Project: Hall D Cryogenic Target

Tittle: General calculations for relief and storage pressures

Document Number: TGT-CALC-401-001

Revision: Original

Author: Dave Meekins Date: 2/6/2012

Checked: Date:

Approved: Date:

Code(s) of Record:
ASME B31.3 2010
ASME B31.12 2011
ASME BPVC VIII D1 2010

Reference Codes
API 520
API 521
NFPA 2,55,497
CGA 5

Reference Drawings
TGT-401-0001-1000

Description:
Hall D target relief calculations and volume estimate. The Schneider MEMO for loss of vacuum in a cryomodule is used as a design basis to determine the heat load from IV loss in the H2 target. Assume gas as it leaves the target is at 300K. This is overly consrvative. The target cell is made of kapton. Other system components are stainless steel. The cell will have the lowest design pressure; it will drive the design. The Weymouth friction factor will be used as it is conservative for all pipe sizes less than 20 inch NPS. Crane 410 is used as guidance.

Design assumptions limits and set points for pressures

$P_{set} := 30 \cdot psi$ Relief set pressure absolute

$P_{atm} := 14.7 \cdot psi$ atm pressure absolute

$P_{cold} := 18 \cdot psi$ assumed cold operating pressure absolute

$P_{max} := 35 \cdot psi$ absolute design pressure of target cell

$P_{plate} := 16.7 \cdot psi$ absolute parallel plate set pressure. Parallel plate is at exit of H2 vent

$P_{over} := P_{max} \cdot 1.16 = 40.6\ psi$ max allowed overpressure by code for redundant relief paths

Fluid Properties for H2, D2 and He:

Properties were determined for He at 5.2K and 35 psia where a test was performed on the JLAB Cryo modules. Properties of H2 were determined at 30 psia and 23 K which are the expected relief pressure and temperature respectively for the Hall D target

Moler masses of H2, D2 and He

$M_{H2} := 2 \cdot \frac{gm}{mol}$ $M_{D2} := 4 \cdot \frac{gm}{mol}$ $M_{He} := 4 \cdot \frac{gm}{mol}$

Latent heat of H2, D2, and He

$\lambda_{H2} := 461 \cdot \frac{J}{gm}$ $\lambda_{D2} := 304\ \frac{J}{gm}$ $\lambda_{He} := 21\ \frac{J}{gm}$

gas constants

$R_{H2} := 4124.3 \cdot \frac{J}{kg \cdot K}$ $R_{D2} := 2064 \cdot \frac{J}{kg \cdot K}$ $R_{He} := 2077.3 \cdot \frac{J}{kg \cdot K}$

density of H2, D2 and He at 300K and 30 psia (P_set)

$\rho_{H2300} := 0.167 \cdot \frac{kg}{m^3}$ $\rho_{D2300} := 0.334 \cdot \frac{kg}{m^3}$ $\rho_{He300} := 0.3316 \cdot \frac{kg}{m^3}$

density of H2, D2, and He at 289K (60 F) and 14.7 psia

$$\rho_{H2std} := 0.0850 \cdot \frac{kg}{m^3} \qquad \rho_{D2std} := 0.1698 \cdot \frac{kg}{m^3} \qquad \rho_{Hestd} := 0.1687 \cdot \frac{kg}{m^3}$$

density of liquid H2 and D2 at the target operating temperatures and pressure

$$\rho_{H2op} := 72.26 \cdot \frac{kg}{m^3} \qquad \rho_{D2op} := 167.4 \cdot \frac{kg}{m^3}$$

densities of H2 and from ideal gas law

$$\rho_{H2}(T,P) := \frac{P}{(R_{H2} \cdot T)}$$

This group of constants are needed to scale the He loss of vacuum data from Schneider to the case of H2

$$K_{H2} := 0.0187 \cdot \frac{W}{m \cdot K}$$ Thermal conductivity of H2 at film boiling condition

$$K_{He} := 0.0257 \cdot \frac{W}{m \cdot K}$$ Thermal conductivity of He (at film boiling condition)

$$K_{D2} := 0.0137 \cdot \frac{W}{m \cdot K}$$ est thermal cond of D2 at film boiling condition

$$T_{He} := 5.2 \cdot K$$ Film boiling test temp for He from Schnieider MEMO

$$T_{H2} := 23 \cdot K$$ Film boiling temp for H2 at target vent condition

$$T_{room} := 300 \cdot K$$ room temperature

Specific heats of H2

$$c_{pH2} := 0.143 \cdot 10^5 \cdot \frac{J}{kg \cdot K} \qquad c_{vH2} := 0.102 \cdot 10^5 \cdot \frac{J}{kg \cdot K}$$

Specific heats of D2

$$c_{vD2} := 5186 \cdot \frac{J}{kg \cdot K} \qquad c_{pD2} := 7251 \cdot \frac{J}{kg \cdot K}$$

Specific heats of He

$$c_{vHe} := 3116 \cdot \frac{J}{kg \cdot K} \qquad c_{pHe} := 5193 \cdot \frac{J}{kg \cdot K}$$

Ratios of specific heats for H2, D2 and He

$$k_{H2} := \frac{c_{pH2}}{c_{vH2}} = 1.402 \qquad k_{D2} := \frac{c_{pD2}}{c_{vD2}} = 1.398 \qquad k_{He} := \frac{c_{pHe}}{c_{vHe}} = 1.667$$

viscosities of each gas at exit. The viscosity in the vent stack will vary from this by less than 1%

$$\mu_{H2300} := 0.8959 \cdot 10^{-5} \cdot Pa \cdot s$$ visc of H2 at 300K and 30 psi

$$\mu_{He300} := 0.1993 \cdot 10^{-4} \cdot Pa \cdot s$$ visc of He at 300K and 30 psi

$$\mu_{D2300} := 1.39 \cdot \mu_{H2300}$$ visc of D2 at 300K and 30 psi.

speed of sound in each gas

$$v_{soundH2} := 1321 \cdot \frac{m}{s}$$ speed of sound for H2 at 300K and 30 psi

$$v_{soundHe} := 1020 \cdot \frac{m}{s}$$ speed of sound in He at 300K and 30 psi

$$v_{soundD2} := \sqrt{k_{D2} \cdot \frac{P_{set}}{\rho_{D2300}}} = 930.528 \ \frac{m}{s}$$ estimated speed of sound in D2 at 300K and 30 psi from ideal gas model

Critical flow pressure ratios for H2, D2, and He. determined using the ideal gas assumptions similar to API 520 eq 3.1

$$Rc_{H2} := \left(\frac{2}{k_{H2}+1}\right)^{\frac{k_{H2}}{k_{H2}-1}} \qquad Rc_{D2} := \left(\frac{2}{k_{D2}+1}\right)^{\frac{k_{D2}}{k_{D2}-1}} \qquad Rc_{He} := \left(\frac{2}{k_{He}+1}\right)^{\frac{k_{He}}{k_{He}-1}}$$

Surface area and volume of liquid vessels

Surface area/volume of the cell:

end cap D00000-03-00-2000

$D_{cap} := 0.628 \cdot in$ diameter of endo cap

$L_{cap} := 0.188 \cdot in$ end cap length

$$A_{cap} := \pi \cdot D_{cap} \cdot L_{cap} + 2\ \pi \cdot \frac{D_{cap}^{\ 2}}{4}$$

$$V_{cap} := 2\ \frac{\pi}{3} \cdot \left(\frac{D_{cap}}{2}\right)^3 + \frac{\pi}{4} \cdot D_{cap}^{\ 2} \cdot L_{cap}$$

cell main body D00000-03-00-2002 is frustum of a cone

$D_1 := 1.046 \cdot in$

$D_2 := 0.61 \cdot in$

$L_{main} := 14.04 \cdot in$

$$A_{main} := \frac{\pi}{2} \cdot \left(D_1 + D_2\right) \cdot \sqrt{\frac{\left(D_1 - D_2\right)^2}{2} + L_{main}^{\ 2}}$$

main cell body surface area

$$V_{main} := \frac{\pi}{3} \cdot L_{main} \cdot \frac{\left(D_1^{\ 2} + D_1 \cdot D_2 + D_2^{\ 2}\right)}{4}$$

main cell body volume

cell entrance tube D00000-03-00-2001

$D_1 := 0.91 \cdot in$ $D_2 := 0.738 \cdot in$ $L_{ent} := 3.79 \cdot in$

$$A_{ent} := \frac{\pi}{2} \cdot \left(D_1 + D_2\right) \cdot \sqrt{\frac{\left(D_1 - D_2\right)^2}{2} + L_{ent}^{\ 2}}$$

surface area of entrance tube

$$V_{ent} := \frac{\pi}{3} \cdot \left(L_{ent} - 1.585 \cdot in\right) \cdot \frac{\left(D_1^{\,2} + D_1 \cdot D_2 + D_2^{\,2}\right)}{4}$$ displaced volume of entrance tube

Fill and return leg tubes on cell D00000-03-00-2005. There are (3) tubes

$D_{fill} := 0.375 \cdot in$ Tube OD

$L_{fill} := 4.25 \cdot in$ est length of tubes to fitting

$A_{fill} := \pi \cdot D_{fill} \cdot L_{fill}$ area of one fill tube

$V_{fill} := \frac{\pi}{4} \cdot D_{fill}^{\,2} \cdot L_{fill}$ volume of one fill tube

tubing from condenser to cell (loop tubing) (2) tubes, supply and return to cell

$L_{loop} := 8 \cdot ft$ estimated length of each tube

$D_{rl} := 0.5 \cdot in$ OD of return

$D_{sup} := 0.25 \cdot in$ OD of supply

$A_{sup} := \pi \cdot D_{sup} \cdot L_{loop}$ area of supply line

$A_{rl} := \pi \cdot D_{rl} \cdot L_{loop}$ area of return line

$A_{loop} := A_{rl} + A_{sup}$ area of loop tubing

$V_{loop} := \frac{\pi}{4} \cdot \left(D_{rl}^{\,2} + D_{sup}^{\,2}\right) \cdot L_{loop}$ volume of loop tubing

Condenser

$L_{cond} := 4 \cdot in$ length of condenser

$D_{cond} := 4 \cdot in$ OD of condenser

$A_{cond} := \pi \cdot D_{cond} \cdot L_{cond} + 2 \cdot \frac{\pi}{4} \cdot D_{cond}^{\,2}$ surface area of condenser

$V_{cond} := \frac{1}{2} \left(\frac{\pi}{4}\right) \cdot D_{cond}^{\,2} \cdot L_{cond}$ conservative estimate of H2 volume in condenser is 1/2 total volume

Total surface areas

$$A_{ins} := A_{cond} + A_{loop} + 3 \cdot A_{fill} = 0.204\ \boldsymbol{m^2}$$ total insulated area

$$A_{uns} := A_{main} + 2 \cdot A_{cap} + A_{ent} = 0.031\ \boldsymbol{m^2}$$ total uninsulated area

Total volume of liquid H2

$$V_{LH2} := V_{cond} + V_{cap} + V_{loop} + 3 \cdot V_{fill} + V_{main} - V_{ent} = 0.93\ \boldsymbol{L}$$

Supply and return lines which feed the target from the outside of the OVC are assumed to contain only gas as they extend to the OVC feedthru. These lines are assumed to be 3 ft long and have one 90 deg elbow inside the OVC and one outside. As they contain gas only, they are not considered in the relief load calculation below as containing liquid.

Required Storage Capacity/Pressure:

500 gal propane tanks are readily available and reasonably priced. These will suit the needs of the target well.

Volumetric storage of the H2 and D2 inventory

$$n_{H2} := V_{LH2} \cdot \rho_{H2op} \cdot \frac{1 \cdot mol}{2 \cdot gm} = 33.618\ mol$$ moles of H2 in liquid

$$n_{D2} := V_{LH2} \cdot \rho_{D2op} \cdot \frac{1 \cdot mol}{4 \cdot gm} = 38.94\ mol$$ moles of D2 in liquid

$$V_{store} := 500 \cdot gal$$ ext H2 storage volume

$$P_{op} := P_{cold}$$ operating pressure

Storage pressure and amount of of H2 at room temperature

$$PH_{store} := n_{H2} \cdot R \cdot \frac{T_{room}}{V_{store}} + P_{op} = 24.426\ psi$$ absolute storage pressure

$$P_{stp} := 14.7 \cdot psi$$ standard pressure

$$T_{stp} := 20\ °C$$ stp temp

$$L_{stp} := \frac{PH_{store}}{P_{stp}} \cdot V_{store} \cdot \frac{T_{stp}}{T_{room}} = \left(3.073 \cdot 10^{3}\right)\ L$$ stp liters of H2

Storage pressure and ammount of D2 at room temperature

$$PD_{store} := n_{D2} \cdot R \cdot \left(\frac{T_{room}}{V_{store}}\right) + P_{op} = 25.443\ psi$$ absolute storage pressure

$$L_{stp} := \frac{PD_{store}}{P_{stp}} \cdot V_{store} \cdot \frac{T_{stp}}{T_{room}} = \left(3.201 \cdot 10^{3}\right)\ L$$ stp liters of D2

Relief load calculation:

The worst case relief mass flow will result from a loss of insulating vacuum (IV). Fire is not a consideration as the magnet bore and all target components with the exception of the cell are metal. Igniting the H2, D2 would require a system breach and preclude a relief. The mass evolution rates resulting from a worst case relief event are scaled from He test data for each species of gas. Extremely conservative assumptions of the exit temperature of the relieving gas (300K at boil point) are used.

Estimated heat load from loss of vacuum:

This is estimated from the heat loads measured and calculated for a vacuum loss in a cryomodule. This is from the MEMO by W.J. Schneider 1999. The calculated heat fluxes are as low as 8 kw/m^2 where 20 kW/m^2 to 35 kW/m^2 were determined from measurement. It has become standard practice to assume ~20 kW/m^2 for insulated surfaces and 38kW/m^2 for uninsulted surfaces. These assumptions are quite conservative. These values can be scaled to H2 by considering the thermal conductivity of the film layers (assuming that they have the same depth) and the temperature difference. The walls of the cell and target piping are assumed to have no thermal resistance. For Helium from the test data we have conservatively

$$Q_{ins} := \left(20 \cdot \frac{kW}{m^2}\right)$$

Heat load for insulated surfaces for He

$$Q_{uns} := \left(38 \cdot \frac{kW}{m^2}\right)$$

Heat load for uninsulated surfaces for He

$$\Delta T_{corr} := \frac{\left(T_{room} - T_{H2}\right)}{T_{room} - T_{He}} = 0.94$$

ratio of delta T for H2 heat load correction. corrects for slightly higher temperature of H2,D2 when compared to He at the test condition

Total mass evolution rate for loss of IV for H2

$$dm_{H2} := \left(Q_{ins} \cdot A_{ins} + Q_{uns} \cdot A_{uns}\right) \cdot \frac{\Delta T_{corr} \cdot K_{H2}}{\lambda_{H2} \cdot K_{He}} = 7.816\ \frac{gm}{s}$$

Total mass evolution rate for loss of IV for D2

$$dm_{D2} := \left(Q_{ins} \cdot A_{ins} + Q_{uns} \cdot A_{uns}\right) \cdot \frac{\Delta T_{corr} \cdot K_{D2}}{\lambda_{D2} \cdot K_{He}} = 8.683\ \frac{gm}{s}$$

Mass evolution rate for loss of IV for He. Note that the mass evolution is much larger than that of H2 and D2 and more relief capacity will be needed for this target fluid. There are no approved plans for He as a target fluid at the time of this calculation.

$$dm_{He} := \left(Q_{ins} \cdot A_{ins} + Q_{uns} \cdot A_{uns}\right) \cdot \frac{1}{\lambda_{He}} = 250.958 \ \frac{gm}{s}$$

Volumetric flow of H2 and D2

$$H2_{scfm} := \frac{dm_{H2}}{\rho_{H2std}} = 194.835 \ \frac{ft^3}{min}$$ volumetric flow of H2 in scfm

$$D2_{scfm} := \frac{dm_{D2}}{\rho_{D2std}} = 108.357 \ \frac{ft^3}{min}$$ volumetric flow of D2 in scfm

From the above, comparison between H2 and D2 flow rates indicates that the H2 case will require the most relief capacity. Thus only this case need be considered.

The internal target components are relieved through the branch line of a tee at the base of the condenser. The worst case failure mode is for this branch to be plugged forcing all flow from the condenser and supply line back through the cell. To determine the pressure in the condenser and supply line for this mode the mass flow from only the condenser and supply line are needed.

Mass flow from only loop supply tube and condenser

$$dm_{cond} := \left(Q_{ins} \cdot \left(A_{sup} + A_{fill} + A_{cond}\right)\right) \cdot \frac{\Delta T_{corr} \cdot K_{H2}}{\lambda_{H2} \cdot K_{He}} = 2.981 \ \frac{gm}{s}$$

$$dm_{cell} := \left(Q_{ins} \cdot A_{fill} + Q_{uns} \cdot A_{uns}\right) \cdot \frac{\Delta T_{corr} \cdot K_{H2}}{\lambda_{H2} \cdot K_{He}} = 1.853 \ \frac{gm}{s}$$

$$dm_{ret} := Q_{ins} \cdot \left(A_{fill} + A_{rl}\right) \cdot \frac{\Delta T_{corr} \cdot K_{H2}}{\lambda_{H2} \cdot K_{He}} = 2.981 \ \frac{gm}{s}$$

Relief of H2 target only:

Pressure drop in relief paths of the target:

Two identical releif valves shall be located on the gas panel. These reliefs shall be considered redundant parallel paths. The ASME allowed pressure rise for this condition is the greater of 16% or 4 psi (UG-125). Stop valves may be in position provided the conditions in VIII D1 M5.6 are met. Each relief valve must exhaust into the hydrogen vent header. This header is maintained at ~1-2 psi above atmospheric pressure with an inert gas to ensure that oxegen is purged from the line. A parallel plate relief is installed at the exit of the header with a set pressure of ~2 psi. An additional line connects the storage tank to the target. The operating pressure of the system is assumed to be 18 psia. The return to the stoage tank outside is not considered as a relief path here.

Parallel plate relief

Consider first the parallel plate relief at the exit of the vent stack. The critical pressure may be used to determine the nature of the flow at the exit, critical or subcritical. The exit of the vent is to atmosphere at 14.7 psia

$Pc_{vent} := Rc_{H2} \cdot P_{plate} \cdot 1.1 = 9.698\ psi$ critical pressure vent relief

The exit pressure is larger than the critical pressure thus, the flow is subcritical at this relief. The upstream pressure will be checked to ensure that the assumption of the plate relief pressure is correct. We follow API 520 3.6.3

$K_{valve} := 0.62$ Coef of discharge

$D_{plate} := 2.245 \cdot in$ most restrictive diameter of relief

$C_{asme} := 17.9 \cdot \frac{hr}{kg} \cdot \sqrt{\frac{gm}{K \cdot mol}} \cdot \frac{kN}{m^2} \cdot mm^2$ Coeff determined from ratio k now for subcritical flow

$P_1 := P_{plate} \cdot 1.1 = 18.37\ psi$ upstream pressure assumed

$P_2 := P_{atm} = 14.7\ psi$ downstream pressure assumed

$r := \frac{P_2}{P_1}$

$$F_2 := \sqrt{\frac{k_{H2}}{k_{H2}-1} \cdot r^{\frac{2}{k_{H2}}} \cdot \left(\frac{1 - r^{\frac{k_{H2}-1}{k_{H2}}}}{1-r} \right)} = 0.887$$ subcritical flow coeff

the required area for the given mass discharge is

$$A_{req} := \frac{dm_{H2} \cdot C_{asme}}{F_2 \cdot K_{valve}} \cdot \sqrt{\frac{T_{room}}{M_{H2} \cdot P_1 \cdot (P_1 - P_2)}} = 0.307\ in^2$$

the required lift of the plate would be

$$h_{lift} := \frac{A_{req}}{\pi \cdot D_{plate}} = 0.044\ in$$

The estimated force on the plate is

$$F_{plate} := (P_1 - P_{atm}) \cdot \pi \cdot \frac{D_{plate}^{\ 2}}{4} = 14.527\ lbf$$

Springs must be chosen to provide the given lift height for this force.

Vent stack pressure drop

Vent stack estimate based on placement of tanks and vent at 100' from building. This is a convient place. NFPA requirement of 40 ft from all buildings and AC vents. Storage tanks to be paced with vent. Flex lines will be needed to connect the vent to the gas panel relief and the relief at the top of the target. The length of these lines is assumed to be 20 ft. The line is assumed to be American BOA Parwrap 1.5" nom hose.

$L_{vent} := 200 \cdot ft$ Length of hard vent pipe

$D_{od} := 2.375 \cdot in$ 2 in pipe nom OD

$t_{wall} := 0.065 \cdot in$ wall thickness for 2" Sch 5 S pipe

$ID_{vent} := D_{od} - t_{wall}$ ID of vent pipe

$A_{vent} := \frac{\pi \cdot ID_{vent}^{\ 2}}{4} = 0.003\ m^2$ cross area of vent stack

$T_{vent} := 300 \cdot K$ $P_{vent} := 1.1 \cdot P_{plate}$ temp and pressure in vent

$$v_{vent} := \frac{dm_{H2}}{\rho_{H2}\left(T_{vent}, P_{vent}\right) \cdot A_{vent}} = 28.239\ \frac{m}{s}$$ velocity in vent line

$$Re_{vent} := \frac{\rho_{H2}\left(T_{vent}, P_{vent}\right) \cdot v_{vent} \cdot ID_{vent}}{\mu_{H2300}} = 1.893 \cdot 10^{4}$$ Reynolds number at relief; flow is turbulent

$$f_{vent} := \frac{0.032 \cdot in^{\frac{1}{3}}}{ID_{vent}^{\frac{1}{3}}} = 0.024$$ Weymouth friction factor

$$K_{vent} := f_{vent} \cdot \frac{L_{vent}}{ID_{vent}}$$ resistance coef for vent

$N_{bends} := 8$ estimated number of street elbows in vent stack

$K_{elbows} := 60 \cdot f_{vent} = 1.452$ worst case factor for elbows

Flex lines to insertion cart:

$L_{flex} := (20 \cdot ft) \cdot 3$ effective length of flex line for insertion cart actual length is 20 ft. The factor of 3 results from measurements of pressure drop in corregated flex hose

$ID_{flex} := 1.5 \cdot in$ ID of flex lines

$$A_{flex} := \pi \cdot \frac{ID_{flex}^{2}}{4}$$ cross area of flex

$$f_{flex} := \frac{0.032 \cdot in^{\frac{1}{3}}}{ID_{flex}^{\frac{1}{3}}} = 0.028$$ Weymouth friction factor

$$v_{flex} := \frac{dm_{H2}}{\rho_{H2}\left(T_{vent}, P_{vent}\right) \cdot A_{flex}} = 66.971\ \frac{m}{s}$$

velocity in flex line

$$K_{flex} := f_{flex} \cdot \frac{L_{flex}}{ID_{flex}} = 13.418$$

resistance coef for flex line

$$\Delta P_{flex} := K_{flex} \cdot \rho_{H2300} \cdot \frac{{v_{flex}}^2}{2} = 0.729\ psi$$

pressure loss in flex line

$$\beta := \frac{ID_{flex}}{ID_{vent}}$$

$$K_{en} := \frac{\left(1-\beta^2\right)^2}{\beta^4} = 1.881$$

Resistance factor for enlargement from flex to main

head loss from height of vent stack

$$h_{stack} := 70 \cdot ft$$

this is negligible

$$\Delta P_{stack} := h_{stack} \cdot g \cdot \rho_{H2}\left(T_{vent}, P_{vent}\right) = 0.003\ psi$$

total pressure loss in vent line from relief valve exit to parallel plate

$$\Delta P_{vent} := \left(K_{vent} + N_{bends} \cdot K_{elbows}\right) \cdot \rho_{H2}\left(T_{vent}, P_{vent}\right) \cdot \frac{{v_{vent}}^2}{2} + \Delta P_{flex} = 0.946\ psi$$

First stage relief (ASME Relief Valve):

The pressure at the back side of the first stage relief is

$$P_2 := P_{plate} \cdot 1.1 + \Delta P_{vent} = 19.316\ psi$$

pressure on upstream of 1st stage relief valve

$$P_1 := P_{set} \cdot 1.1 = 33\ psi$$

upstream pressure assumed

$$Pc_1 := Rc_{H2} \cdot P_{set} \cdot 1.1 = 17.422\ psi$$

critical pressure at 1st stage relief

The flow at the 1st stage relief will be subcritical

$$r := \frac{P_2}{P_1}$$ ratio of outlet to inlet pressures

$$F_2 := \sqrt{\frac{k_{H2}}{k_{H2}-1} \cdot r^{\frac{2}{k_{H2}}} \cdot \left(\frac{1 - r^{\frac{k_{H2}-1}{k_{H2}}}}{1-r}\right)} = 0.747$$ subcritical flow coeff

$$K_{valve} := 0.878 \cdot 0.9$$ Coef of discharge

$$D_{plate} := 2.245 \cdot in$$ most restrictive diameter of relief

$$C_{asme} := 17.9 \cdot \frac{hr}{kg} \cdot \sqrt{\frac{gm}{K \cdot mol}} \cdot \frac{kN}{m^2} \cdot mm^2$$ Coeff determined from ratio k now for subcritical flow

the required area for the given mass discharge is

$$A_{req} := \frac{dm_{H2} \cdot C_{asme}}{F_2 \cdot K_{valve}} \cdot \sqrt{\frac{T_{room}}{M_{H2} \cdot P_1 \cdot \left(P_1 - P_2\right)}} = 0.111\ in^2$$

Relief valve:

Based on the above a Flow Safe F85 Series relief valve 01-4167M-203 with viton seat will be more than adequate for our needs. The pressure at the entrance of the relief is assumed to be.

$$P_{relief} := 1.1 \cdot P_{set} = 33\ psi$$

Piping from cell to relief

For all piping from the main relief line tee, located below the condenser, to the relief at the panel the temperatureand pressure of the H2 is assumed to be the same as that at the relief valve. This is a very conservative assumption. Thus the density and volumetric flow are

$$\rho := \rho_{H2}\left(T_{vent}, P_{relief}\right) = 0.184\ \frac{kg}{m^3}$$

$$dV_{H2} := \frac{dm_{H2}}{\rho} = 0.043\ \frac{m^3}{s}$$

Piping from Target Top flange to Relief Valve:

The relief valve will be mounted on the gas panel. The gas panel is assumed to be 10 ft from the top of the target by hose. This connection is assumed to be made using 1" nominal flex hose. These lines are named the connection lines. There is also an abrupt enlargement from 3/4" tube to 1 in ID. The flow must pass through a 1" Tee branch to reach the relief valve.

Flex lines:

$$L_{cl} := (10 \cdot ft) \cdot 3$$

effective length of flex line for connection lines from gas panel to target is 6 ft. The factor of 3 results from measurements of pressure drop in corregated flex hose

$$ID_{cl} := 1 \cdot in$$

ID of flex lines

$$A_{cl} := \pi \cdot \frac{ID_{cl}^{\ 2}}{4}$$

cross area of flex

$$f_{cl} := \frac{0.032 \cdot in^{\frac{1}{3}}}{ID_{cl}^{\ \frac{1}{3}}} = 0.032$$

Weymouth friction factor

$$v_{cl} := \frac{dV_{H2}}{A_{cl}} = 83.881\ \frac{m}{s}$$

velocity in flex line

$K_{cl} := f_{cl} \cdot \frac{L_{cl}}{ID_{cl}} = 11.52$ resistance coef for flex line

$\Delta P_{cl} := K_{cl} \cdot \rho_{H2300} \cdot \frac{v_{cl}^{2}}{2} = 0.982\ psi$ pressure loss in flex line

Gas panel:

$L_{gp} := (2 \cdot ft)$ estimated length of gas panel tubing to valve

$t_{wall} := 0.035 \cdot in$

$OD := 1 \cdot in$

$ID_{gp} := OD - 2 \cdot t_{wall}$ ID of gas panel return tube

$A_{gp} := \pi \cdot \frac{ID_{gp}^{2}}{4}$ cross area of return tube

$f_{gp} := \frac{0.032 \cdot in^{\frac{1}{3}}}{ID_{gp}^{\frac{1}{3}}} = 0.033$ Weymouth friction factor

$v_{gp} := \frac{dV_{H2}}{A_{gp}} = 96.983\ \frac{m}{s}$ velocity in return tube

$K_{gp} := f_{gp} \cdot \frac{L_{gp}}{ID_{gp}} = 0.846$ resistance return

$K_{tee} := 60 \cdot f_{gp}$ resistance of tee branch

$K_{elbow} := 60 \cdot f_{gp}$ resistance of elbow at tgt top

$\Delta P_{gp} := (K_{tee} + K_{elbow} + K_{gp}) \cdot \rho \cdot \frac{v_{gp}^{2}}{2} = 0.6\ psi$

Enlargement from 3/4 tube to 1" id flex

$d_1 := (0.75 - 2 \cdot 0.035) \cdot in$ ID of target return line at top of target

$A_1 := \frac{\pi}{4} \cdot d_1^{\ 2} = 0.363\ in^2$ cross area

$v_1 := \frac{dV_{H2}}{A_1} = 181.403\ \frac{m}{s}$ velocity at tgt top

$d_2 := 1 \cdot in$ ID of flex

$$\beta := \frac{d_1}{d_2}$$

$$K_{en} := \frac{\left(1 - \beta^2\right)^2}{\beta^4} = 1.352$$

$$\Delta P_{en} := K_{en} \cdot \rho \cdot \frac{v_{gp}^{\ 2}}{2} = 0.17\ psi$$

Total pressure drop on tgt external return to relief valve

$$\Delta P_{ext} := \Delta P_{en} + \Delta P_{gp} + \Delta P_{cl} = 1.751\ psi$$

Internal target piping pressure loss:

Escaping gas from the cell must pass through several piping sections prior to reaching the valve. Some of these sections are inside the OVC and are cold for some portion. From the cell to the tee below the condenser, the escaping gas is assumed to have a temperature of 23.4K and pressure of 33 psi. From the relief tee to the target top flange the assume temperature is 300 K. The worst case failure mode would be for the condenser to relief tee to be blocked while the target vacuum is lost. All flow must then pass through the return side plumbing from the cell.

From relief tee to target top flange

$L_{ret} := 3 \cdot ft$ Length of return lines

$D_{ret} := 0.75 \cdot in$ OD of supply and return lines

$D_{tee} := 0.5 \cdot in$ nominal diameter of relief tee

$t_{wall} := 0.035 \cdot in$ wall thickness of lines

$ID_{ret} := D_{ret} - 2 \cdot t_{wall}$ ID of supply and return lines

$ID_{tee} := D_{tee} - 2 \cdot t_{wall}$ ID of lines at tee

$A_{ret} := \pi \cdot \frac{ID_{ret}^{\,2}}{4} = 0.363\ in^2$ cross area of return

$f_{ret} := \frac{0.032 \cdot in^{\frac{1}{3}}}{ID_{ret}^{\frac{1}{3}}} = 0.036$ Weymouth friction factor (conservative)

$v_{ret} := \frac{dV_{H2}}{A_{ret}} = 181.403\ \frac{m}{s}$ velocity in return line

$K_{ret} := f_{ret} \cdot \frac{L_{ret}}{ID_{ret}} = 1.927$ resistance coef for return line

$K_{elbow} := f_{ret} \cdot 60 = 2.183$ resistance coef for miter bends in line assume 2

$\beta := \frac{ID_{tee}}{ID_{ret}}$

$K_{en} := \frac{\left(1-\beta^2\right)^2}{\beta^4} = 2.252$ resistance factor for enlargement

pressure loss in ret line to relief valve

$$\Delta P_{ret} := \left(K_{ret} + 2 \cdot K_{elbow} + K_{en}\right) \cdot \rho \cdot \frac{v_{ret}^{\;2}}{2} = 3.75\ psi$$

Cell to relief tee line

$L_{rl} := 12 \cdot ft$ Length of line 6 ft plus 2 ft flex

$D_{rl} := 0.5 \cdot in$ OD of supply and return lines

$t_{wall} := 0.035 \cdot in$ wall thickness of lines

$ID_{rl} := D_{rl} - 2 \cdot t_{wall}$ ID of supply and return lines

$A_{rl} := \pi \cdot \frac{ID_{rl}^{\;2}}{4} = 0.145\ in^2$ cross area of return

$\rho_{H2} := 2.81 \cdot \frac{kg}{m^3}$ density of H2 at 33 psi and 23.4K (boiling point)

$f_{rl} := \frac{0.032 \cdot in^{\frac{1}{3}}}{ID_{rl}^{\;\frac{1}{3}}} = 0.042$ Weymouth friction factor (conservative)

$v_{rl} := \frac{dm_{H2}}{A_{rl} \cdot \rho_{H2}} = 29.688\ \frac{m}{s}$ velocity in return line

$K_{rl} := f_{rl} \cdot \frac{L_{rl}}{ID_{rl}} = 14.198$ resistance coef for return line

$K_{elbow} := f_{rl} \cdot 20 = 0.848$ resistance coef for short radius r=d bends in line assume 2

$K_{tee} := f_{rl} \cdot 60$ resistance coef for branch line at tee pressure loss in ret line to relief valve

$$\Delta P_{rl} := \left(K_{rl} + 2 \cdot K_{elbow} + K_{tee}\right) \cdot \rho_{H2} \cdot \frac{{v_{rl}}^2}{2} = 3.311 \; psi$$

loss from cell legs

$L_{leg} := 5 \cdot in$ Length of leg

$D_{leg} := 0.375 \cdot in$ OD of leg

$t_{wall} := 0.035 \cdot in$ wall thickness of line

$ID_{leg} := D_{leg} - 2 \cdot t_{wall}$ ID of leg

$A_{leg} := \pi \cdot \frac{{ID_{leg}}^2}{4} = 0.073 \; in^2$ cross area of leg

$\rho_{H2} := 2.81 \cdot \frac{kg}{m^3}$ density of H2 at 33 psi and 23.4K (boiling point)

$f_{leg} := \frac{0.032 \cdot in^{\frac{1}{3}}}{{ID_{leg}}^{\frac{1}{3}}} = 0.048$ Weymouth friction factor (conservative)

$v_{leg} := \frac{dm_{H2}}{A_{leg} \cdot \rho_{H2}} = 59.009 \; \frac{m}{s}$ velocity in leg

$K_{leg} := f_{leg} \cdot \frac{L_{leg}}{ID_{leg}} = 0.779$ resistance coef for leg

$$\beta := \frac{ID_{leg}}{ID_{rl}}$$

$K_{en} := \frac{\left(1 - \beta^2\right)^2}{\beta^4} = 0.975$ resistance factor for enlargement

$$\Delta P_{leg} := \left(K_{leg} + K_{en}\right) \cdot \rho_{H2} \cdot \frac{{v_{leg}}^2}{2} = 1.245 \; psi$$

Flow must exit the cell first through a tapered anulus that preceeds the leg. To estimate this flow the hydraulic diameter will be used. the flow is from the cell and condenser only. The entrance to the leg tube is also acounted for

annulus exit from cell

$$D_{in} := \frac{(0.738 \cdot in + 0.906 \cdot in)}{2} = 0.822\ in$$ avg small diameter of anulus

$$D_{out} := (0.479 + 0.516) \cdot in = 0.995\ in$$ avg large diameter of anulus

$$P_{in} := D_{in} \cdot \pi$$ average perimeter inner

$$P_{out} := D_{out} \cdot \pi$$ average perimeter outer

$$A := \frac{\pi}{4} \cdot \left(D_{out}^{2} - D_{in}^{2}\right) = 0.247\ in^{2}$$ flow area

$$D_h := \frac{4 \cdot A}{\left(P_{in} + P_{out}\right)} = 0.173\ in$$ hydraulic diameter

$$\rho_{H2} := 2.81 \cdot \frac{kg}{m^{3}}$$ density of H2 at 33 psi and 23.4K (boiling point)

$$f_{cell} := \frac{0.032 \cdot in^{\frac{1}{3}}}{D_h^{\frac{1}{3}}} = 0.057$$ Weymouth friction factor (conservative)

$$v_{cell} := \frac{dm_{cond} + dm_{cell}}{\pi \cdot \frac{D_h^{2}}{4} \cdot \rho_{H2}} = 113.446\ \frac{m}{s}$$ velocity in cell annulus

$$K_{cell} := f_{cell} \cdot \frac{2.8 \cdot in}{D_h} = 0.929$$ resistance coef for leg

$$\beta := \frac{ID_{leg}}{D_h} = 1.763$$ ratio for contraction to 3/8 tube

$$K_{cont} := 0.5 \cdot \frac{\left(1-\beta^2\right)}{\beta^4}$$

estimate of pressure drop in cell annulus and exit

$$\Delta P_{cell} := \left(K_{cell} + K_{cont}\right) \cdot \rho_{H2} \cdot \frac{{v_{cell}}^2}{2} = 2.152\ psi$$

Total maximum cell pressure:

Max total cell absolute pressure from the above calculations and assumptions

$$P_{cell} := \Delta P_{cell} + \Delta P_{ret} + \Delta P_{rl} + \Delta P_{leg} + P_{relief} + \Delta P_{ext} = 45.209\ psi$$

Loss in supply line

$L_{sup} := 12 \cdot ft$ Length of leg 6 ft + 2 ft of flex

$D_{sup} := 0.25 \cdot in$ OD of leg

$t_{wall} := 0.035 \cdot in$ wall thickness of line

$ID_{sup} := D_{sup} - 2 \cdot t_{wall}$ ID of leg

$A_{sup} := \pi \cdot \frac{{ID_{sup}}^2}{4} = 0.025\ in^2$ cross area of leg

$\rho_{H2} := 2.81 \cdot \frac{kg}{m^3}$ density of H2 at 33 psi and 23.4K (boiling point)

$f_{sup} := \frac{0.032 \cdot in^{\frac{1}{3}}}{{ID_{sup}}^{\frac{1}{3}}} = 0.057$ Weymouth friction factor (conservative)

$v_{sup} := \frac{dm_{cond}}{A_{sup} \cdot \rho_{H2}} = 64.629\ \frac{m}{s}$ velocity in leg

$K_{sup} := f_{sup} \cdot \frac{L_{sup}}{ID_{sup}} = 45.34$ resistance coef for leg

$\beta := \frac{ID_{sup}}{ID_{leg}}$

$K_{en} := \frac{\left(1-\beta^2\right)}{\beta^4} = 5.372$ resistance factor for enlargement

$K_{ent} := 0.5$ resistance coef for cond pipe entrance

The maximum pressure in the condenser for the worst case failure mode where the main relief connection is plugged.

$$P_{cond} := P_{cell} + \left(K_{en} + K_{ent} + K_{sup}\right) \cdot \rho_{H2} \cdot \frac{{v_{sup}}^2}{2} = 88.799 \; \boldsymbol{psi}$$

the dominant loss is in the 1/4 in line as expected

$$\Delta P_{sup} := K_{sup} \cdot \rho_{H2} \cdot \frac{{v_{sup}}^2}{2} = 38.591 \; \boldsymbol{psi}$$