Muon Design Note #9

Subsystem: ☐ CCM ☐ CVM ☒ Cryoplant

TITLE: Heat Exchanger - EX-8

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DATE: March 31, 1986

OBJECTIVE:

To demonstrate that Heat Exchanger, EX-8, conforms to the room temperature pressure vessel standard, (SD-36).

DESCRIPTION:

The exchanger consists of several parallel coils of copper tubing immersed in liquid nitrogen at approximately atmospheric pressure. The coil is hung from the top plate of the nitrogen container. The container consists of a flat welded bottom plate, an eight inch Sch 10 pipe and a flat bolted top plate with five penetrations. The bottom and sides of the exchanger are surrounded by 3.5 inches of foam insulation. The top of the exchanger has a dead gas space and is not insulated.

ANALYSIS:

The Nitrogen Container

This container will not be considered a pressure vessel by laboratory standards since it will not see pressures above approximately 10 psig (=10 psid since it is not vacuum jacketed). The normal operating pressure will be approximately 1 psig. The vessel was tested to 20 psig but will be defined to have an MAWP of only 14 psig. See Appendix A for design calculations and Appendix B for pressure drop calculations. The outlet of the vessel is open to atmosphere through 20 feet of 2 inch foam insulated line and 30 feet of 4 inch uninsulated pipe. Table 1 gives the pressure ratings of the different components. See Appendix C for relief calculations on the internal piping. Appendix D addresses the problem of a rupture of the internal piping into the nitrogen container.

The Internal Piping

The internal piping consists of 3/4" Sch 10 SS pipe, 3/4" x 0.049" wall SS tubing, stainless steel fittings and 1/2" refrigeration service copper tubing. Stainless to stainless joints will be welded and stainless-to-copper and copper-to-copper joints silver soldered. The piping will normally operate in the 20 to 40 psig range. The relief is set for 85 psig and the piping has been pressure checked at 150 psig. The lowest pressure rating for any of the internal components is 630 psig. Table 2 gives the pressure ratings for the different components.

Table 1

Component	Code Allowable Stress (psi)	Thickness (in)	Internal Design Pressure (psi)	External Design Pressure (psi)
Bottom plate	18,800	0.375	92	92
8" Sch 10 shell	16,000	0.148	445	125
Top plate	18,800	0.438	31.8	31.8

Table 2

Component	Internal Design Pressure	External Design Pressure
3/4" SS pipe	2424	>500
3/4" SS tube	1970	>500
SS fittings	1586	>500
1/2 Cu tube	630	150

CONCLUSION:

It has been shown that heat exchanger EX-8 has been designed in the spirit of the ASME Code. All components are adequately designed to withstand somewhat more pressure than they will see under normal operations. The relief valve and vent pipe are of adequate size to prevent overpressurization for failure conditions.

REVIEWED BY

4/4/86

Appendix A: Shell Pressure Calculations
for Heat Exchanger EX-8

OBJECTIVE:

To determine the MAWP of the nitrogen container of heat exchanger EX-8.

REFERENCES:

ASME Boiler and Pressure Vessel Code Section VIII, Division 1.

CALCULATIONS:

Since this is an in-house built item all code allowable stress values will be multiplied by 0.8.

Shell

In order to determine the internal MAWP both longitudinal and hoop stress must be considered.

Longitudinal stress	$P = 2\ SEt/(R - 0.4\ t)$
Hoop (circumferential) stress	$P = SEt/(R + 0.6\ t)$

where
- R = inside radius of shell (in)
- t = shell thickness (in)
- S = maximum allowable stress (psi)
- E = joint efficiency

When using 304 welded pipe use SE = 16000 in hoop stress formula if no additional longitudinal welds are made.

Hoop stress

$SE = 16000 \times 0.8 = 12800$ psi

$t = 0.148$ 8" SCH 10 pipe

$R = 4.164$

$\therefore P = 445.4$

Longitudinal stress

$S = 18800 \times 0.8$ $E = 0.6$

$t = 0.148$

$R = 4.164$

$\therefore P = 650.6$

To determine the external MAWP see Section VIII, Division 1 UG-28.

D_o = outside diameter of shell = 8.625 in

L = unsupported length = 59 in

t = thickness = 0.148 in

$$D_o/t = \frac{8.625}{0.148} = 58.3 \qquad L/D = \frac{59}{8.625} = 6.8$$

Look up Fig. 5 - UGO - 28.0 in App 5.

Factor A = 0.0004

Look up Fig. 5 - UHA - 28.1 (304 SS)

Factor B = 5500

The maximum allowable external pressure is

$$P_a = 4B/3(D_o/t) = \frac{4(5500)}{3(58.3)}$$

$$= 125.8$$

<u>Bottom Flat Plate</u>

Both the internal and external MAWP of the welded bottom flat plate are given by

$$P = (t/d)^2 \, SE/C$$

where

t = thickness of flat head = 0.375 in

d = diameter of head (ID of shell) = 8.329 in

S = maximum allowable stress = 18800 psi

E = joint efficiency = 1 (no joints in plate)

C = attachment factor [Fig. UG-13.2(b)] = 0.33

Since this is an in-house built item the maximum allowable stress must be multiplied by 0.8. Using the above relation we have

$$P = \left(\frac{0.375}{8.329}\right)^2 \frac{(18800 \times 0.8)(1)}{(0.33)} = 92.4$$

Top Plate

The minimum required thickness of a flat circular bolted head is given by $t = d\sqrt{CP/SE + 1.9\ Wh_G/SEd^3}$ where

$d = G$ = diameter of sealing surface center = 9.625 in
t = flat head thickness = 0.438 in
P = MAWP = (psi)
S = maximum allowable stress = 18800 psi (x 0.8 for in house construction)
E = joint efficiency = 1 (no joints in plate)
C = attachment factor = 0.30 [see Fig. UG-34(k)]
W = total bolt load
h_G = gasket moment arm = 0.6875 in

The total bolt load = $0.785\ G^2P$ for self energizing gaskets. (See Section VIII, Division 1, Appendix 2 for details.)

There are five openings in the top plate. All have weld reliefs 1/16" deep several of these openings are slightly less than twice their average diameter apart. The limits of reinforcement are equal to the diameter of the opening on either side of the axis. If we use only 0.95 the diameter of each opening as a limit then the reinforcements for two holes will not overlap. Take the thickness to be the actual thickness - the weld relief. Now a MAWP can be easily calculated and the results will be a bit conservative.

The area required for reinforcement of a hole is given by $A = 0.5\ dt$

where

d = diameter of circular opening (in)
t = required thickness of flat head (in)

The area available for reinforcement is

$A = 0.9\ d\ (0.438 - t)$

Set required area = available area

$0.5\ t = 0.9\ (0.438 - t)$
$1.4\ t = 0.394$
$t = 0.282$ in - is required thickness

Therefore the design pressure is 31.8 psig.

CONCLUSION

Both the internal and external design pressure of the nitrogen container are well above the pressure that this vessel will be subject to and above the MAWP of 14 psig.

Appendix B: Venting Pressure Drop

OBJECTIVE:

To determine that the vent line on the nitrogen container is adequately sized to prevent overpressuring the nitrogen container.

REFERENCES:

1) CGA S-1.3, Pressure Relief Device Standards
2) Crane Technical Paper No. 410

CALCULATIONS:

Consider two cases, 1) maximum required venting either due to operations or an error and 2) venting due to fire.

1) The maximum normal flow from EX-8 will be ~90 g/s. At least part of the same vent system will be used by EX-6, the satellite, the He dewar shield and boiloff from CCM shield, CVM shield and pumps. If all of these were operating in addition to EX-8 the total vent flow would be 125 g/s. However if there is a simultaneous failure of the pressure control on the nitrogen dewar and the fill valve on EX-8 sticks open approximate 15 gallons per minute of LN_2 could enter EX-8. We will consider this 15 gallons per minute (710 g/s) as the maximum operational amount to be vented.

   The vessel has no relief valve. It is vented directly to atmosphere through 20 feet of 2" foam insulated copper line and 30 feet of 4" uninsulated pipe. There are no shut off valves in the line.

   Look first at the 2" insulated line. The heat leak through this line is low enough (~150 watts) that 710 g/s of gas flowing through the line will warm less than one degree. Assume all liquid which flows into EX-8 is vaporized.

   Assume the flow through the 2" line to be at 83.3 K (150 R) and an average pressure of 20 psia. (Boiling point of 10 psig N_2 is 82.2 K.)

$$\rho = 0.3653 \text{ lb/ft}^3$$

$$\text{Flow} = 1.56 \text{ lb/sec} = 4.28 \text{ ft}^3\text{/sec}$$

$$2'' \text{ Cu tube cross section} = 0.02093 \text{ ft}^2$$

$$\text{Velocity} = 204.5 \text{ ft/sec}$$

The pressure drop as given by Crane is $\Delta P = 0.0001078\, K\rho V^2$. To find K we first need Reynolds Number.

$$R_N = \frac{\rho V D}{\mu} = \frac{(0.3653)(204.5)(0.16325)}{(0.389 \times 10^{-5})}$$

$$= 3.1 \times 10^6$$

$\therefore f = 0.019$ and

$K = 3.5$

$\Delta P = 0.0001078\ (3.5)\ (0.3653\ (204.5)^2$

$= 5.8$ psi

Therefore the assumptions we have made are reasonable and a little conservative.

Now look at the 4" pipe. This line is uninsulated and the gas will inevitability warm. Consider gas at 300 K (540 R) and 15 psia.

$\rho = 0.0725\ lb/ft^3$

Flow = 1.56 lb/sec = 21.51 ft^3/sec

4" SS pipe cross section = 0.09898 ft^2

Velocity = 217.4 ft/sec

$$R_N = \frac{\rho VD}{\mu} = \frac{(0.0725)(217.4)(0.355)}{1.21 \times 10^{-5}} = 4.6 \times 10^5$$

$f = 0.017$ and $K = 2.5$

$\therefore P = 0.001078\ K\rho V^2 = 0.0001078\ (2.5)(0.0725)(217.4)^2$

$= 0.92$

We therefore get a total pressure drop of 6.4 psi.

Venting Due to Fire

For an uninsulated container under fire conditions, the required relieving capacity is given by CGA S-1.3 to be $Q_a = G_u A^{0.82}$

where

Q_a = flow capacity of free air in ft^3/min

G_u = gas factor (see CGA Table)

A = total outside surface in ft^2

This relation is normally used to size a relief valve but we can take the flow determined above and calculate the pressure drop in the pipe. The insulation around the nitrogen bucket is encased in a metal skin but would decompose under fire conditions.

$Q = (59)(12)^{0.82}$ (G_u is <59 but this is lowest value in Table)

$= 453$ SCFM air

$= 7.54$ SCFS

If we assume the existing gas is at 1660 R (1200 ^{o}F) the pressure drop in the 2" line is still only 9.6 psi and that in the 4" line is 0.42 psi.

CONCLUSION

Therefore for either operations or fire conditions the vent line is adequately sized to prevent an overpressure of the nitrogen container.

Appendix C: Relief Calculations for the Helium Piping

OBJECTIVE

To demonstrate that the trapped volume relief is adequate to prevent overpressurizing the helium piping.

REFERENCE

"Cryogenic Systems", Randall Barron.

ASSUMPTION

Both ends of the heat exchanger helium piping were valved off before the heat exchanger warmed.

CALCULATIONS

Heat flux to the helium piping. Barron gives the heat flux to an uninsulated liquid oxygen line as 1.8 kW/m^2. This is about the same as the helium pipes will be. There are approximately 2.1 m^2 of surface. This gives an upper limit on the heat leak of 3.8 kW. The volume contained within the pipe is ~5.1 L. If we assume the helium is at 3 atm abs and 90 K the mass contained within the pipe is 8.1 g. At a heat input of 3.8 kW it would take approximately 2 seconds for this gas to warm to room temperature. Even if the whole volume were vented in 1 second it would be approximately equivalent to a flow of 100 SCFM. The 1/2" Circle Seal relief will vent approximately 470 SCFM of helium at room temperature at 100 psig.

CONCLUSION

The relief is adequately sized to prevent an overpressure on the internal helium piping.

Appendix D: Rupture of Internal Piping

OBJECTIVE

To demonstrate that a rupture of the internal piping will not result in overpressurizing the nitrogen vessel.

REFERENCES

Crane Technical Paper No. 410.

CALCULATIONS

PV-514-H serves as a flow regulator on the warm high pressure helium supply to heat exchanger 8 (EX-8). This valve will permit a maximum of 24 g/s of helium into EX-8.

If this line were to rupture above the nitrogen bath there would be a warm helium flow of 5.2 CFS. In this case there would be very little nitrogen venting from EX-8 and the normal nitrogen venting from other sources into the line (EX-6, pumps, etc) would be less than 50 g/s. At 50 g/s and assuming the nitrogen has warmed totally (it won't) from mixing with the helium the density of the mixture at 1 atmosphere and 300 K would be 0.378 g/ℓ and the total flow would be 75 g/s or 6.76 SCFS.

Using $\Delta P = 0.0001078\ K\rho V^2$ from Crane with average ρ and μ (see Appendix B) the total ΔP through the vent line is slightly less than 1 psi.

If the helium line breaks after the helium has cooled the total nitrogen venting flow from all sources would not be greater than ~175 g/s (50 g/s from other sources and 125 g/s due to cooling 24 g of helium). In this case the flow would be cold - at least in the insulated section of piping. Using average (175 g of N_2 and 24 g of He) ρ and combined helium and nitrogen flows the total vent line pressure drop would not be greater than 1.2 psi.

The helium will not pressurize the liquid nitrogen vessel. The 30 sq in clear cross section in the nitrogen vessel and the approximate foot of gas space between the liquid nitrogen and the vent allow the helium gas to exit the nitrogen vessel without forcing the liquid out.

CONCLUSION

A rupture of the helium line in the nitrogen container will not result in overpressuring the liquid nitrogen vessel.