent.ohiou.edu/~thermo/>)

Fig. 6 Compressibility Factor, pure gasses

Number of moles:

$$n_{Xe} := \frac{P_{MOP} \cdot V_h}{Z_{Xe_20\text{bar}} \cdot R \cdot T_{amb}} \quad n_{Xe} = 18.793 \text{ mol} \quad \rho_{mol} := \frac{n_{Xe}}{V_h} \quad \rho_{mol} = 0.942 \frac{\text{mol}}{\text{L}}$$

Weight:

$$W_{Xe} := M_{a_Xe} \cdot n_{Xe} \quad W_{Xe} = 2.47 \text{ kg}$$

Volume of LXe in reclamation cylinder (at freeze-out)

$$\text{density: } \rho_{LXe} := 3.05 \frac{\text{gm}}{\text{mL}} \quad @ \text{ boiling, 1 bar, } -101.8 \text{ C}$$

$$V_{LXe} := \frac{W_{Xe}}{\rho_{LXe}} \quad V_{LXe} = 0.809 \text{ L}$$

Xenon reclamation cylinder volume

$$V_{rc} := \frac{\pi}{4} \cdot d_{rc}^2 \cdot l_{rc} \quad V_{rc} = 5.451 \text{ L}$$

Pressure in Reclamation Cylinder

we need to guess initial value and iterate to find Z. From Lee-Kesler chart above it looks like it could be as low as 0.4, but heated to 50C it could be:

$$\rho_{mol_rc} := \frac{n_{Xe}}{V_{rc}} \quad \rho_{mol_rc} = 3.448 \frac{\text{mol}}{\text{L}}$$

$$P_{rc_guess} := 3 \cdot P_{MOP} \quad P_{rc_guess} = 60.2 \text{ bar}$$

$$P_{r_rc} := \frac{P_{rc_guess}}{P_{c_Xe}} \quad P_{r_rc} = 1.032$$

$$T_{hot} := (273 + 50) \text{ K} \quad T_{r_hot} := \frac{T_{hot}}{T_{c_Xe}} \quad T_{r_hot} = 1.12$$

from chart above:

$$Z_{Xe_rb_press} := .7$$

$$P_{rc} := \frac{n_{Xe} \cdot Z_{Xe_rb_press} \cdot R \cdot T_{amb}}{V_{rc}} \quad P_{rc} = 58.4 \text{ bar} \quad P_{rc} = 873 \text{ psi} \quad \text{close enough to guess}$$

Alternately, we can use a pressure density curve:

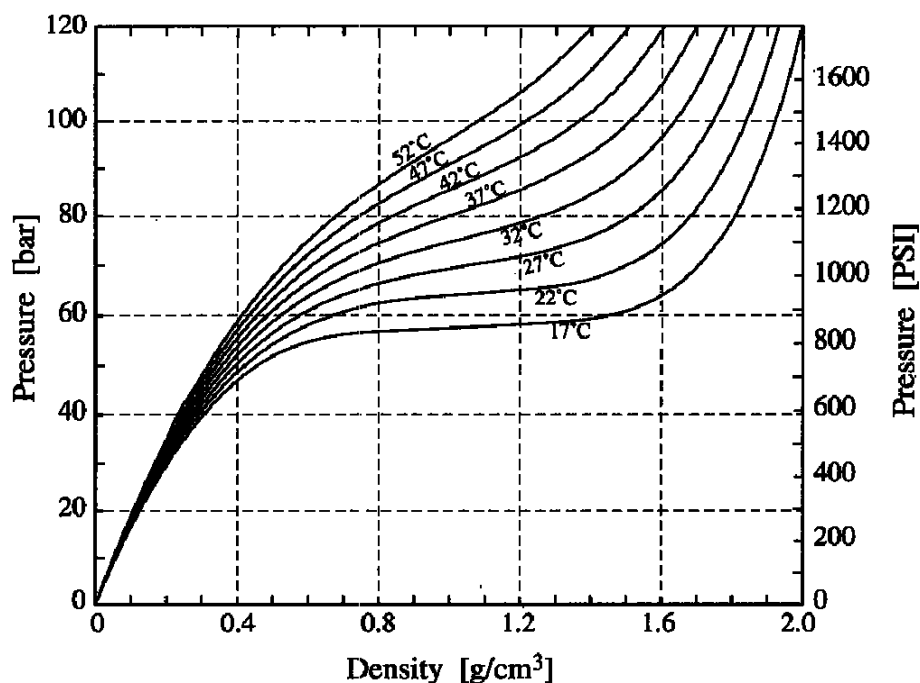


Fig. 7 Pressure-Density Curves for Xenon

ref : [Thermophysical Properties of Neon, Argon, Krypton, and Xenon](#)
V.A. Rabinovitch, A.A. Vasserman,
V.I. Nedostup, L.I. Veksler,
Hemisphere Publishing Co (1985)
via:
[A Portable Gamma Ray Spectrometer using Compressed Xenon](#)
G.J. Mahler, et. al. IEEE
Trans. Nuc. Sci. 45(3) p.
1029(1998)

for $\rho_{\text{mass_rc}} := \rho_{\text{mol_rc}} \cdot M_{a_Xe}$ $\rho_{\text{mass_rc}} = 0.453 \frac{\text{gm}}{\text{cm}^3}$

we find a maximum pressure of

$P_{\text{max_rc}} := 63\text{bar}$ $P_{\text{max_rc}} = 941\text{ psi}$ at 50C, which is the maximum temperature we expect to see.
The gas purifiers have a maximum temperature of 40C.

Note: The reclamation cylinder will not be heated when condensing out, or when full. It will only be heated as needed to assist in refilling; this will only happen at a low pressure, after the vessel has been mostly refilled. As such it's typical maximum pressure will be determined by the room ambient temperature. Assuming this is 30C:

$P_{\text{typ_max_rc}} := 57\text{bar}$ $P_{\text{typ_max_rc}} = 852\text{ psi}$

Stored Energy in Reclamation cylinder

$$U_{\text{rc}} := \frac{P_{\text{max_rc}} \cdot V_{\text{rc}}}{\gamma - 1} \left[1 - \left(\frac{P_1}{P_{\text{max_rc}}} \right)^{\frac{\gamma}{\gamma - 1}} \right] \quad U_{\text{rc}} = 43\text{ kJ} \quad @50\text{C}$$

4. Vacuum Valve:

Valve is a Carten HF2000 process valve which is designed not only to hold high vacuum, but also to hold high pressure:

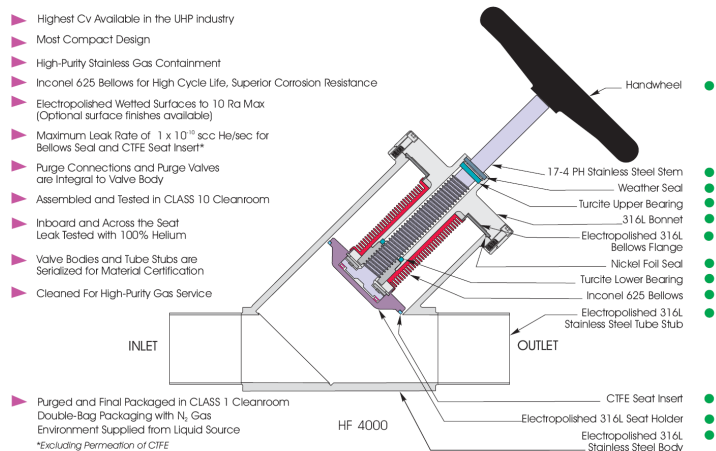
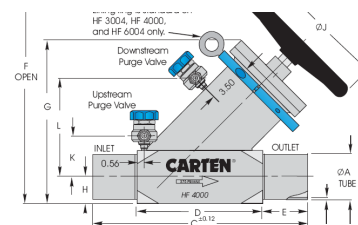


Fig. 8 Carten HF2000 process valve



Standard purge valve connection sizes are:
HF 500, HF 751, HF 1000, and HF 1501 = 1/4" purge connectors
HF 1502 and larger valves = 1/2" purge valves

| CAT. NO. | A* | B* | C | D | E | F | G | H | J |
|----------|------|-------|--------------------|-------------------|-------------------|--------------------|-------------------|------------------|-------------------|
| HF 500 | 0.50 | 0.049 | 9.50 (241.1mm) | 3.45 (87.9mm) | 3.02 (76.7mm) | 4.75 (120.7mm) | 3.25 (82.8mm) | 0.50 (12.7mm) | 2.50 (63.5mm) |
| HF 751 | 0.75 | 0.065 | 12.85 (326.6mm) | 4.8 (121.9mm) | 4.03 (102.4mm) | 7.97 (202.4mm) | 5.85 (148.8mm) | 0.75 (19.1mm) | 3.94 (100.1mm) |
| HF 1000 | 1.00 | 0.065 | 10.84 (275.3mm) | 4.8 (121.9mm) | 2.98 (75.7mm) | 7.97 (202.4mm) | 5.85 (148.8mm) | 0.75 (19.1mm) | 3.94 (100.1mm) |
| HF 1501 | 1.50 | 0.065 | 14.75 (374.9mm) | 4.8 (121.9mm) | 4.98 (126.5mm) | 7.97 (202.4mm) | 5.85 (148.8mm) | 0.75 (19.1mm) | 3.94 (100.1mm) |
| HF 1502 | 1.50 | 0.065 | 17.16 (435.9mm) | 6.98 (177.3mm) | 5.09 (129.3mm) | 13.15 (334.0mm) | 8.85 (225.0mm) | 1.31 (33.3mm) | 7.87 (199.9mm) |
| HF 2000 | 2.00 | 0.065 | 15.24 (387.1mm) | 6.98 (177.3mm) | 4.13 (104.9mm) | 13.15 (334.0mm) | 8.85 (225.0mm) | 1.31 (33.3mm) | 7.87 (199.9mm) |

Fig. 9 Carten HF2000 process valve dimensions

Note: manufacturer has agreed to weld valve to a 4 5/8" CF flange and pressure certify to 350 psig MOP. Nevertheless, here are some calculations. We see that the pressure capability of this valve, in the closed position will be determined by the wall thickness B. From ASME Section VIII UG-27 Thickness of Shells under Internal Pressure:

(c) *Cylindrical Shells*. The minimum thickness or maximum allowable working pressure of cylindrical shells shall be the greater thickness or lesser pressure as given by (1) or (2) below.

(1) *Circumferential Stress (Longitudinal Joints)*. When the thickness does not exceed one-half of the inside radius, or P does not exceed $0.385SE$, the following formulas shall apply:

$$t = \frac{PR}{SE - 0.6P} \quad \text{or} \quad P = \frac{SEt}{R + 0.6t} \quad (1)$$

(2) *Longitudinal Stress (Circumferential Joints)*.¹⁶ When the thickness does not exceed one-half of the inside radius, or P does not exceed $1.25SE$, the following formulas shall apply:

$$t = \frac{PR}{2SE + 0.4P} \quad \text{or} \quad P = \frac{2SEt}{R - 0.4t} \quad (2)$$

MAWP

Weld efficiency

$$P_{MAWP} = 350 \text{ psi}$$

$$E_w := 0.7 \text{ (est.)}$$

Maximum Allowable Stress, 304 stainless steel:

Pipe and Tube:

From ASME Pressure Vessel Code (2007) Section II, Materials

TABLE 1A (CONT'D)
SECTION I; SECTION III, CLASSES 2 AND 3; SECTION VIII, DIVISION 1; AND SECTION XII
MAXIMUM ALLOWABLE STRESS VALUES S FOR FERROUS MATERIALS
(* See Maximum Temperature Limits for Restrictions on Class)

| Line No. | Nominal Composition | Product Form | Spec No. | Type/Grade | Alloy Designation/UNS No. | Class/Condition/Temp | Size/Thickness, in. | P-No. | Group No. |
|----------|---------------------|------------------|----------|------------|---------------------------|----------------------|---------------------|-------|-----------|
| 16 | 18Cr-8Ni | Seam & weld pipe | SA-312 | TP304 | S30400 | ... | ... | 8 | 1 |
| 17 | 18Cr-8Ni | Weld pipe | SA-312 | TP304 | S30400 | ... | ... | 8 | 1 |
| 18 | 18Cr-8Ni | Weld pipe | SA-312 | TP304 | S30400 | ... | ... | 8 | 1 |

TABLE 1A (CONT'D)
SECTION I; SECTION III, CLASSES 2 AND 3; SECTION VIII, DIVISION 1; AND SECTION XII
MAXIMUM ALLOWABLE STRESS VALUES S FOR FERROUS MATERIALS
(* See Maximum Temperature Limits for Restrictions on Class)

| Maximum Allowable Stress, ksi (Multiply by 1000 to Obtain psi), for Metal Temperature, °F, Not Exceeding | | | | | | | | | | | | |
|--|------------|-----|------|-----|------|------|------|------|------|------|------|------|
| Line No. | -20 to 100 | 150 | 200 | 250 | 300 | 400 | 500 | 600 | 650 | 700 | 750 | 800 |
| 16 | 20.0 | ... | 20.0 | ... | 18.9 | 18.3 | 17.5 | 16.6 | 16.2 | 15.8 | 15.5 | 15.2 |
| 17 | 20.0 | ... | 16.7 | ... | 15.0 | 13.8 | 12.9 | 12.3 | 12.0 | 11.7 | 11.5 | 11.2 |
| 18 | 20.0 | ... | 17.0 | ... | 16.1 | 15.5 | 14.8 | 14.1 | 13.8 | 13.5 | 13.2 | 12.9 |
| | 17.0 | ... | 14.2 | ... | 12.7 | 11.7 | 11.0 | 10.4 | 10.2 | 10.0 | 9.8 | 9.6 |

pg. 90

pg. 92

note: lower 17 ksi values include joint efficiency $E = 0.85$ (N.A. here)

$$S_{TP304} := 20 \text{ ksi}$$

Flange is fabricated (typically) from 304 plate. Strength of 304 plate, also from Section II, Materials pgs. 90,92:

| Maximum Allowable Stress, ksi (Multiply by 1000 to Obtain psi), for Metal Temperature, °F, Not Exceeding | | | | | | | | | | | | |
|--|------------|-----|------|-----|------|------|------|------|------|------|------|------|
| Line No. | -20 to 100 | 150 | 200 | 250 | 300 | 400 | 500 | 600 | 650 | 700 | 750 | 800 |
| 1 | 20.0 | ... | 20.0 | ... | 18.9 | 18.3 | 17.5 | 16.6 | 16.2 | 15.8 | 15.5 | ... |
| 2 | 20.0 | ... | 16.7 | ... | 15.0 | 13.8 | 12.9 | 12.3 | 12.0 | 11.7 | 11.5 | ... |
| 3 | 20.0 | ... | 16.7 | ... | 15.0 | 13.8 | 12.9 | 12.3 | 12.0 | 11.7 | 11.5 | 11.2 |
| 4 | 20.0 | ... | 20.0 | ... | 18.9 | 18.3 | 17.5 | 16.6 | 16.2 | 15.8 | 15.5 | 15.2 |

$$S_{304} := 20000 \text{ psi}$$

wall thickness

inner radius

$$t_{\text{neck}} := .065 \text{ in} \quad R_{i_neck} := 1.0 \text{ in}$$

$$t_{\text{neck_min_circ}} := \frac{P_{MAWP} R_{i_neck}}{S_{304} E_w - 0.6 P_{MAWP}}$$

$$t_{\text{neck_min_circ}} = 0.025 \text{ in} \quad \text{OK}$$

$$t_{\text{neck_min_long}} := \frac{P_{\text{MAWP}} \cdot R_{i_neck}}{2S_{304} \cdot E_w + 0.4P_{\text{MAWP}}} \quad t_{\text{neck_min_long}} = 0.012 \text{ in} \quad \text{OK}$$

5. Spool

A connecting spool will be attached to the central 2.75" CF integral flange of the 350 psi MOP head. This spool will carry signal and power cabling to a Kimball Physics octagon vacuum chamber (AKA octagon) having (8) 2.75" CF ports. The spool has a 2.75" CF flange on one end and a 6" CF flange on the other end. To prevent additional loading of the tube from impact or handling forces applied to the octagon or attached cabling, the octagon will be secured by an angle bracket to the table top, which is a 3/4" thick aluminum plate. See figs 3, 4. We include moment from static weight of octagon and cabling per subsection UG-22 Loadings:

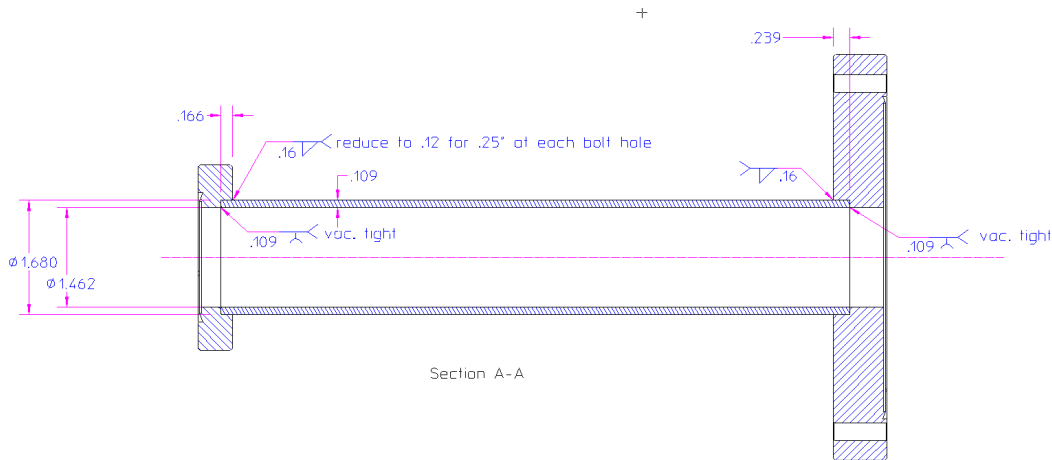


Fig. 10, Spool cross section

Spool Tube

Spool tube is a 1.25" schedule 10S pipe TP304 stainless steel, per ASME SA-312 specification (ASTM A 312)

spool tube diameter, length, thickness, inner radius:

$$d_{o_sp_tube} := 1.66 \text{ in} \quad l_{\text{tube}} := 9.5 \text{ in} \quad t_{\text{sp_tube}} := .109 \text{ in} \quad (\text{from})$$

$$d_{i_sp_tube} := d_{o_sp_tube} - 2t_{\text{sp_tube}} \quad R_{i_sp_tube} := 0.5d_{i_sp_tube} \quad R_{i_sp_tube} = 0.721 \text{ in}$$

First we calculate minimum thickness required for tube to support weight of octagon and cables. This weight load occurs before the angle bracket restraint can be tightened and is "frozen in by the bracket" before pressure is applied. The load produces a bending moment on the tube which is highest where it is welded to the 2.75 in CF flange. This results in a longitudinal stress. We will then add this minimum thickness to that calculated for longitudinal stress due to pressure.

Weights:

octagon cabling and feedthrus CF flanges source insertion tube and flange

$$W_{\text{oct}} := 13 \text{ lbf} \quad W_{\text{cables}} := 5 \text{ lbf} \quad W_{6\text{in_CF}} := 5.5 \text{ lbf} \quad W_{\text{so_tube}} := 2 \text{ lbf} \quad l_{\text{oct}} = 0.076 \text{ m}$$

$$W_{\text{cp_tot}} := W_{\text{oct}} + W_{\text{cables}} + 2 \cdot W_{6\text{in_CF}} + W_{\text{so_tube}}$$

$$M_{\text{sp_tube}} := (l_{\text{tube}} + 0.5l_{\text{oct}}) \cdot W_{\text{cp_tot}} \quad M_{\text{sp_tube}} = 341 \text{ lbf} \cdot \text{in}$$

$$I_{\text{sp_tube}} := \frac{\pi}{64} (d_{o_sp_tube}^4 - d_{i_sp_tube}^4) \quad I_{\text{sp_tube}} = 0.16 \text{ in}^4$$

Engineering Note

$$\sigma_{\text{sp_tube_mom}} := \frac{M_{\text{sp_tube}} \cdot 0.5 d_{\text{o_sp_tube}}}{I_{\text{sp_tube}}} \quad \sigma_{\text{sp_tube_mom}} = 1763 \text{ psi}$$

Since ASME Pressure Vessel code calculates required thickness, we can perform a similar calculation for the minimum thickness required to withstand the applied bending moment and add this thickness to that require for pressure containment. Using an alternative approximate formula for moment of Inertia, I (using average diameter and thickness):

$$d_{\text{avg_sp_tube}} := 0.5(d_{\text{i_sp_tube}} + d_{\text{o_sp_tube}})$$

$$I_{\text{sp_tube2}} := \frac{\pi}{16} d_{\text{avg_sp_tube}}^3 \cdot t$$

Note: Equations (assignments) which have a small black square in their upper right corner are disabled (not active).

$$\sigma := \frac{M \cdot c}{I} \quad \sigma := \frac{M \cdot c}{\frac{\pi}{16} \cdot d^3 \cdot t} \quad \sigma := S \cdot E$$

Solving for t (we need weld efficiency E): $E_{\text{w_fw}} := 0.55$ double fillet weld from Table UW-12 (see weld calc below)

$$t_{\text{sp_tube_M}} := \frac{M_{\text{sp_tube}} \cdot 0.5 d_{\text{avg_sp_tube}}}{\frac{\pi}{16} d_{\text{avg_sp_tube}}^3 \cdot S_{\text{TP304}} \cdot E_{\text{w_fw}}} \quad t_{\text{sp_tube_M}} = 0.033 \text{ in}$$

Minimum tube thickness required for pressure load, as above, from UG-27:

$$t_{\text{sp_tube_min_circ}} := \frac{P_{\text{MAWP}} \cdot R_{\text{i_sp_tube}}}{S_{\text{TP304}} \cdot E_{\text{w_fw}} - 0.6 \cdot P_{\text{MAWP}}} \quad t_{\text{sp_tube_min_circ}} = 0.023 \text{ in} \quad \text{OK}$$

$$t_{\text{sp_tube_min_long}} := \frac{P_{\text{MAWP}} \cdot R_{\text{i_sp_tube}}}{2 S_{\text{TP304}} \cdot E_{\text{w_fw}} + 0.4 P_{\text{MAWP}}} \quad t_{\text{sp_tube_min_long}} = 0.011 \text{ in} \quad \text{OK}$$

Adding the two minimum thicknesses required for longitudinal stress:

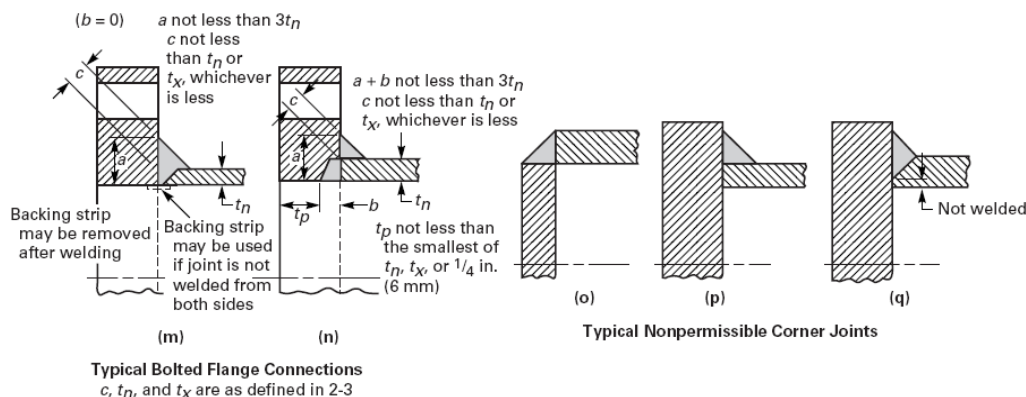
$$t_{sp_tube_long_total} := t_{sp_tube_min_long} + t_{sp_tube_M} \quad t_{sp_tube_long_total} = 0.044 \text{ in} \quad \text{OK}$$

This total required thickness is greater than that required for circumferential pressure, but still less than actual thickness.

Weld design:

From fig. UW-12 welds on both ends of tube are type 4 double full fillet welds, Category C weld (subsection UW-9 Design of Welded Joints, fig. UW-3) of type (n) below and must conform to rules in the figure

FIG. UW-13.2 ATTACHMENT OF PRESSURE PARTS TO FLAT PLATES TO FORM A CORNER JOINT (CONT'D)



weld dimensions:

$$\begin{array}{ll} \text{outer} & \text{inner} \\ h_{o_sp} := .16 \text{ in} & h_{i_sp} := .082 \text{ in} \end{array}$$

dimensions for fig (n) above:

$$\begin{array}{lll} c_{sp} := \frac{\sqrt{2}}{2} h_{o_sp} & c_{sp} = 0.113 \text{ in} & t_{n_sp} := t_{sp_tube} \\ a_{sp} := t_{sp_tube} + h_{o_sp} & a_{sp} = 0.269 \text{ in} & b_{sp} := h_{i_sp} \end{array}$$

weld criteria for fig (n) above:

$$\begin{array}{lll} c_{sp} = 0.113 \text{ in} & > & t_{n_sp} = 0.109 \text{ in} \quad \text{OK} \\ a_{sp} + b_{sp} = 0.351 \text{ in} & > & 3t_{n_sp} = 0.327 \text{ in} \quad \text{OK} \end{array}$$

CF flange calcs

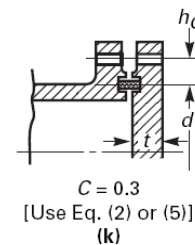
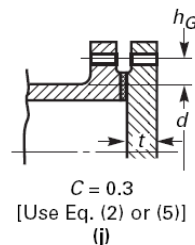
First we consider blank flanges, then consider those with central openings no larger than $0.5D$; these are both considered flat unstayed heads. This is the case for the 6 in CF flange of the spool connecting to the octagon, and also for the 6 inch CF flange on the back of the octagon, which will have a central 2.75CF (1.5in dia) opening. From subsection UG-34, Unstayed Flat Heads and Covers :

(2) The minimum required thickness of flat unstayed circular heads, covers and blind flanges shall be calculated by the following formula:

$$t = d \sqrt{CP/SE} \quad (1)$$

except when the head, cover, or blind flange is attached by bolts causing an edge moment [sketches (j) and (k)] in which case the thickness shall be calculated by

$$t = d \sqrt{CP/SE + 1.9Wh_G/SEd^3} \quad (2)$$



We can use mathCAD's ability to analyze a large number of CF flanges simultaneously. The following calculations are parallel calculations (not matrix or vector calcs). Read straight across from desired flange size, OD_{CF} , in order to find associated quantities:

| Flange size | Number of bolts | Knife edge diameter | |
|---|---|--|---|
| $OD_{CF} := \begin{pmatrix} 1.33 \\ 2.125 \\ 2.75 \\ 3.375 \\ 4.5 \\ 4.625 \\ 6 \\ 8 \\ 10 \\ 13.25 \end{pmatrix} \text{ in}$ | $N_{CF} := \begin{pmatrix} 6 \\ 4 \\ 6 \\ 8 \\ 8 \\ 10 \\ 16 \\ 20 \\ 24 \\ 30 \end{pmatrix}$ | $d_{ke} := \begin{pmatrix} .72 \\ 1.15 \\ 1.65 \\ 2.25 \\ 2.75 \\ 3.25 \\ 4.54 \\ 6.25 \\ 8.54 \\ 11.5 \end{pmatrix} \text{ in}$ | $\begin{matrix} <- \text{checked} \\ <- \text{checked} \\ <- \text{checked} \\ <- \text{checked} \\ <- \text{checked} \end{matrix}$ |

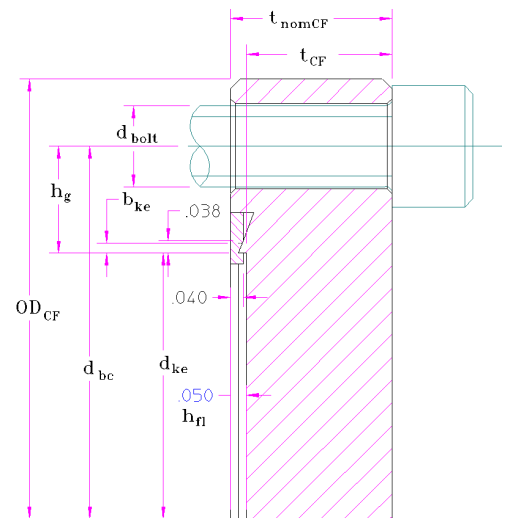


Fig. 11 CF (conflat) flange dimensions

| Flange size | Bolt circle dia. | Flange thickness | Bolt dia. | Height of bolt flange |
|--|---|---|--|---|
| $OD_{CF} = \begin{pmatrix} 1.33 \\ 2.125 \\ 2.75 \\ 3.375 \\ 4.5 \\ 4.625 \\ 6 \\ 8 \\ 10 \\ 13.25 \end{pmatrix} \text{ in}$ | $d_{bc} := \begin{pmatrix} 1.062 \\ 1.625 \\ 2.312 \\ 2.85 \\ 3.628 \\ 4.03 \\ 5.128 \\ 7.128 \\ 9.128 \\ 12.06 \end{pmatrix} \text{ in}$ | $t_{nomCF} := \begin{pmatrix} .285 \\ .47 \\ .5 \\ .62 \\ .68 \\ .75 \\ .78 \\ .88 \\ .97 \\ 1.12 \end{pmatrix} \text{ in}$ | $d_{bolt} := \begin{pmatrix} .16 \\ .25 \\ .3125 \\ .3125 \\ .3125 \\ .3125 \\ .3125 \\ .3125 \\ .3125 \\ .375 \end{pmatrix} \text{ in}$ | $h_{fl} := \begin{pmatrix} .05 \\ .05 \\ .05 \\ .05 \\ .05 \\ .05 \\ .05 \\ .05 \\ .05 \\ .05 \end{pmatrix} \text{ in}$ |

Bolt Load W:

We have several choices here, use the flange mfr.'s recommended bolt torque, a typical fastener torque (T_{CF_SAE5}), a torque found to pull flanges together (see ANL note in Appendix) or use a value bolt torque (T_{MAWP}) back calculated to withstand the required pressure (times a suitable safety factor) without exceeding

Engineering Note

ASME allowable flange stress for loose flanges, which the 2.75 OD flange is. This is the controlling configuration, and is treated in the section below for Flanges with Large Central Openings. It turns out that higher torques are not necessarily better, the additional edge moment creates flange stresses higher than allowed. If the joint fully closes (flange faces fully touching under bolts), then the joint design is changed and edge moment is reduced or eliminated, however this is not a reliably achievable condition. The Appendix contains a note testing this method (no pressure tests however). We use this back calculated torque T_{rec} (recommended torque) below by assigning T_{rec} to T_{CF} :

Torques, bolt

$$OD_{CF} = \begin{pmatrix} 1.33 \\ 2.125 \\ 2.75 \\ 3.375 \\ 4.5 \\ 4.625 \\ 6 \\ 8 \\ 10 \\ 13.25 \end{pmatrix} \text{ in} \quad T_{CF_ANL} := \begin{pmatrix} 40 \\ 163 \\ 163 \\ 197 \\ 217 \\ 190 \\ 217 \\ 246 \\ 260 \\ 330 \end{pmatrix} \text{ lbf} \cdot \text{in} \quad \begin{matrix} \text{from ref. 3,} \\ \text{ANL CF} \\ \text{pressure} \\ \text{capacity} \\ \text{document,} \\ \text{torque to} \\ \text{pull CF} \\ \text{flanges fully} \\ \text{together} \end{matrix} \quad T_{CF_SAE5} := \begin{pmatrix} 4 \\ 10 \\ 19 \\ 19 \\ 19 \\ 19 \\ 19 \\ 19 \\ 19 \\ 30 \end{pmatrix} \text{ lbf} \cdot \text{ft} \quad T_{rec} := \begin{pmatrix} .65 \\ 5.5 \\ 4 \\ 7 \\ 8.4 \\ 8.4 \\ 9.5 \\ 7 \\ 11 \\ 19 \end{pmatrix} \text{ lbf} \cdot \text{ft}$$

$$T_{CF} := T_{rec}$$

Total Bolt Load:

$$W_{CF} := \frac{N_{CF} \cdot 5 T_{CF}}{d_{bolt}} \quad OD_{CF} = \begin{pmatrix} 1.33 \\ 2.125 \\ 2.75 \\ 3.375 \\ 4.5 \\ 4.625 \\ 6 \\ 8 \\ 10 \\ 13.25 \end{pmatrix} \text{ in} \quad W_{CF} = \begin{pmatrix} 1463 \\ 5280 \\ 4608 \\ 10752 \\ 12902 \\ 16128 \\ 29184 \\ 26880 \\ 50688 \\ 91200 \end{pmatrix} \text{ lbf}$$

Engineering Note

Flange Thickness,
effective:

$$t_{CF} := \overrightarrow{(t_{nomCF} - h_{fl})}$$

$$OD_{CF} = \begin{pmatrix} 1.33 \\ 2.125 \\ 2.75 \\ 3.375 \\ 4.5 \\ 4.625 \\ 6 \\ 8 \\ 10 \\ 13.25 \end{pmatrix} \text{ in} \quad t_{CF} = \begin{pmatrix} 0.235 \\ 0.42 \\ 0.45 \\ 0.57 \\ 0.63 \\ 0.7 \\ 0.73 \\ 0.83 \\ 0.92 \\ 1.07 \end{pmatrix} \text{ in}$$

radial distance from
gasket load center to
bolt circle:

$$h_g := 0.5 \overrightarrow{(d_{bc} - d_{ke})}$$

$$OD_{CF} = \begin{pmatrix} 1.33 \\ 2.125 \\ 2.75 \\ 3.375 \\ 4.5 \\ 4.625 \\ 6 \\ 8 \\ 10 \\ 13.25 \end{pmatrix} \text{ in} \quad h_g = \begin{pmatrix} 0.171 \\ 0.238 \\ 0.331 \\ 0.3 \\ 0.439 \\ 0.39 \\ 0.294 \\ 0.439 \\ 0.294 \\ 0.28 \end{pmatrix} \text{ in}$$

$$E := 1 \quad C_j := 0.3$$

Solving for pressure in eq (2) above:

$$P_j := \frac{S_{304} \cdot E}{C_j} \overrightarrow{\left(\frac{t_{CF}^2}{d_{ke}^2} - \frac{1.9 \cdot W_{CF} \cdot h_g}{S_{304} \cdot E \cdot d_{ke}^3} \right)}$$

$$P_j = \begin{pmatrix} 2858 \\ 3670 \\ 2808 \\ 2485 \\ 1774 \\ 1932 \\ 1143 \\ 870 \\ 622 \\ 471 \end{pmatrix} \text{ psi}$$

All pressures are greater than:

$$P_{MAWP} = 350 \text{ psi}$$

so all CF blank flanges are suitable for use

CF gasket calculationsFrom Appendix 2 Section VIII-Div. 1 Rules for Bolted Flange Connections with Ring type Gaskets subsection 2-5, Bolt Loads:

Engineering Note

The required bolt load for the operating conditions W_{m1} is determined in accordance with eq. (1).

$$\begin{aligned} W_{m1} &= H + H_p \\ &= 0.785G^2P + (2b \times 3.14GmP) \end{aligned} \quad (1)$$

(2) Before a tight joint can be obtained, it is necessary to seat the gasket or joint-contact surface properly by applying a minimum initial load (under atmospheric temperature conditions without the presence of internal pressure), which is a function of the gasket material and the effective gasket area to be seated. The minimum initial bolt load required for this purpose W_{m2} shall be determined in accordance with eq. (2).

$$W_{m2} = 3.14bGy \quad (2)$$

where G is the gasket diameter

for flat copper gaskets (from Table 2-5.1):

$$m_{Cu_flat} := 4.75 \quad y_{Cu_flat} := 13000\text{psi}$$

effective width b is taken to be 80% of the width of the interference (.0384 in) of the knife edge (to allow for less than full joint closure) and the gasket (.08" thk.):

$$b_{ke} := 80\% \cdot .0384\text{in} \quad .0384\text{ in. measured from 2.75 in flange MDC CAD model; assume same for all flanges}$$

$$b_{ke} = 0.031\text{ in}$$

$$G := d_{ke} + 2b_{ke} \quad \text{outer diameter of effective compressed gasket area}$$

solving eq (1) above for maximum pressure, (in two stages, to allow concurrent calculation)

$$P_{m1} := \frac{1}{\left(0.785G^2 + 2\pi b_{ke} \cdot m_{Cu_flat} \cdot G\right)}$$

$$P_{m1} := \left(P_{m1} \cdot W_{CF}\right)$$

and eq(2):

$$W_{m2} := 3.14b_{ke} \cdot G \cdot y_{Cu_flat}$$

Engineering Note

| | | | | | | | | | | | | |
|--------------------|---|----|-------------------|---|-----|-------------------|---|-----|------------|-------------------|---|-----|
| OD _{CF} = | 1.33 2.125 2.75 3.375 4.5 4.625 6 8 10 13.25 | in | P _{m1} = | 1223 2333 1191 1703 1469 1385 1400 725 768 789 | psi | W _{m2} = | 980 1519 2146 2899 3526 4153 5770 7914 10786 14498 | lbf | compare--> | W _{CF} = | 1463 5280 4608 10752 12902 16128 29184 26880 50688 91200 | lbf |
|--------------------|---|----|-------------------|---|-----|-------------------|---|-----|------------|-------------------|---|-----|

We see that the gasket preloading requirement W_{m2} is easily exceeded by the actual preload W_{CF} , and that the gaskets can hold far higher pressure than necessary (350 psi).

CF Blank Flange maximum opening diameter:

UG-39(b) Single and multiple openings in flat heads that have diameters equal to or less than one-half the head diameter may be reinforced as follows:

UG-39(b)(1) Flat heads that have a single opening with a diameter that does not exceed one-half the head diameter or shortest span, as defined in UG-34, shall have a total cross-sectional area of reinforcement for all planes through the center of the opening not less than that given by the formula

$$A = 0.5dt + t_n(1 - f_{r1})$$

where d , t_n , and f_{r1} are defined in UG-37 and t in UG-34.

The 2.75 inch CF flange of the spool does not meet the above requirement, and is considered a loose flange, in a subsequent section. Nevertheless it is useful at this point to check to see if flanges that meet the requirement above are adequately reinforced for MAWP. Assume in formula above, that nozzle thickness is zero. First we determine minimum thickness required: t (here t_{min}). From subsection UG-34 :

from sketches (j), (k) $C := 0.3$

weld efficiency: $E := 1$ (assume stock flanges only)

$$t_{min_CF} := \left(OD_{CF} \sqrt{\frac{C \cdot P_{MAWP}}{S_{304} \cdot E} + \frac{1.9 W_{CF} h_g}{S_{304} \cdot E \cdot OD_{CF}^3}} \right)$$

minimum flange thickness

thickness available for reinforcement

(2) The minimum required thickness of flat unstayed circular heads, covers and blind flanges shall be calculated by the following formula:

$$t = d \sqrt{CP/SE} \quad (1)$$

except when the head, cover, or blind flange is attached by bolts causing an edge moment [sketches (j) and (k)] in which case the thickness shall be calculated by

$$t = d \sqrt{CP/SE + 1.9 W h_g / SE d^3} \quad (2)$$

Engineering Note

$$t_{\min_CF} = \begin{pmatrix} 0.165 \\ 0.282 \\ 0.304 \\ 0.388 \\ 0.475 \\ 0.491 \\ 0.57 \\ 0.69 \\ 0.816 \\ 1.051 \end{pmatrix} \text{ in} \quad t_{CF} - t_{\min_CF} = \begin{pmatrix} 0.07 \\ 0.138 \\ 0.146 \\ 0.182 \\ 0.155 \\ 0.209 \\ 0.16 \\ 0.14 \\ 0.104 \\ 0.019 \end{pmatrix} \text{ in}$$

Area available for reinforcement

$$A_{\text{rein_CF}} := \overrightarrow{[0.5 \cdot OD_{CF} \cdot (t_{CF} - t_{\min_CF})]} \quad A_{\text{rein_CF}} = \begin{pmatrix} 0.047 \\ 0.146 \\ 0.201 \\ 0.307 \\ 0.348 \\ 0.482 \\ 0.48 \\ 0.56 \\ 0.518 \\ 0.125 \end{pmatrix} \text{ in}^2$$

Maximum central opening diameter:

$$d_{i_max_CF} := \frac{A_{\text{rein_CF}}}{t_{CF}} \quad d_{i_max_CF} = \begin{pmatrix} 0.199 \\ 0.348 \\ 0.446 \\ 0.539 \\ 0.553 \\ 0.689 \\ 0.658 \\ 0.675 \\ 0.563 \\ 0.117 \end{pmatrix} \text{ in}$$

Note that the above bolt torques, calculated to give maxim allowable flange stress, essentially "use up" the reserve thickness in the flange so that only small central openings are permitted. These torques can be modified if needed to give larger central openings.

CF flanges with large central openings (ID>0.5OD):

For the small 2.75 inch flange on the spool (or for any central opening larger than that computed above) we consider this as a loose flange, per mandatory Appendix 2 of Section VIII- Div. 1, Rules for Bolted Flange Connections with Ring-type Gaskets, subsection 2-4 Circular Flange Types, as the attached tube does not contribute any strength to the flange. From subsection 2-6 Flange Moments:

Flange Moment

$$M_0 := W \cdot \frac{(C - G)^2}{2} \quad M_0 := \overrightarrow{(W_{CF} \cdot h_g)} \quad M_0 = \begin{pmatrix} 250 \\ 1254 \\ 1525 \\ 3226 \\ 5664 \\ 6290 \\ 8580 \\ 11800 \\ 14902 \\ 25536 \end{pmatrix} \text{ lbf} \cdot \text{in}$$

Flange Stresses:

From mandatory Appendix 2, subsection 2-7 Flange Stresses:

Engineering Note

First, compute several factors:

$$A := OD_{CF} \quad A = \begin{pmatrix} 1.33 \\ 2.125 \\ 2.75 \\ 3.375 \\ 4.5 \\ 4.625 \\ 6 \\ 8 \\ 10 \\ 13.25 \end{pmatrix} \text{ in} \quad \text{Flange maximum inner diameter (from MDC catalogue)} \quad ID_{CF} := \begin{pmatrix} .625 \\ 1 \\ 1.75 \\ 2 \\ 2.5 \\ 3 \\ 4 \\ 6 \\ 8 \\ 10.75 \end{pmatrix} \text{ in} \quad B := ID_{CF} \quad B = \begin{pmatrix} 0.625 \\ 1 \\ 1.75 \\ 2 \\ 2.5 \\ 3 \\ 4 \\ 6 \\ 8 \\ 10.75 \end{pmatrix} \text{ in}$$

$$K := \frac{A}{B} \quad K = \begin{pmatrix} 2.128 \\ 2.125 \\ 1.571 \\ 1.688 \\ 1.8 \\ 1.542 \\ 1.5 \\ 1.333 \\ 1.25 \\ 1.233 \end{pmatrix} \quad Y := \left[\frac{1}{K-1} \left[0.66845 + 5.717 \cdot \left(\frac{K^2 \cdot \log(K)}{K^2 - 1} \right) \right] \right] \quad Y = \begin{pmatrix} 2.726 \\ 2.731 \\ 4.47 \\ 3.885 \\ 3.474 \\ 4.659 \\ 4.961 \\ 6.903 \\ 8.83 \\ 9.406 \end{pmatrix}$$

Flange Stresses (eqs. 9):

Tangential:

$$S_T := \frac{Y \cdot M_0}{t_{CF}^2 B} \quad S_T = \begin{pmatrix} 19751 \\ 19414 \\ 19240 \\ 19284 \\ 19832 \\ 19937 \\ 19969 \\ 19708 \\ 19433 \\ 19516 \end{pmatrix} \text{ psi}$$

$$S_{304} = 2 \times 10^4 \text{ psi}$$

$$S_T < S_{304} \quad \text{OK}$$

Radial and Axial stresses = 0

6. Kimball Physics Octagon

This is a 304 stainless steel machined octagonal vacuum chamber. It has eight 2.75 in CF ports, which will be used for feedthroughs and as above, we use subsection UG-27:

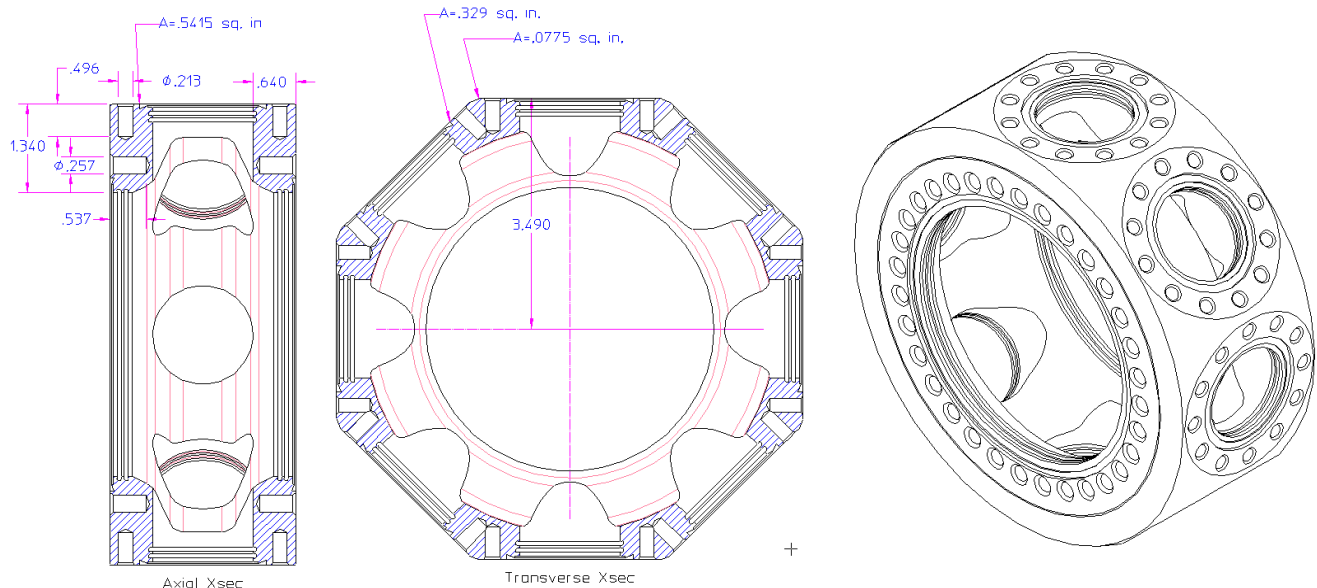


Fig. 12 Kimball Physics octagonal vacuum chamber ("octagon")

Areas, minimum of half cross sections:

$$A_{\text{circ}} := 2 \cdot 0.5415 \text{ in}^2 \quad A_{\text{circ}} = 1.083 \text{ in}^2 \quad A_{\text{long}} := 4 \cdot (0.329 + 0.0775) \text{ in}^2 \quad A_{\text{long}} = 1.626 \text{ in}^2$$

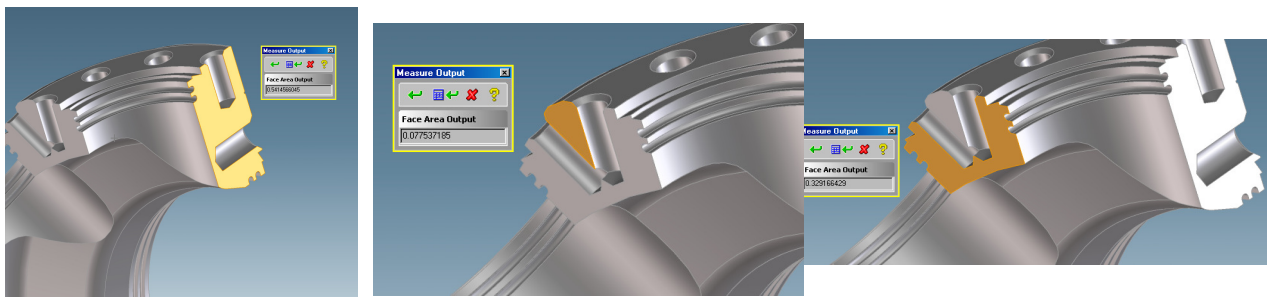


Fig. 13, section area measurements, octagon

Radii: $R_{i_oct} := 3.5 \text{ in}$ note: this is largest radius (at the 2.75 in CF flanges)

Equivalent thicknesses (by dividing out radius)

$$t_{\text{oct_circ}} := \frac{A_{\text{circ}}}{R_{i_oct}} \quad t_{\text{oct_circ}} = 0.309 \text{ in}$$

$$t_{\text{oct_long}} := \frac{A_{\text{long}}}{R_{i_oct}} \quad t_{\text{oct_long}} = 0.465 \text{ in}$$

Weld Efficiency:

$$E = 1 \quad \text{machined, not welded}$$

Minimum equivalent thicknesses:

$$t_{\text{oct_min_circ}} := \frac{P_{\text{MAWP}} \cdot R_{i_oct}}{S_{304} \cdot E - 0.6 \cdot P_{\text{MAWP}}} \quad t_{\text{oct_min_circ}} = 0.062 \text{ in} \quad \text{compare --> } t_{\text{oct_circ}} = 0.309 \text{ in}$$

$$t_{\text{oct_min_long}} := \frac{P_{\text{MAWP}} \cdot R_{i_oct}}{2S_{304} \cdot E + 0.4P_{\text{MAWP}}}$$

$$t_{\text{oct_min_long}} = 0.031 \text{ in} \quad \text{compare -->} \quad t_{\text{oct_long}} = 0.465 \text{ in}$$

7. Source Tube

This is a closed end tube welded to a 2.75 " CF flange for the purpose of introducing a small radioactive source into the chamber without opening up the vessel. The vessel pressure acts on the end and outer diameter of the tube, thus tube buckling is a possible failure mode. We use subsection UG-28 Thickness of Shells and Tubes Under External Pressure:

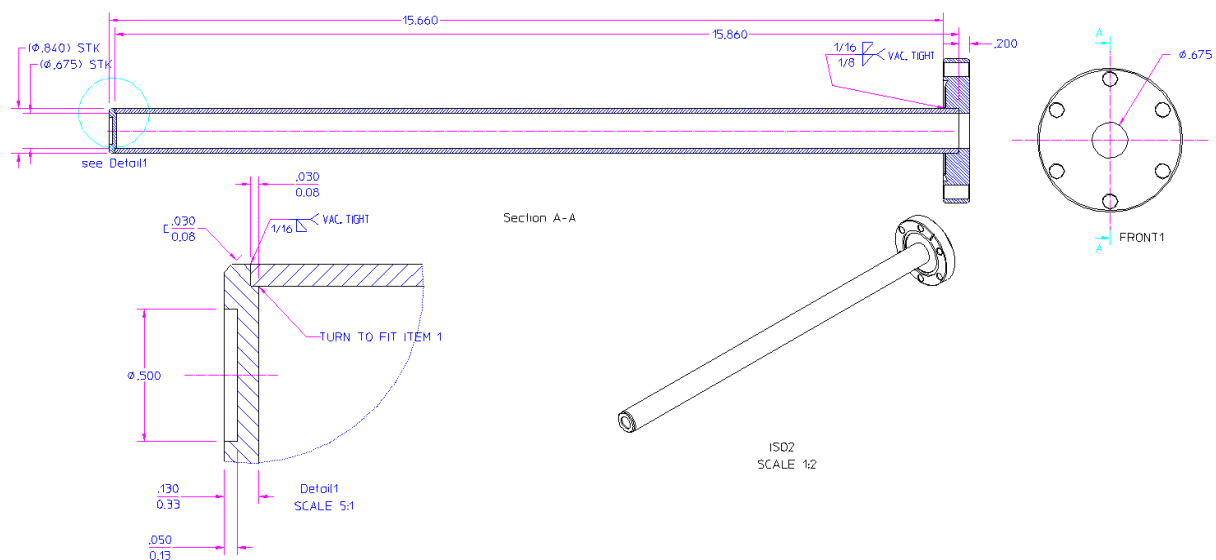


Fig 14, Source Insertion Tube

Tube is a 1/2 in. schedule 10S, ASME SA312 TP304 stainless pipe

$$D_{o_st} := .84 \text{ in} \quad L_{st} := 16 \text{ in} \quad t_{st} := .083 \text{ in}$$

$$\text{External pressure, maximum: } P_{st} := -P_{\text{MAWP}}$$

The maximum allowable working external pressure is determined by the following procedure:

Compute the following two dimensionless constants:

$$\frac{L_{st}}{D_{o_st}} = 19 \quad \frac{D_{o_st}}{t_{st}} = 10$$

From the above two quantities, we find, from fig. G in subpart 3 of Section II, the factor:

$$A_{st} := .012$$

Using the factor A in the applicable material (304 S.S.) chart (HA-1) in Subpart 3 of Section II, Part D, we find the factor B:

$$B_{st} := 14000 \text{ psi}$$

A08 FIG. G GEOMETRIC CHART FOR COMPONENTS UNDER EXTERNAL OR COMPRESSIVE LOADINGS (FOR ALL MATERIALS) [NOTE (14)]

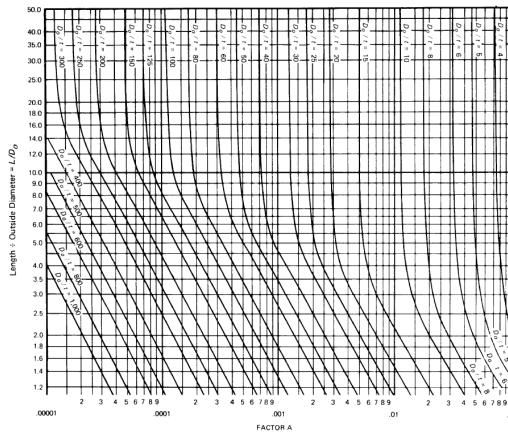
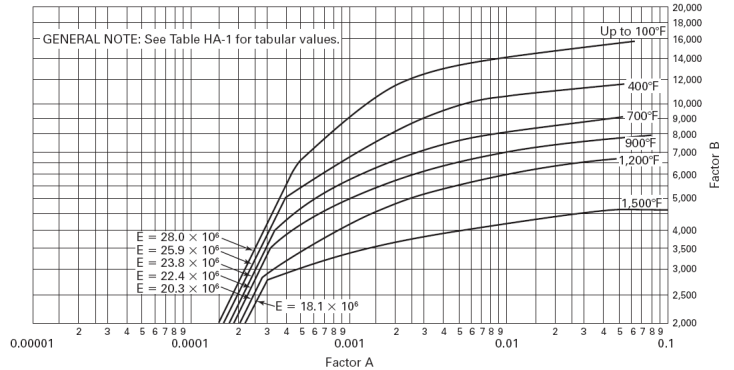


FIG. HA-1 CHART FOR DETERMINING SHELL THICKNESS OF COMPONENTS UNDER EXTERNAL PRESSURE DEVELOPED FOR AUSTENITIC STEEL 18Cr-8Ni, TYPE 304



The maximum allowable working external pressure is then given by :

$$P_{\max_st} := \frac{4B_{st}}{3 \left(\frac{D_{o_st}}{t_{st}} \right)} \quad P_{\max_st} = 1844 \text{ psi (external)}$$

$$P_{\max_st} > 1.5P_{MAWP} \quad \text{so the source tube is safe from buckling under test pressure load}$$

There is a bending moment on the tube where welded to the flange from the weight of the source collimator

Tube weight:

$$W_{st} := \rho_{SS} \cdot \pi \cdot D_{o_st} \cdot t_{st} \cdot L_{st} \cdot g \quad \rho_{SS} := 8 \frac{\text{gm}}{\text{cm}^3} \quad W_{st} = 1.013 \text{ lbf}$$

Collimator is either tungsten (19.3 gm/cc) or hevimet (19gm/cc). Maximum possible dimensions:

$$l_{col} := L_{st} \quad d_{col} := D_{o_st} - 2t_{st} \quad d_{col} = 0.674 \text{ in} \quad \rho_W := 19.3 \frac{\text{gm}}{\text{cm}^3}$$

Weight of collimator :

$$W_{col} := \frac{\pi}{4} d_{col}^2 \cdot l_{col} \cdot \rho_W \cdot g \quad W_{col} = 3.98 \text{ lbf}$$

Moment on tube

Moment of Inertia, source tube

$$M_{st} := W_{col} \cdot (L_{st} - 0.5l_{col}) + W_{st} \cdot 0.5L \quad M_{st} = 39.9 \text{ lbf} \cdot \text{in} \quad I_{st} := \frac{\pi}{64} (D_{o_st}^4 - d_{col}^4) \quad I_{st} = 0.014 \text{ in}^4$$

Stress, bending:

$$\sigma_{st} := \frac{M_{st} \cdot 0.5D_{o_st}}{I_{st}} \quad \sigma_{st} = 1172 \text{ psi} \quad \text{negligible}$$

Axial Compressive Stress on tube:

The tube is relatively long and may be subject to Euler buckling. ASME code treats this as an alternate maximum allowable stress, rather than a maximum loading. From subsection UG-23 Maximum Allowable Stress Values, maximum allowable axial compressive stress, is smaller of :

S, from above (20 ksi) or:
B, as computed below

First, determine minimum required thickness (not sure why actual thickness is not used here):

$$t_{st_min} := .023 \text{ in} \quad \text{found using external pressure formula above for 500 psi (test pressure)}$$

Then, determine the quantity:

$$A_{stl} := \frac{0.125}{\left[\frac{(0.5D_{o_st})}{t_{st_min}} \right]} \quad A_{stl} = 0.007$$

From Subpart 3 of Section II, Part D, chart HA-1:

$$B_{st_max} := 13500 \text{ psi}$$

Actual compressive stress (at test pressure of 1.5x MAWP):

$$\sigma_{st_ax} := \frac{1.5P_{MAWP} \cdot D_{o_st}}{4t_{st}} \quad \sigma_{st_ax} = 1328 \text{ psi} \quad \text{OK}$$

Welds are nonstructural, and do not carry pressure loads (other than vacuum); they are primarily for sealing.

Window stress (mtl:304SS):

From subsection UG-34, Unstayed Flat Heads and Covers :

(2) The minimum required thickness of flat unstayed circular heads, covers and blind flanges shall be calculated by the following formula:

$$t_w := 1.5 \text{ mm} \quad R_w := .25 \text{ in}$$

$$E_w = 0.7 \quad (\text{outside HAZ, but use any})$$

$$t = d \sqrt{CP/SE} \quad (1)$$

$$t_{min_w} := 2R_w \cdot \sqrt{\frac{C \cdot P_{MAWP}}{S_{304} \cdot E_w}}$$

$$t_{min_w} = 1.1 \text{ mm} \quad \text{OK}$$

8. Gas System (in detail) (Tom Miller, designer)



In operation, the procedures are sequential, unless otherwise indicated. There are steps inserted for checking valve status, **Valves** listed in **bold red** are **closed**; **Valves** listed in **nonbold green** are **open**.

a. Close V1, V2 and V10. Open R1 and R2 one turn each.

- b. Open V4, V5, V11, V13-V16. DO NOT open V6-V9.
- c. **V1 V2 V3 V4 V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17**
- d. Turn on the backing pump and convectron gauge controller
- e. When the convectron gauge reads $< 1\text{e-}2$ torr, turn on the turbo pump and cold cathode gauge controller. Open V3 and V12.
- f. When the cold cathode gauge reads $< 5\text{e-}5$ torr, open V17 and turn on the RGA.
- g. If the system pressure and RGA scan are acceptable, turn off the RGA. If not, continue to pump until the pressure improves to an acceptable level.
- h. Close V3, V4, V13-V17. Back off R1 and R2.
- i. Turn off pumps and controllers.
- j. **V1 V2 V3 V4 V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17**
- k. Proceed to step 3.

2. System pump-down with xenon in the Xenon reclamation cylinder

- a. Close V1, V2 and V10. Open R1 and R2 one turn each.
- b. Open V4, V5, V11-V13, V16. DO NOT open V6-V9.
- c. **V1 V2 V3 V4 V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17**
- d. Turn on the backing pump and convectron gauge controller
- e. When the convectron gauge reads $< 1\text{e-}2$ torr, turn on the turbo pump and cold cathode gauge controller. Open V3.
- f. When the cold cathode gauge reads $< 5\text{e-}5$ torr, open V17 and turn on the RGA.
- g. If the system pressure and RGA scan are acceptable, turn off the RGA.
- h. Close V3, V4, V13, V16 and V17. Back off R1 and R2.
- i. Turn off pumps and controllers.
- j. **V1 V2 V3 V4 V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17**
- k. Proceed to step 3.

3. Argon purge

- a. **V1 V2 V3 V4 V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17**
- b. Back off R1. Open V1
- c. Set R1 to 20psig
- d. Open V4.
- e. Wait for P3 to read > 5 psi. Open V10 1/4 turn. Argon will bleed out the 5psig relief.
- f. Wait 5 minutes, then close V10.
- g. Start pump1
- h. Once P3 reads 20psi, close V1 and V4. Back off R1.
- i. Continue pumping for desired interval.
- j. Turn off pump1.
- k. Open V10 to vent argon.
- l. When P3 reads < 6 psi, close V10, V12.
- m. **V1 V2 V3 V4 V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17**
- n. Proceed to step 4

4. Post-purge pump-down

- a. **V1 V2 V3 V4 V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17**
- b. Check that P3 reads < 6 psi. Open V10 to relieve pressure. Close V10 when done.
- c. Open V4 and crank down R1 1 turn.
- d. Start the backing pump and convectron gauge controller
- e. Slowly open V16.
- f. When the convectron gauge reads $< 1\text{e-}2$ torr, turn on the turbo pump and cold cathode gauge controller.
- g. When the cold cathode gauge reads $< 5\text{e-}5$ torr, open V17 and turn on the RGA.
- h. Close V4 and back off R1.
- i. If the system pressure and RGA scan are acceptable, turn off the RGA, close V16 and V17.
- j. Turn off pumps and controllers.
- k. **V1 V2 V3 V4 V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17**

- l. If the partial pressures are not acceptable, repeat procedure from step 3.
- m. If the Xenon reclamation cylinder is filled, proceed to step 6.

5. Xenon reclamation cylinder fill procedure

- a. **V1 V2 V3 V4 V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17**
- b. Back off R2. Open V2 and V12.
- c. Open V13 and V14. Check that V10 is closed.
- d. Set R2 to 200psig
- e. Carefully open V4
- f. Once P3 reads 200psig, close V4
- g. Read the gas temperature at the TC. When T > 15 deg C, continue
- h. Set R2 to 300psig (225psig initial)
- i. Open V4
- j. Once P3 reads 300psig (225psig initial), close V2 and back off R2.
- k. Chill C1 with LN until P4 bases out.
- l. Close V4 and V14.
- m. Open V2. Set R2 to 50psig
- n. Open V4
- o. Once P3 reads 50 psig, close V2, V4 and back off R2.
- p. Open V14.
- q. Continue to chill C1 with LN until P4 bases out.
- r. Close V13 and V14. Stop chilling C1.
- s. **V1 V2 V3 V4 V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17**
- t. Proceed to step 6

6. Chamber fill from Xenon reclamation cylinder

- a. **V1 V2 V3 V4 V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17**
- b. Close V11
- b. Back off R3. Open V14
- c. If P5 < 300psig (225psig initial) at any point in step 6, turn on heat to C1
- d. Once P5 > 300psig (225psig initial), set R3 to 200psig(150psig initial)
- e. Close V4.
- f. Open V13
- g. Open V6, V8
- h. When P3 reads 200psig, close V13
- i. Check the temperature at the TC. When T > 15 deg C, Continue
- j. Set R3 to 300psig(225psig initial)
- k. Open V13
- l. When P3= 300psig (225psig initial), close V13 and V14
- m. Close V5, V6, V8. Back off R3.
- n. TPC is ready to operate
- o. **V1 V2 V3 V4 V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17**

7. TPC operation

- a. **V1 V2 V3 V4 V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17**
- b. Open V6,V7 or V8,V9 and V11
- d. Start pump1
- e. Monitor total flow with FM1. Adjust pump controller as required
- f. Log flow and pressure at P4, if desired
- g. **V1 V2 V3 V4 V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17** (V8,V9 may be open instead of V6,V7)

8. TPC shutdown

- a. **V1 V2 V3 V4 V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17** (V8,V9 may be open instead of V6,V7)
- b. Stop pump1

- c. Close V6-V9, as required.
- d. Stop data logger
- e. V1 V2 V3 V4 V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17

9. Cryogenic Xenon reclamation from TPC

- a. V1 V2 V3 V4 V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17
- b. Open V5, V13, V14. Close V12
- c. Chill C1 with LN.
- d. Once P4 bases out, close V13.
- e. Close V14.
- f. V1 V2 V3 V4 V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17

10. Let-up to Argon

- a. V1 V2 V3 V4 V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17
- b. Back off R1. Open V1
- c. Set R1 to 15psig
- c. Open V4
- d. When P3 > 0psig, close V1. Back off R1.
- f. Open V10.
- g. Once the 5psi relief is closed, close V10, V11
- h. Proceed with disassembly of TPC. Leave 1 main flange bolt loosely in place until any residual pressure is vented.
- i. V1 V2 V3 V4 V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17

11. Replacement of Argon gas supply cylinder

- a. V1 V2 V3 V4 V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17
- b. Make certain V1 is closed. Back off R1.
- c. Disconnect R1 from Ar cylinder.
- d. Connect new Ar cylinder to R1.
- e. Crank down R1 1 turn.
- f. Open V3
- g. Start backing pump and convectron gauge
- h. When the convectron gauge reads < 1e-2 torr, turn on the turbo pump and cold cathode gauge controller.
- g. When the cold cathode gauge reads < 5e-5 torr, close V3 and turn off pumps.
- h. Back off R1.
- i. V1 V2 V3 V4 V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17

12. Replacement of Xenon gas supply cylinder

- a. V1 V2 V3 V4 V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17
- b. Make certain V2 is closed. Back off R1.
- c. Disconnect R2 from Xe cylinder.
- d. Connect new Xe cylinder to R1.
- e. Crank down R2 1 turn.
- f. Open V3
- g. Start backing pump and convectron gauge
- h. When the convectron gauge reads < 1e-2 torr, turn on the turbo pump and cold cathode gauge controller.
- g. When the cold cathode gauge reads < 5e-5 torr, close V3 and turn off pumps.
- h. Back off R2.
- i. V1 V2 V3 V4 V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17

Relief Valve Capacity

There are no credible conditions whereby a sudden pressure rise can occur. Relief valve on main pressure

vessel is a High Pressure ASME soft seal valve (McMaster-Carr P/N 5825T21):

Brass High-Pressure ASME Pop-Safety Valve

• Meet ASME Code Section VIII for air and gas.

Perfect for multistage air compressors, aftercoolers, and instrument and control lines. Valve has a brass body and seal, Vespel disc, stainless steel spring, and a pull ring for testing. It discharges to atmosphere. Temperature range is -20° to +300° F. **Connections:** NPT male bottom inlet and vented side outlet. **To Order:** Please specify set pressure: 60, 100, 250, 300, 400, 500, 750, 1000, 1500, 2000, 2500, 3000, 3500, or 4000 psi.

① Click here for additional information about the flow capacities of these valves.

Pipe Size 1/4" HL 3.78" Each 5825T21 \$71.99

Air Flow Capacities for Brass High-Pressure ASME Pop-Safety Valves



| AIR FLOW CAPACITY STANDARD CUBIC FEET PER MINUTE (SCFM) | |
|--|----------------|
| Set Pressure, psi | 5825T21 (1/4") |
| 60 | 15 |
| 100 | 23 |
| 250 | 54 |
| 300 | 64 |
| 400 | 85 |

$$\text{SCFM} := \frac{\text{ft}^3}{\text{min}} @ 1 \text{ atm}$$

$$Q_{s_250\text{psig}} := 54 \text{ SCFM} \quad \text{for air}$$

$$Q_{s_350\text{psig}} := 74 \text{ SCFM}$$

$$M_{\text{Xe}} := 136 \frac{\text{gm}}{\text{mole}} \quad M_{\text{air}} := 29 \frac{\text{gm}}{\text{mole}}$$

Converting these flow rates to Xenon:

From Fike technical bulletin TB8102:

$$Q_{s_250\text{Xe}} := Q_{s_250\text{psig}} \cdot \sqrt{\frac{M_{\text{Xe}}}{M_{\text{air}}}} \quad Q_{s_250\text{Xe}} = 0.055 \frac{\text{m}^3}{\text{s}} \quad Q_{s_250\text{Xe}} = 117 \text{ SCFM}$$

$$Q_{s_350\text{Xe}} := Q_{s_350\text{psig}} \cdot \sqrt{\frac{M_{\text{Xe}}}{M_{\text{air}}}} \quad Q_{s_350\text{Xe}} = 0.076 \frac{\text{m}^3}{\text{s}} \quad Q_{s_350\text{Xe}} = 160 \text{ SCFM}$$

For air,

$$W_a = CKAP \sqrt{\frac{M}{T}}$$

(U.S. Customary Units)

$$C = 356$$

$$M = 28.97 \text{ mol. wt.}$$

$$T = 520 \text{ when } W_a \text{ is the rated capacity}$$

(SI Units)

$$C = 27.03$$

$$M = 28.97 \text{ mol. wt.}$$

$$T = 293 \text{ when } W_a \text{ is the rated capacity}$$

For any gas or vapor,

$$W = CKAP \sqrt{\frac{M}{T}}$$

Engineering Note

TPC Gas System parts list

| ID | MFR. | Part Number | Note/Product Description | Pressure rating (psig) |
|-----------------|----------------------------------|-----------------------|---|------------------------|
| Swagelok | | | | |
| | | SS-8BG-V47-VD | 1/2" valve Female VCR | 1000 |
| | | SS-8BG-VCR-VD | 1/2" valve Male VCR | 1000 |
| | | SS-CHVCR8-1/3 | 1/2" VCR check valve 1/3 psi opening | 6000 |
| | | SS-R4M8F8-SC11 | Relief valve .25 orifice | 6000 |
| | | SS-4R3A5 | Relief valve .14 orifice | 6000 |
| | | 177-R3A-K1-A | 350-750 psi spring kit for line 6 | - |
| | | 177-R3A-K1-A | 0-350 psi spring kit for line 6 | - |
| | | 177-13K-R4-A | 0-350 psi spring kit for line 5 | - |
| | | SS-FM4RM4RF4-12 | 1/4" VCR hose M/F fittings 12" lg | 3100 |
| | | SS-4-VCR-7-8VCRF-SC11 | 1/2" to 1/4" VCR reducing adapter | 14300 |
| | | SS-8-WVCR-6-DF-SC11 | 1/2" VCR close coupling | 5800 |
| | | SS-8-VCR-T-SC11 | 1/2" VCR Tee | 10900 |
| | | Ni-8-VCR-2-SC11 | - 1/2" Ag plated Ni VCR gasket | - |
| | | Ni-4-VCR-2-SC11 | - 1/4" Ag plated Ni VCR gasket | - |
| | | SS-8-VCR-CP-SC11 | 1/2" VCR cap | - |
| | | SS-8-VCR-P-SC11 | 1/2" VCR plug | - |
| | | SS-8-VCR-9-SC11 | 1/2" VCR elbow | 10900 |
| | | SS-4-VCR-2-4-SC11 | 1/4" VCR elbow | 14300 |
| Filter | | SS-6TF2-15-SC11 | 15 micron TF type filter 3/8 MPT | 3000 |
| | | SS-8-VCR-7-6-SC11 | 3/8 NPT to 1/2" VCR female connector | 5300 |
| | | SS-8-VCR-7-8-SC11 | 1/2 NPT to 1/2" VCR female connector | 4900 |
| | | SS-4-VCR-1-4-SC11 | 1/4 NPT to 1/4" VCR male connector | 8000 |
| | | SS-8-VCR-4-SC11 | 1/2" VCR Male tube nut | - |
| | | SS-8-VCR-1-SC11 | 1/2" VCR female tube nut | - |
| | | SS-4-VCR-4-SC11 | 1/4" VCR Male tube nut | - |
| | | SS-4-VCR-1-SC11 | 1/4" VCR female tube nut | - |
| | | SS-8-VCR-3-SC11 | 1/2" VCR socket weld | 3000 |
| | | SS-6-VCR-3-SC11 | 1/2" VCR socket weld 3/8 tube | 8200 |
| | | SS-FM4RF4RF4-36 | 1/4" VCR hose F fittings 36" lg | 3100 |
| | | SS-FM4RM4RF4-48 | 1/4" VCR hose M/F fittings 48" lg | 3100 |
| | | SS-FM4RF4RF4-24H | 1/4" VCR hose F fittings 24" lg | 3100 |
| | | SS-6-RB-4-SC11 | 3/8 NPT to 1/4 NPT reducing bushing | 3000 |
| | | 6LV-8-VCR-3S-4TB7 | 1/2 VCR to 1/4" tube reducing gland | 5100 |
| | | - | 3/8 OD x .035W 316SST Tubing | 2936 |
| | | - | 1/4 OD x .035W 316SST Tubing | 4375 |
| | | SS-8-VCR-CS | 1/2" VCR cross | 10900 |
| | | SS-4-WVCR-1-4 | 1/4 NPT male to 1/4 VCR female | 10200 |
| | | SS-4-VCR-T | 1/4" VCR tee | 14300 |
| | | SS-4-VCR-CS | 1/4" VCR cross | 14300 |
| | | SS-DSV51 | 1/4" VCR diaphragm valve | 2500 |
| | | SS-4-WVCR-7-4 | 1/4" fem VCR to 1/4 fem NPT | 6600 |
| | | SS-8-VCR-3-4TSW | 1/2 VCR to 1/4" tube reducing gland | 13600 |
| | | SS-4-VCR-3 | 1/4 VCR socket weld gland | 5500 |
| | | SS-8-VCR-6-DM-4 | Double male VCR reducing union 1/2 to 1/4 | 10900 |
| | | SS-4-VCR-7-4 | 1/4 male VCR to 1/4" NPT female | 6600 |
| | | SS-4-VCR-1-00032 | 1/4 male VCR to 9/16-18 adapter | 14300 |
| | | SS-8-VCR-1-01081 | 1/2 male VCR to 9/16-18 adapter | 15000 |
| | | SS-4-VCR-3-4TA | 1/4 swage to 1/4 VCR gland | 10200 |
| P1,P2 | | 4066K418 | 0-600 psig dry gauge | 600 |
| P3 | | 4005K48 | 0-400 psig dry gauge | 400 |
| P5 | | 3852K24 | 0-2000 psig dry gauge | 2000 |
| | Acme Cryogenics (for LLNL orig.) | | | |
| C1 | C1 | | Xenon condensation cylinder | 3000 |
| | Pump Works Inc. | | | |
| P1 | PW2070 | | Positive displacement pump | 1400 |
| | SAES Pure Gas inc. | | | |
| | HP190 | | inert gas purifier | 1000 |
| | MC50 | | inert gas purifier | 1000 |
| | Carten | | | |
| V16 | HF2000 | | 2" straight thru valve | 250 |

Engineering Note

| QTY | Part Number | Description | Unit Price |
|----------|----------------------------|---------------------------------------|------------|
| | Matheson | | |
| R3 | 3818-580 | 15-350psi regulator with G type inlet | 3500 |
| | Omega | | |
| FM1, FM2 | FMA1818 | flowmeter 5slpm | 500 |
| P | MMG500V10P3C0T3A6 | 500psig pressure transducer | 500 |
| TC | EI1202105/TC-K-NPT-U-72/3" | Pipe plug TC probe | 2500 |