Relief Valve Sizing for the ^3He Recirculation

System of the MP-9 Polarized Target^S

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A. Introduction

This report contains pressure safety analyses for the relief valving of the ^3He pump system, as distinct from the dilution refrigerator (DR). However, in a few instances it has been convenient to include here some aspects of the interaction between the DR and the gas loop proper. The more localized safety aspects of certain elements of the DR, such as the vacuum jacket and window, the Still, and the Phase Separator, will be addressed in a separate analysis.

Since the Fermilab safety guidelines do not view pressure-switch/motor-control interlocks as primary pressure safety devices for closed-loop pumps, it has been necessary to add several more relief valves to the ^3He loop. Since, owing to technical constraints, some of these valves must be of spill-to-room type, and since they all contain additional O-ring seals, both static and dynamic, some degradation of system security and performance is expected. Moreover, since gas spills must still be avoided, the customary pressure-switch interlocks must be retained.

All of this lends an increased degree of complexity to system operations and to system safety analyses. However, I have attempted to keep the system

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changes as simple as possible; in particular I have tried to minimize the number of new spill-to-room valves. The modified system configuration is shown in the attached schematic and key dated 03-MAR-89. The central points to keep in mind are that the pressure switches will be set to act before the corresponding relief valves can open, but the pressure safety analyses assume that the pressure switches are unreliable.

B. Pressure Switch Set Points

PS1

1.5 torr is the factory setting.

PS2

The factory setting was 1.5 psig = 16.2 psia. We will lower it to 11.6 psia in order to turn off the pump well below the spill point of H3-SV2.

PS3

The factory setting was 35 psig = 50 psia. We will lower it to 44 psia so that it will normally turn off the pump before H3-SV3 can open. If H3-SV3 ever opens, there is a probability that gas will spill out H3-SV2. We will give H3-SV3 the factory setting of 50 psia.

PS12

The manufacturer rates pump H3-P12 at a MAWP of 1.5 ata = 22 psia. Valve H3-SV12 will be set at this pressure, and PS12 at 20 psia will normally turn off the pump before H3-SV12 can open.

PS21

The manufacturer rates pump H3-P21 at a MAWP of 2 psig = 16.7 psia. Switch PS21, set at 14.5 psia, will normally turn off the pump before H3-SV21 can spill at 15.4 psia.

PS(MIV)

The manufacturer rates pump MIV-P2 at a MAWP of 22 psia. However, gauge MIV-G2 will lose calibration if subjected to more than 4 psig. Valve MIV-SV2 will be set at this pressure, and PS at 15 psia will normally turn off the pump before this point is reached.

C. Calculation of Required Relief Valve Capacities and Comparison to Actual Capacities

H3-SV1

The system contains a total He charge of around 750 L(STP). The available volume in the low-pressure area (mainly 12" pipe) is around 1200 L. Hence, if all of the He expands into the low-pressure volume, the pressure is less than 1 ata. Valve H3-SV1 is therefore only necessary to handle the possibility of cryopumped air released under warm-up of the DR.

The normal heat gain of the DR is less than 2W. If we posit ten times this heat gain in some situation in which massive amounts of air have been cryopumped, we have liquid air generated at a rate

$$\begin{aligned} Q(\text{liq.}) &\approx (20W)/h_f \\ &= 0.78 \text{ g/s} \\ &= 47 \text{ g/min,} \end{aligned}$$

where $h_f = 25.8 \text{ J/g}$ is the heat of fusion of N_2 . If we assume that the liquid is able to flow to a warm part of the DR where unlimited quantities of heat are available at room temperature, this converts to

$$\begin{aligned} Q_a &\approx (47 \text{ g/min}) (0.79 \text{ ft}^3/\text{mol}) / (28 \text{ g/mol}) \\ &= 1.3 \text{ SCFM(air).} \end{aligned}$$

The rated flow capacity of H3-SV1 is 45 SCFM(air) at 4 psig.

H3-SV2

Pump H3-P2 has a speed of 265 CFM at high inlet pressures. For a worst-case condition of 1 ata(air) at the inlet, we require a relief capacity $Q_a \approx 265$ SCFM(air) at an exhaust pressure not exceeding 2 psig = 16.7 psia. The required valve flow coefficient C_v is therefore (for subsonic flow)

$$\begin{aligned} C_v(\text{min.}) &= Q_a / (16.05) [(P_1^2 - P_2^2) / T]^{1/2} \\ &= 265 / (16.05) [(16.7^2 - 14.7^2) / 520]^{1/2} \\ &= 47.5. \end{aligned}$$

Circle Seal says that valve 259B-16PP-.07 will be fully open at $\Delta p = 2$ psi and has a rated $C_v = 51$.

H3-SV3

Pump H3-P3 has a speed of 18 CFM at high inlet pressures. For a worst-case condition of 1 ata(air) at the inlet, we require a relief capacity of $Q_a \approx 18$ SCFM(air) at an exhaust pressure not exceeding 35 psig = 50 psia. The required valve flow coefficient is (for sonic flow)

$$\begin{aligned} C_v(\text{min.}) &= Q_a / 0.597 P_1 \\ &= 18 / 0.597 (50) \\ &= 0.60. \end{aligned}$$

Valve 5559A-2PP has a rated $C_v = 0.7$.

H3-SV4A,B

These valves provide relief to the cryogenic traps in the event that a trap is warmed up while isolated from the system via closure of H3-V5,6.

First we estimate the maximum plausible heat gain to a trap. The built-in electrical heater is capable of delivering around 200W. If the LN vessel is removed from a trap while cold, exposure to warm air can deliver around 900 Btu/hr · ft² (Barron, p. 504, 90K-surface, 8 mph wind). The surface area of the trap is

$$\begin{aligned} A &= \pi D(D/4 + L) \\ &= \pi(5.13)(5.13/4 + 16)\text{in}^2 \\ &= 1.93 \text{ ft}^2, \end{aligned}$$

so

$$\begin{aligned} q(\text{air exposure}) &\approx (900 \text{ Btu/hr} \cdot \text{ft}^2) (1.93 \text{ ft}^2) \\ &= 1740 \text{ Btu/hr} \\ &= 510\text{W}. \end{aligned}$$

Another possibility is the fire condition. The difference between the O.D. of the trap and the O.D. of the LN vessel is

$$\begin{aligned} 2\Delta R &= 9.75" - 5.13" \\ \Delta R &= 2.3" \\ &= 0.19 \text{ ft}. \end{aligned}$$

If the outside of the LN vessel is at 1200°F = 1660R, and the vessel insulating vacuum is spoiled by 1 ata N₂, we have a heat gain

$$\begin{aligned} q(\text{fire}) &= KA\Delta T/\Delta R \\ &= (0.0223 \text{ Btu/hr} \cdot \text{ft}^2 \cdot \text{R})(1.93 \text{ ft}^2) (1660\text{R} - 139\text{R})/(0.19 \text{ ft}) \\ &= 345 \text{ Btu/hr} \\ &= 101 \text{ W}, \end{aligned}$$

where we have used the conductivity of N_2 gas at the mean temperature of 900R.

It is seen that the worst-case hypothesis is the "air exposure" case, $q = 510W$.

We now assume that the trap is saturated with liquid air, and we get a vent rate of

$$\begin{aligned}\dot{m}(\text{air}) &= q/h_v \\ &= (510W)/(193 \text{ J/g}) \\ &= 2.6 \text{ g/s} \\ &= 5.5 \text{ mol/min} \\ &= 4.3 \text{ SCFM(air)},\end{aligned}$$

where $h_v = 193 \text{ J/g}$ is the latent heat of vaporization of air at 35 psig.

Valve 533B-2M-30 has a rated capacity of 5.6 SCFM(air) at a pressure rise of 5 psi, i.e., at an inlet pressure of 35 psig.

A related matter is the sizing of the relief valve on the vacuum jacket of the LN vessel. This open-mouth vessel has a liquid capacity of 14L. CGA S-1.3 specifies a relief area of

$$\begin{aligned}a &= (14L) (2.2 \text{ lb/L}) (0.00024 \text{ in}^2/\text{lb}) \\ &= 0.007 \text{ in}^2.\end{aligned}$$

The Cryolab valve SV8-82-5W1 has a relief area of 0.06 in^2 .

H3-SV5

The purpose of this valve is to pass the working gas back into #1 storage in the event of flow stoppage into the DR, or a warm-up of the DR. It is clear that this valve is large enough to handle the maximum discharge of pump H3-P3, by analogy with valve H3-SV3 of the same size, since the pressure in #1

storage can never exceed 1 ata of He (tank volume is 753L), and the valves have a higher volume flow capacity for He than for air (approx. X3).

It remains to consider catastrophic warm-up of the DR, causing the LHe in the condenser to boil out in a reversed-flow condition. We consider spoiling of the external insulating vacuum with He, or with air.

a. E.I.V. Spoils with He

The condenser is a racetrack-shaped winding of area-enhanced tubing which is shaped to conform to the re-entrant wall of the mixer. The length of the racetrack is $l \approx 39$ cm. It conforms to the cylindrical wall at a radius $r \approx 3.5$ cm and subtends about $1/3$ of the circle. In terms of the frontal area presented to radial heat flow there is a further reduction of $\sim 1/2$ for the porosity of the structure:

$$\begin{aligned} A &\approx (1/3) (2\pi r l) (\text{porosity}) \\ &= (1/3) (2\pi) (3.5 \text{ cm}) (39 \text{ cm}) (1/2) \\ &= 143 \text{ cm}^2. \end{aligned}$$

The total radial path, through He gas at ~ 1 ata, separating the condenser from the room temperature wall would be

$$\Delta R \approx 0.8 \text{ cm}.$$

The thermal conductivity of the gas, at a mean temperature of 150K, is

$$k = 0.97 \text{ mW/cm} \cdot \text{K},$$

so the total heat gained by the condenser would be

$$\begin{aligned}\dot{H}_c &= kA\Delta T/\Delta R \\ &\approx (0.00097) (143) (300)/0.8 \\ &= 52W.\end{aligned}$$

For ^3He at a pressure of 3 ata, the specific heat input $\theta = V(\partial h/\partial V)_p$ reaches a minimum value of $\theta_{\min} \approx 30 \text{ J/g}$ at a temperature of 3.8K, so

$$\begin{aligned}\dot{m} (^3\text{He}) &\approx (52W)/(30 \text{ J/g}) \\ &= 1.7 \text{ g/s}.\end{aligned}$$

In terms of gas flow at STP,

$$\begin{aligned}Q(^3\text{He}) &= (1.7 \text{ g/s}) (60 \text{ s/min}) (0.79 \text{ ft}^3/\text{mol})/(3\text{g/mol}) \\ &= 27 \text{ SCFM } (^3\text{He})\end{aligned}$$

or

$$\begin{aligned}Q_a &= 27(3/29)^{1/2} \\ &= 8.7 \text{ SCFM(air)}.\end{aligned}$$

b. E.I.V. Spoils with Air

In this case we assume air condensation on the wall of the Still vessel adjacent to the condenser, which again resides in He gas at a pressure of ~ 1 ata. The condenser is radially separated from this wall by $\Delta R \approx 0.5 \text{ cm}$, and for air condensation we assume a wall temperature of 80K and a gas conductivity

$$k \approx 0.41 \text{ mW/cm} \cdot \text{K},$$

corresponding to the mean temperature of $\sim 40\text{K}$. Thus,

$$\begin{aligned}\dot{H}_c &= KA \Delta T / \Delta R \\ &\approx (0.00041) (143) (80) / 0.5 \\ &= 9.4W.\end{aligned}$$

Therefore, case (a) is the more stringent, and $Q_a = 8.7$ SCFM(air).

Valve H3-SV5 has a rated $C_v = 0.7$, and a set point of 41 psia. For sonic flow this gives a capacity of

$$\begin{aligned}Q_a &= 0.597 C_v P_1 \\ &= 0.597 (0.7) (41) \\ &= 17 \text{ SCFM(air)}.\end{aligned}$$

H3-SV11

The MAWP of pump H3-P12 is 1.5 ata = 22 psia. H3-SV11 has a set point of 19 psia. The worst-case condition is if pump H3-P3 delivers 18 SCFM(air) to H3-SV11. At this flow rate, H3-SV11 will experience a pressure rise of around $\Delta p = 1$ psi.

H3-SV12

Here the worst-case condition is the same as above for H3-SV11, with pump H3-P12 running. The speed of H3-P12 is 2.9 CFM which, combined with an air inlet pressure of $19 + \Delta p = 20$ psia, gives a flow rate $Q_a = 3.9$ SCFM(air). The required C_v is (subsonic flow)

$$\begin{aligned}C_v(\text{min.}) &= 3.9 / 16.05 [(22^2 - 20^2) / 520]^{1/2} \\ &= 0.60.\end{aligned}$$

The valve has a rated $C_v = 0.7$.

H3-SV13

The only function of this valve is to prevent the possibility of back-pressuring pump H3-P12, and thus avoid the necessity of another spill-to-room valve.

H3-SV21

Pump H3-P21 has a speed of 18 CFM at high inlet pressures. For a worst-case condition of 1 ata (air) at the inlet, we require a relief capacity $Q_a = 18 \text{ SCFM(air)}$ at an exhaust pressure not exceeding 2 psig = 16.7 psia. Valve H3-SV21 has a rated capacity of 38 SCFM(air) at 2 psig.

MIV-SV1

The Mixer Insulating Vacuum is basically a guard vacuum around the Mixer. Because the Mixer seal is prone to occasional leakage, the MIV pump efflux is collected in a small tank (Ballast Volume) both for recovery of the ^3He and, by way of the measurable pressure rise, as a diagnostic for the seal quality. (In normal operation, valve MIV-V2 is closed.)

Valve MIV-SV1 provides the basic pressure relief. It vents to the low-pressure area to assure that ^3He will not be lost; however, it is expected in the worst-case scenario, that is, rupture of the Mixer wall, that the spilled LHe attains a temperature ($\leq 1\text{K}$) and pressure ($\leq 1 \text{ torr}$) about equal to those of the Still, so that the valve is not called upon to open.

We can establish a minimum required flow capacity according to CGA S-1.3. The volume of the Mixer plus Still is around 1L. This requires a relief area

$$\begin{aligned} a &= (1\text{L})(2.2 \text{ lb/L})(0.00024 \text{ in}^2/\text{lb.}) \\ &= 0.0005 \text{ in}^2. \end{aligned}$$

The Circle Seal 119B-4PP, as a 1/2-in.-diameter valve, clearly has more than enough flow area.

MIV-SV2

Here the worst-case condition is 1 ata(air) at the inlet of pump MIV-P2, which has a speed of 2.9 CFM. The required C_v is (subsonic flow)

$$C_v = 2.9/16.05[(19^2 - 15^2)/520]^{1/2}$$

$$= 0.35.$$

The valve has a rated $C_v = 0.7$.

D. Summary

<u>Valve</u>	<u>Required</u>		<u>Actual</u>	
	C_v	or Capacity SCFM (air)	C_v	or Capacity SCFM (air)
H3-SV1		1.3		45 @ 4 psig
H3-SV2	47.5		51	
H3-SV3	0.60		0.7	
H3-SV4A,B		4.3		5.6 @ 35 psig
H3-SV5		8.7		17 @ 41 psia
H3-SV11		18		18 @ 20 psia
H3-SV12	0.60		0.7	
H3-SV21		16		38 @ 2 psig
MIV-SV1		a = 0.0005 sq. in.		d = 1/2 in.
MIV-SV2	0.35		0.7	

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