Fermilab

Particle Physics Division
Mechanical Department Engineering Note

Number: PPD doc   Date: Oct 31, 2011

Project: CMS Upgrade Cooling System Test Design

Title:CMS CO_2 Half Disk Assembly Piping Note

Author(s): Erik Voirin

Reviewer(s): Andy Stefanik

Key Words: Piping note, 31.3, ASME, 5031

Abstract Summary:

The CMS CO_2 half disk experiment contains a cooling loop from a half disk of the CMS FPIX detector. It will attach to the CMS CO2 test stand via ¼" copper tube. The design pressure of the experiment assembly is the same as the CO_2 cooling test stand (1200psi). This note quantifies the strength of the assembly and provides details on the tubing system and its components, showing it conforms to ASME 31.3 code for process piping.

Table of Contents

1. FESHM 5031.1 PIPING ENGINEERING NOTE FORM

Prepared by: **Erik Voirin** Preparation Date: **10-31-2011**

Piping System Title: **CMS CO_2 Half Disk Experiment**

Lab Location: **Lab C** Location code: **604**

Purpose of system: **Two Phase Carbon Dioxide Cooling Experiments**

Piping System ID Number: **none assigned to date**

Appropriate governing piping code: **ASME B31.3 Category: Normal Fluid Service**

Fluid Service Category (if B31.3): **Normal Fluid Service**

Fluid Contents: **Carbon Dioxide**

Design Pressure: **1200 psi**

Piping Materials: **304 SS and Copper tubing**

Drawing Numbers (PID's, weldments, etc.): **none**

Designer/Manufacturer: **Fermilab**

Test Pressure: **1320 psig** Test Fluid: **Nitrogen** Test Date: **Nov 1, 2011**

Statements of Compliance

Piping system conforms to FESHM 5031.1, installation ***is not*** exceptional: **Yes**

Piping system conforms to FESHM 5031.1, installation ***is*** exceptional and has been designed, fabricated, inspected, and tested using sound engineering principles: **N/A**

Reviewed by: ______________________________ (Print Name)

Signature: ______________________________Date: __________

D/S Head's Signature: ______________________________Date: __________

The following signatures are required for exceptional piping systems:

ES&H Director's Signature: ______________________________Date: __________

Director's Signature or Designee: ________________________Date: ____________

Pipe Characteristics

Size**: ¼" copper tubingS: ½" to 1.5": Refer to Drawings** Volume: **< 75 mL**

Relief Valve Information:

Type: **Spring Loaded** Manufacturer: **Kepner**

Set Pressure: not applicable Relief Capacity: **1200 psig**

Relief Design Code: **ASME**

Is the system designed to meet the identified governing code? **Yes**

Fabrication Quality Verification:

Process and Instrumentation diagram appended? **Yes**

Process and Instrumentation component list appended? **Yes**

Is an operating procedure necessary for safe operation? **No**

If 'yes', procedure must be appended.

Exceptional Piping System

Is the piping system or any part of it in the above category? **No**

If "Yes", follow the requirements for an extended engineering note for Exceptional Piping Systems.

Quality Assurance

List vendor(s) for assemblies welded/brazed off site: **None**

List welder(s) for assemblies welded/brazed in-house: **None**

Append welder qualification Records for in-house welded/brazed assemblies. **N/A**

Append all quality verification records required by the identified code (e.g. examiner's

certification, inspector's certification, test records, etc.) **Yes**

2. Description and Identification

The tubing in the CMS CO_2 Half Disk assembly is an experimental setup which will be used to test the cooling characteristics of two phase carbon dioxide. The assembly and all components designed to accommodate 1200 psi of internal pressure. This design pressure was chosen so the assembly would match the design pressure of the CMS CO2 Cooling Test Stand, which it will connect to. Information on the piping note and design criteria for the CMS CO2 cooling test stand can be found in PPD-Doc 1347. All tubing is 0.25" OD x 0.03" wall copper tubing purchased from the Fermilab stockroom. The half disk assembly is a custom 304SS micro-tube with dimensions 1.6mm OD x 1mm wall. A system overview can be seem in Fig.1

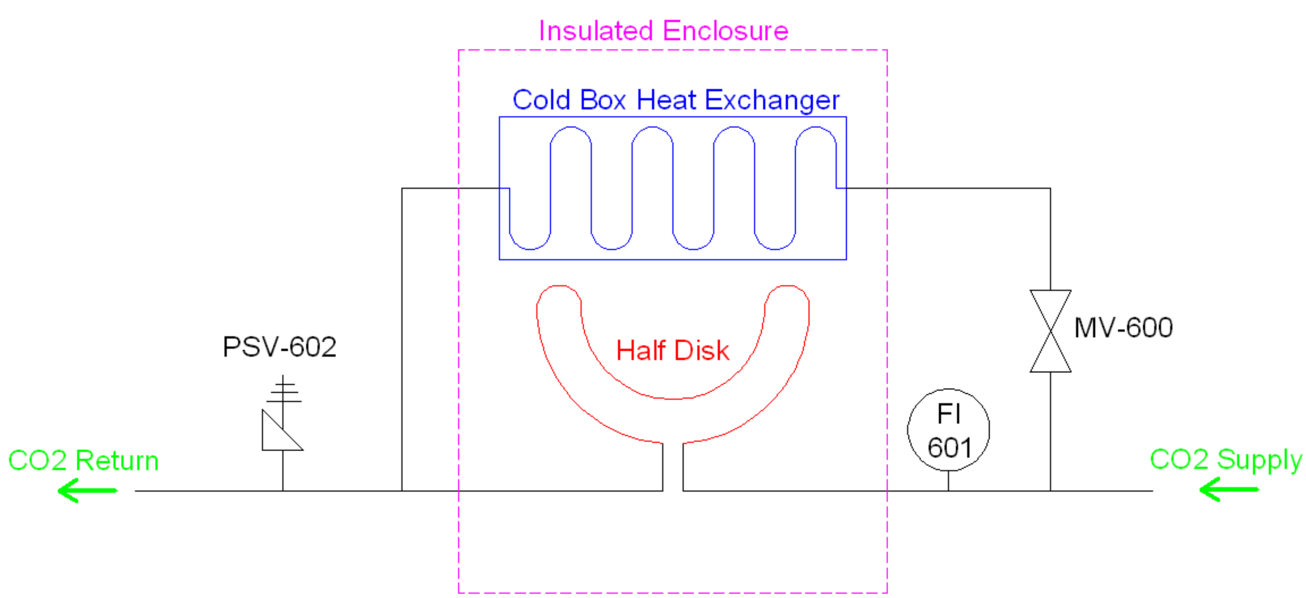


Figure 1: CMS CO2 half disk assembly.

3. Design Verification

Applicable Code:

The tubing and half disk assembly meets the requirements of Section 5031.1 of the Fermilab ES&H Manual. This section states that this piping system falls under the category of Normal Fluid Service and shall adhere to the requirements of the ASME Process Piping Code B31.3.

Materials:

The half disk micro-tube is fabricated from 304 stainless steel. The allowable stress for this material from Table A-1 of ASME B31.3 is 16,700 psi. Custom adapters also made of 304 stainless steel are used in the assembly which connect the micro tube to standard ¼” compression fittings. The copper tube at its fully annealed state (weakest) has an allowable stress of 6300 psi.

The experiment will be operated at -20C. This is above the minimum temperature listed for 304/316 stainless steel pipe or tube (19 K) as well as copper (4K). According to Table 323.2.2 of the Code, impact testing is not required for these austenitic stainless steels. (Reference “Bo LarTPC Cryostat Piping System Engineering Note” by T. Tope)

Stress analysis:

Calculations were done for stress due to internal pressure. The design uses standard compression fittings, which are rated to a minimum of 1600 psi.

ASME code formulas for stress due to internal pressure have shown to not give true values for pipe stress; in addition they require conversion factors to be used if the thickness to diameter ratio is above a certain value. If these conversion values are not used stress can be severely underestimated. For these reasons the stress due to internal pressure is calculated using the actual formula for stress in a hollow cylinder due to internal pressure. This formula has shown to give higher values than the ASME formula so if anything it is more conservative without the correction factors that can easily be forgotten. This shows a stress due to internal pressure below the allowable limit of 16.7 ksi for the stainless steel and 6.3 ksi for the copper.

$$\sigma_{hoop}(r) := \frac{r_i^2 \cdot p_i}{r_o^2 - r_i^2} \cdot \left(1 + \frac{r_o^2}{r^2}\right)$$ (eq: 3.50 Cengal[1])

Where: p_i = internal design pressure

r_i = inside radius of cylinder (manufacturers nominal value is used)

r_o = outside radius of cylinder (manufacturers nominal value is used)

r = radius where stress is evaluated (maximum stress is at inner wall)

Calculations for copper tubing and stainless steel parts:

Copper Tubing

$p_i := 1200\text{psi}$

$r_o := 0.125\text{in}$ $t_{wall} := 0.03\text{in}$ $r_i := r_o - t_{wall}$

$$\sigma_{hoopCopper} := \frac{r_i^2 \cdot p_i}{r_o^2 - r_i^2} \cdot \left[1 + \frac{r_o^2}{(r_i)^2}\right] = 4482\,\text{psi}$$

Stainless Steel Micro Tubing

$r_o := 0.8\text{mm}$ $t_{wall} := 0.1\text{mm}$ $r_i := r_o - t_{wall}$

$$\sigma_{hoopMicroTube} := \frac{r_i^2 \cdot p_i}{r_o^2 - r_i^2} \cdot \left[1 + \frac{r_o^2}{(r_i)^2}\right] = 9040\,\text{psi}$$

Custom Adapters

$r_o := 0.125\text{in}$ $r_i := 0.8\text{mm}$

$$\sigma_{hoopAdapter} := \frac{r_i^2 \cdot p_i}{r_o^2 - r_i^2} \cdot \left[1 + \frac{r_o^2}{(r_i)^2}\right] = 1363\,\text{psi}$$

4. Pressure Containment / Relief System

Relief Valves:

The half disk and tubing assembly is equipped with a trapped volume relief valve. This relief valve is set to open at 1200 psig. Manufactured by Kepner, the relief valves are equipped with an orifice 0.267in in diameter.

Calculations were performed which show the capacity of these valves more than meets the criteria of API 521 and ASME standards. Inlet and outlet pressure drop is not calculated since the valve is attached directly to the tubing and does not vent through an outlet tube. Details of these calculations are shown in the following pages.

Scenario Check List (API 521)

1. Closed outlets - N/A Item 9 will be analyzed including abnormal heat input, hydraulic expansion, and closed outlets.
2. Coolant failure - Not applicable.
3. Top reflux failure - Not applicable.
4. Side reflux failure - Not applicable
5. Lean Oil failure to absorber - Not applicable.
6. Accumulation of noncondensables - Not applicable,
7. Entrance of highly volatile material - Not applicable.
8. Overfilling - Overfilling is possible but is not a source of overpressure The available supply pressure less than vessel design (MAWP) pressure.
9. **Control Failure - Heater could remain on at maximum heat input of 50W with closed supply and return line (This Item will cover items 1 and 14).**
10. Abnormal heat or vapor input - worst case would be item 9
11. Split exchanger tube - NA
12. Internal explosion - NA
13. Chemical reaction - NA
14. Hydraulic expansion - N/A Item 9 will be analyzed including abnormal heat input, hydraulic expansion, and closed outlets.
15. **Exterior fire - Possible that small quantity of flammables (box/papers) are near the assembly.**
16. Power failure (steam, electric, air, other) - same as item 8

Item 9, and 15 above are identified as possible sources of overpressure. Calculations show item 9 requires a relief rate of 1.25 kg/kr and item 15 requires 2.1 kg/hr. The relief valve is capable of over 10000 kg/hr and is more than adequate for any possible relief rates.

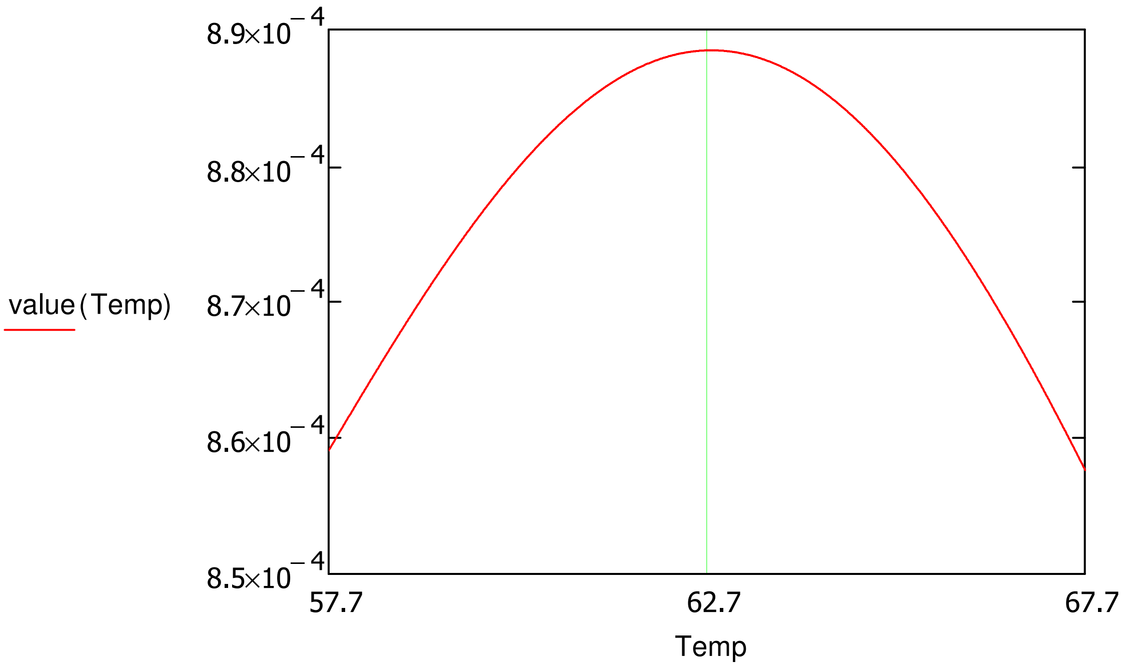
Evaluation of Overpressure Scenario 9 - Control Failure

According to Compressed gas assocoation, the critical temperature for which calculations should be made for relieving a supercritical fluid are when: $\frac{\sqrt{v}}{v\cdot\left(\frac{\delta h}{\delta v_p}\right)}$ is at a maximum. CGA states at 200 psia the maximum value for hydrogen occurs at 62.7R. A Calculation method will be tested against hydrogen's given value to test for accuracy of the method.

$$dh_{dv}(Temp) := -0.514512683Temp^3 + 110.595964Temp^2 - 7937.122633Temp + 193723.0553$$

$$rootV(Temp) := -0.0002Temp^2 + 0.0345Temp - 1.0974$$

$$value(Temp) := \frac{1}{\left[(dh_{dv}(Temp))\cdot(rootV(Temp))\right]}$$



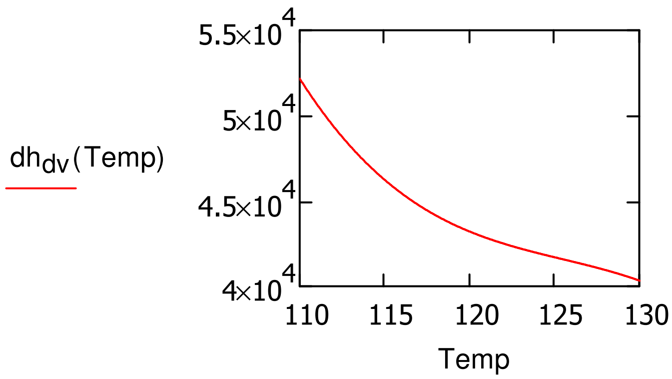
Method Works and is consistant with hydrogen gas value from Compressed gas association

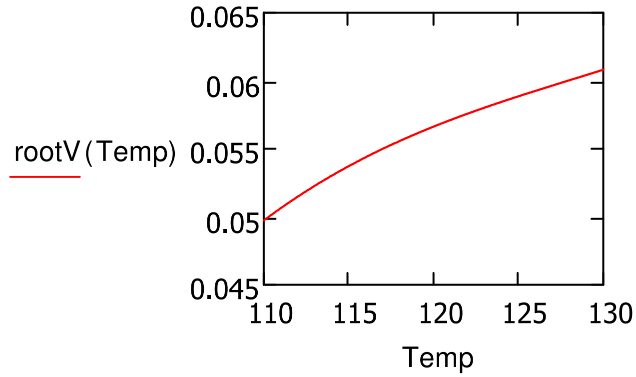
Same method will be udes to find the relief valve calculation Temperature of Carbon Dioxide at 1320psi

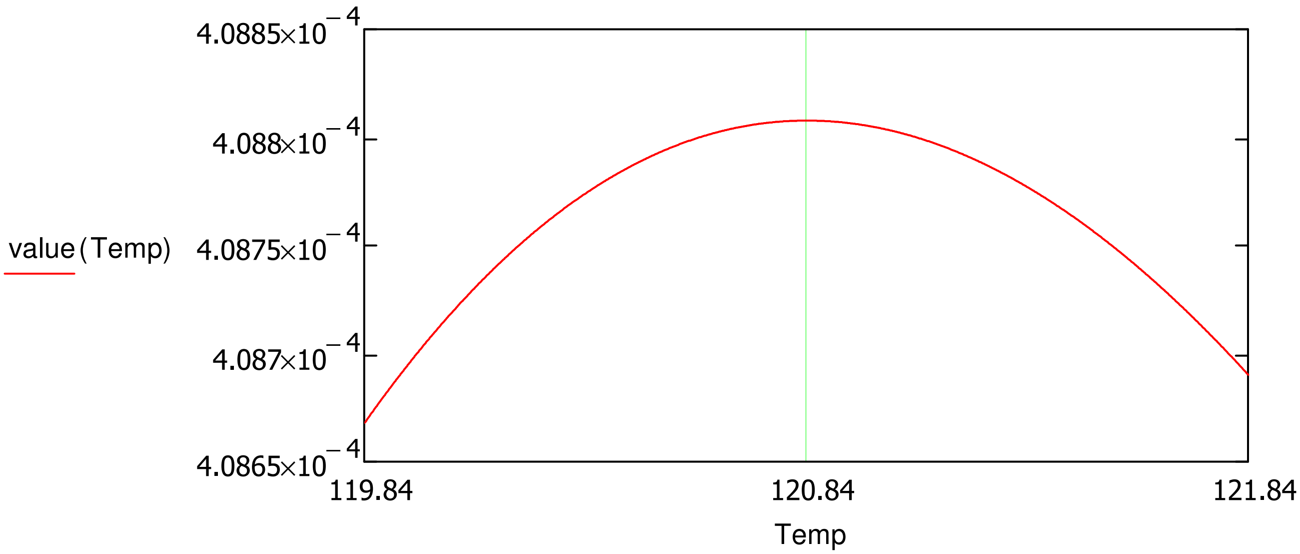
$$dh_{dv}(Temp) := -1.846799534\cdot Temp^3 + 695.2825211Temp^2 - 87493.47076Temp + 3721622.95$$

$$rootV(Temp) := 5.39422\cdot 10^{-7}Temp^3 - 0.000207814Temp^2 + 0.027073145Temp - 1.131746719$$

$$value(Temp) := \frac{1}{\left[(dh_{dv}(Temp))\cdot(rootV(Temp))\right]}$$







Temperature for Supercritical fluid relief calculations will be made using this temperature of 120.84 F.

Table generated by RefProp

Temperature (°F)	Pressure (psig)	Density (kg/m³)	Volume (m³/kg)	Enthalpy (kJ/kg)	Entropy (kJ/kg-°R)	Heat of Vapor. (kJ/kg)	Viscosity (μPa-s)
108.84	1320.0	424.45	0.0023560	362.93	0.84417	Undefined	30.562
120.84	1320.0	307.50	0.0032520	405.78	0.91887	Undefined	24.165
140.84	1320.0	243.57	0.0041056	440.59	0.97792	Undefined	21.889

$$\frac{dV}{dH} \quad \text{is} \quad dV_{dh} := \frac{(0.0041056 - 0.0023560)\dfrac{m^3}{kg}}{(440.59 - 362.93)\dfrac{kJ}{kg}} = 2.253 \times 10^{-5} \cdot \frac{m^3}{kJ}$$

derivative approach:

$$Volume(H) := 4.91347 \cdot 10^{-8} H^2 - 1.67055 \cdot 10^{-5} H + 0.001939965$$

$$\frac{d}{dH} Volume(H) \rightarrow 9.82694e\text{-}8 \cdot H - 0.0000167055 \qquad H := 405.78$$

$$9.82694e\text{-}8 \cdot H - 0.0000167055 = 2.317 \times 10^{-5}$$ virtually the same

$$\rho_{co2} := 307.50 \frac{kg}{m^3}$$

$$Heater_{Power} := 50W$$

Required Relief Rate for scenario 9

METHOD 1 API std 520

$$ReliefRate_{50W\_heater} := dV_{dh} \cdot Heater_{Power} \cdot \rho_{co2} = 1.247 \cdot \frac{kg}{hr}$$

Back Pressure Factor

$$K_b := 1.0$$

Coefficient of discharge

$$K_d := 0.816$$

Combination Factor

$$K_c := 1.0$$

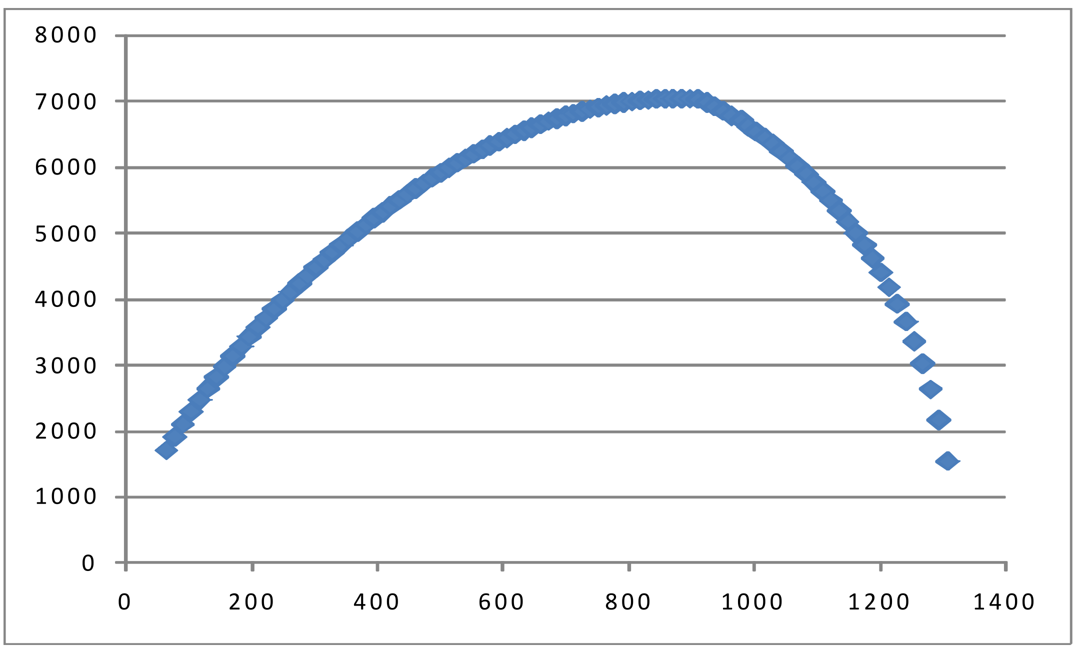
$$\Pi K := K_b \cdot K_d \cdot K_c$$

$$W_R := ReliefRate_{50W\_heater}$$

Theoretical Mass flux rate

$$G := 7030.31 \frac{lb}{s \cdot ft^2}$$

found by methods listed in API std 520



(API std 520 equation B.5)

$$W_R = G \cdot Area_{orifice} \cdot \Pi K$$

$$Area_{orifice} := \frac{W_R}{G \cdot \Pi K} = 0.00002 \cdot in^2$$

This area seems extremely small, however with a calculated relief pressure of 1320psi the calculation is accurate. Subsequent orifice calculations will follow to test for consistancy.

Required Relief Rate for scenario 9 METHOD 2

Relief Rate

$W_R = 2.7 \cdot \frac{lb}{hr}$

Unitless Relief Rate

$W_u := \frac{W_R}{\frac{lb}{hr}}$

Compressibility factor

$Z := .49103$

Coeff. of Discharge

$K_1 := K_d = 0.816$

C Value for CO2

$C := 345$

Backpressure Coefficient

$K_b = 1$

Molecular weight

$M := 44$

10% Overpressure

$P_1 := 1320 + 14.3$

Absolute temperature

$T := (120.8 + 460)$

$$Area := \frac{W_u \cdot \sqrt{T} \cdot \sqrt{Z}}{C \cdot K_1 \cdot P_1 \cdot K_b \cdot \sqrt{M}} = 0.00002\ in^2$$

which is very consistant with the previous method

Evaluation of Overpressure Scenario 15 - Exterior Fire

Calculate relief rate based on a blocked in fire scenario

Per API 521 sec. 5.15.1.1
To detemine vapour generation, it is necessary to recognize only the portion of the piping that is wetted by its internal liquid and is equal to or less than 25 ft above the flame.

Relief valve Set Pressure vessel Design P (MAWP)

$P_{set} := 1200 \cdot psi$

Equivalent Lenth of Vessel

$L_E := 75in$

Tubing ID:

$D := 0.25in - 2 \cdot 0.03in$

$Pipe_{area} := \pi \cdot L_E \cdot D = 0.03\, m^2$

$Pipe_{area} = 0.3 \cdot ft^2$

Total Vessel Wetted Surface Area:

$Av := Pipe_{area} = 0.3 \cdot ft^2$

$Av = 0.03\, m^2$

Physical Properties of vapor @ Relieving Conditions:

Molecular Weight

$M_w := 44.01 \cdot \frac{kg}{kgmole}$

Supercritical Temperature at relieving pressure

$T_{in} := 322.51 \cdot K$

Gas Compressibility

$Z := 0.49103$

Heat Capacity Ratio

$\gamma := 4.3081$

Heat Capacity

$Cpgas := 2.3788 \cdot \frac{kJ}{kg \cdot K}$

Viscocity

$\mu := 24.165 \mu Pa \cdot s$

Determination of Insulation Credit (per API 521 5.15.5.4)

Insulation Thermal Conductivity (ambient conditions)

$k_{ins.ambient} := 0.035 \cdot \frac{W}{m \cdot K}$

Insulation Thickness

$Insul_{Th} := 0.5in$

API Calculation for F, with units added to factor for unit consistency

$$F := \frac{k_{ins.ambient} \cdot \left[(904 + 273.15)K - T_{in}\right]}{66570 \cdot \frac{kg}{s^3} \cdot Insul_{Th}} = 0.0354$$

API 521 eq. 13
sect. 5.15.5.4
The implied units of the API conversion factor are kg/sec^3.

CHECK: Same calculation forcing the units choice to use the API formula in unitless fashion. The result is the same.

$$\frac{k_{ins.ambient} \cdot \frac{1}{\frac{W}{m \cdot K}} \cdot \left[(904 + 273.15)K - T_{in}\right] \cdot \frac{1}{degC}}{66570 \cdot Insul_{Th} \cdot \frac{1}{m}} = 0.0354$$

Required Relief Rate for scenario 15 - Exterior Fire

$$Qv := 21000 \cdot \left(\frac{BTU}{hr}\right) \cdot F \cdot \left(\frac{Av}{ft^2}\right)^{0.82}$$

$Qv = 285 \cdot \frac{BTU}{hr}$

$Qv = 83.5 \cdot W$

Equation from API 521

$ReliefRate_{fire} := dV_{dh} \cdot Qv \cdot \rho_{co2} = 2.1 \cdot \frac{kg}{hr}$

Comparing Scenario Relief Rates

The relief rate of the fire scenario is higher than the 50W heat input, so this value will be used to rate the relief valve.

Required Relief Rate for scenario 15   METHOD 1 API std 520

Back Pressure Factor

$K_b := 1.0$

Coefficient of discharge

$K_d := 0.816$

Combination Factor

$K_c := 1.0$

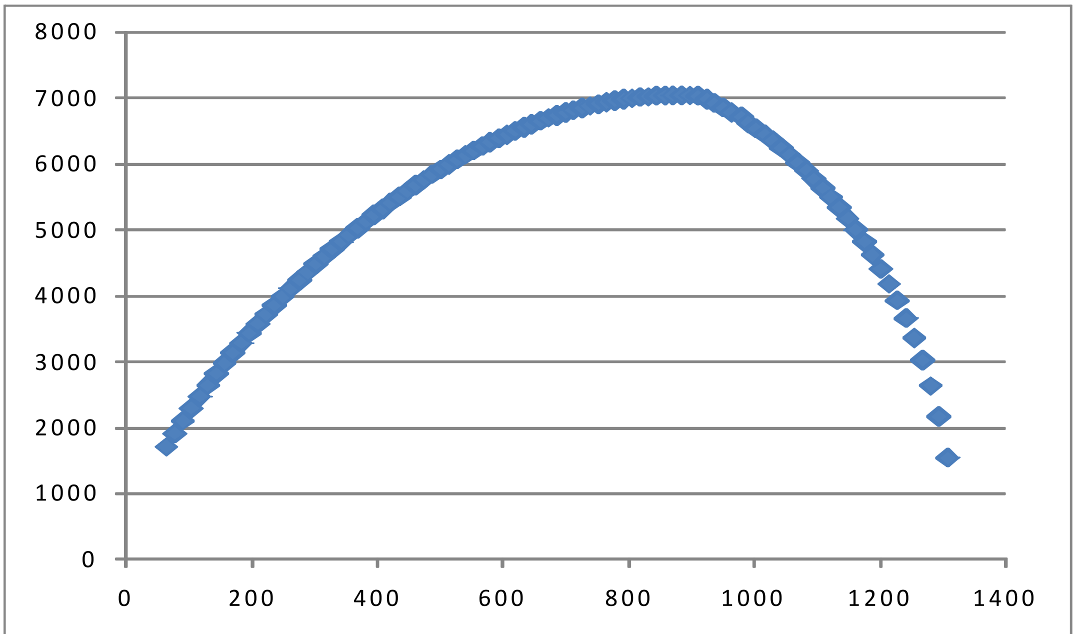
$\Pi K := K_b \cdot K_d \cdot K_c$

$W_R := ReliefRate_{fire}$

Theoretical Mass flux rate

$$G := 7030.31 \frac{lb}{s \cdot ft^2}$$

found by methods listed in API std 520



(API std 520 equation B.5)

$W_R = G \cdot Area_{orifice} \cdot \Pi K$

$$Area_{orifice} := \frac{W_R}{G \cdot \Pi K} = 0.00003 \cdot in^2$$

This area seems extremely small, however with a calculated relief pressure of 1320psi the calculation is accurate. Subsequent orifice calculations will follow to test for consistancy.

Required Relief Rate for scenario 15   METHOD 2

Relief Rate

$W_R = 4.6 \cdot \frac{lb}{hr}$

Unitless Relief Rate

$W_u := \frac{W_R}{\frac{lb}{hr}}$

Compressibility factor

$Z := .49103$

Coeff. of Discharge

$K_1 := K_d = 0.816$

C Value for CO2

$C := 345$

Backpressure Coefficient

$K_b = 1$

Molecular weight

$M := 44$

21% Overpressure

$P_1 := 1200 \cdot 121\% + 14.3$

Absolute temperature

$T := (120.8 + 460)$

$$\text{Area} := \frac{W_u \cdot \sqrt{T} \cdot \sqrt{Z}}{C \cdot K_1 \cdot P_1 \cdot K_b \cdot \sqrt{M}} = 0.00003 \ in^2$$

which is very consistant with the previous method

Actual Relief Rate - Based on a selected relief valve flow chart

The selected orifice size must be equal or greater than the required size.

The following flow orifice size was given by the manufacturer: orifice size=0.069in^2

METHOD 1

$W_{Relief} := G \cdot 0.069 in^2 \cdot \Pi K = 9896 \cdot \frac{lb}{hr}$

$Vol_{Relief} := \frac{W_{Relief}}{\rho_{co2}} = 0.143 \cdot \frac{ft^3}{sec}$

METHOD 2

$$W_{relieved} := \left(\frac{0.069 \cdot C \cdot K_1 \cdot P_1 \cdot K_b \cdot \sqrt{M}}{\sqrt{T} \cdot \sqrt{Z}} \right) \frac{lb}{hr} = 5075 \cdot \frac{kg}{hr}$$

Relief needed: $W_R = 2.1 \cdot \frac{kg}{hr}$

This shows even the smallest orifice size is more than large enough. No inlet or outlet piping pressure drops are calculated since the relief valve is mounted directly on the tubing assembly and does not relieve through an outlet line.

5. Component Identification

Process and Instrument diagram:

The process and instrument diagram is shown below in Figure 2, which is a copy of Figure 1, placed here for easy access. Table 1 lists all the relevant components in the assembly.

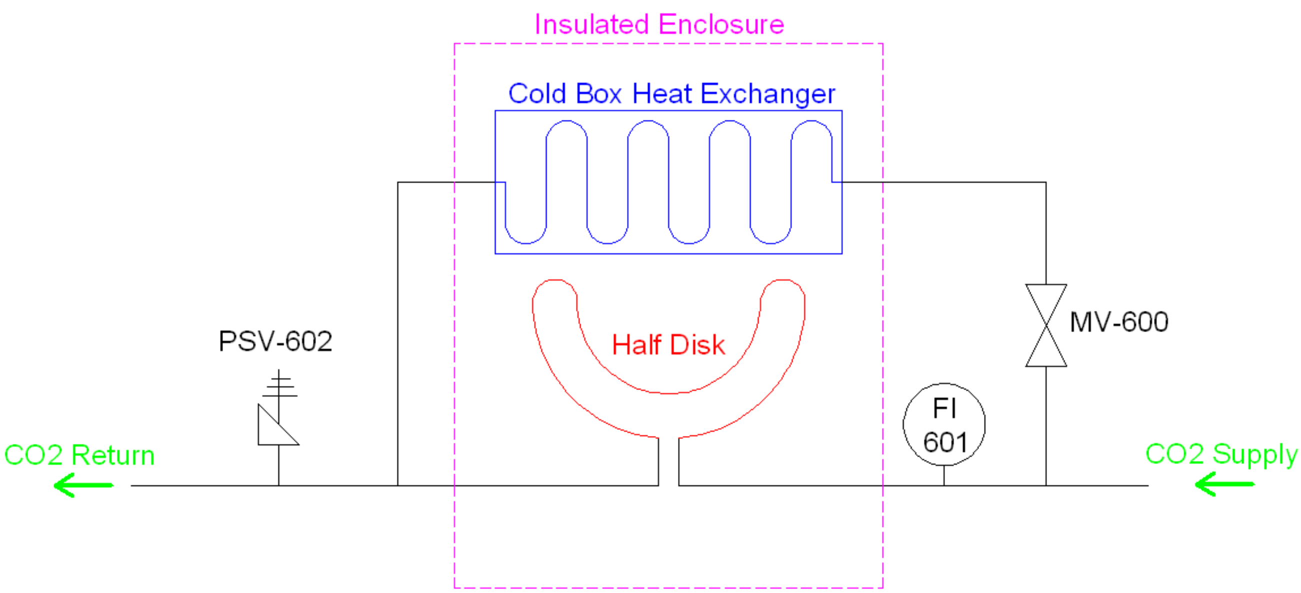


Figure 2: P&ID of half disk assembly

Table 1: Half disk assembly components and pressure ratings

Component	Sourced From	Part Number	Pressure Rating
MV-600	McMaster	7832K22	3000 psi
FI-601	McMaster	4089K712	2000 psi
PSV-602	McMaster	5026K31	1200 psi
Copper tube	Fermi Stockroom	1065-006000	1593 psi
Heat Exchanger	Coiled Copper tube	1065-006000	1593 psi

6. Leak / Pressure Test Procedures

Testing Procedures:

The CMS CO_2 Half Disk Tubing Assembly will be leak checked and pressure tested in accordance with FESHM 5034 and ASME 31.3 code for process piping. The layout of the half disk cooling assembly in seen in Figure 1. For the pressure test, the tube which connects to the supply side of the CO_2 system will be capped off and pressure will be raised from the return side.

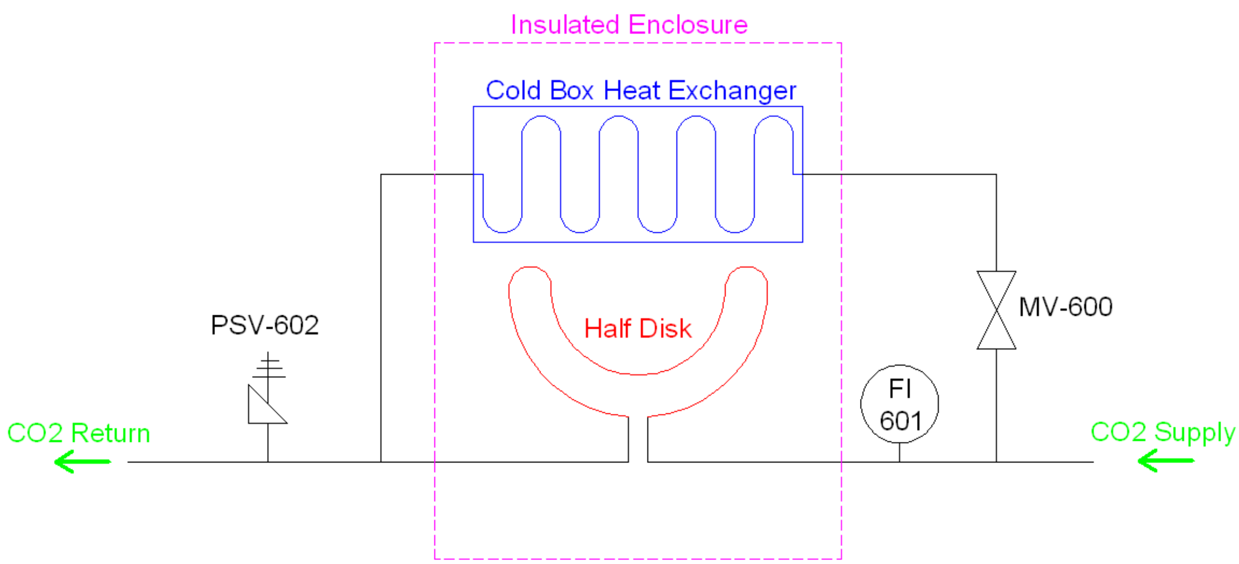


Figure 3: Diagram of cooling loop and tubing which connects to CO_2 cooling system

Design and Test Pressure:

Design pressure of the assembly is the same at the CO2 cooling system itself, which is 1200 psi. The pressure test will be 110% of design pressure which is required by applicable ASME code. The pressure source will be a nitrogen supply cylinder which will connect to the assembly by a ¼" copper tube. The cylinder will contain a Swagelok manual valve for throttling flow. The relief valve (PSV-602) was set to 1350 psi by Bob Barger which allows the test to be conducted at 110% design pressure. The cylinder will be run from the high (unregulated) side of the cylinder regulator since the low (regulated) side is unable to supply the high pressure involved in the test. An additional pressure gauge will be connected immediately following the regulator.

Pressure Step 1: 25 psi

Pressurization will begin by slowly opening the valve and pressurizing to 25psi as given by the pressure gage. At this time the system pressure monitored for pressure holding in an attempt to find gross leaks. After 3 minutes, testers bubble test all welds, joints, and fittings for leaks.

Pressure Step 2: 330 psi

If no leaks are found the pressure will be raised slowly to 330 psi, and held for 5 minutes monitoring the system pressure for changes via the pressure gage. If the pressure decreases, implying a leak, the system pressure will be reduced back to pressure step 1 (25 psi) where another bubble test will be performed in an attempt to locate the leak. If the system pressure does not decrease pressurization will proceed to pressure step 3.

Pressure Step 3: 660 psi

The pressure will be raised slowly to 660 psi, and held for 5 minutes monitoring the system pressure for changes. The previous circumstances for moving to the next pressure step or reducing pressure and bubble testing will be followed in this pressure step as well as any subsequent pressure steps.

Pressure Step 4: 990 psi

The pressure will be raised slowly to 990 psi, and held for 5 minutes monitoring the system pressure for changes.

Pressure Step 5: 1320 psi

The pressure will be raised slowly to 990 psi, and held for 10 minutes monitoring the system pressure for changes. 10 minutes is the time required by ASME code to certify a pressure test.

Pressure Step 6: 1200 psi

The pressure will be decreased slowly to 1200 psi. All joints, welds, gaskets and flex hoses will be visually examined and bubble tested. If all piping areas pass the visual inspection and the reading on the pressure gage has not decreased, the system will be considered to pass the leak and pressure test.

Testing Equipment:

- Test Pressure Fluid:
  - Pneumatic Test Using compressed nitrogen cylinder.
- Test Pressure:
  - 110% of design pressure. 110% * 1200 psi = 1320 psi
- Relief Valve: (PSV-602)
  - Tamper-Resistant Adj Steel Relief Valve 1/4 NPT Male Inlet, 1/4 NPT Fem Outlet, 900-2000 PSI
  - Purchased from McMaster-Carr Part #5026K31
- Supply Tubing:
  - ¼" OD by 0.030" wall rated at 1593 psi MAWP
  - Purchased from Fermilab Stockroom: 1065-006000
- Test Gauge:
  - Multipurpose Gauge +/-2% MID-Scale Accuracy 2-1/2" Dial, 1/4" NPT Male Bottom, 0 - 2000 PSI
  - Purchased from McMaster-Carr; Item 4089K712
- Manual Valve on regulator:
  - Swagelok SS-4P4T4 rated to 3000 psi
    - http://www.nhtko.com/submenu2/plus/valves_plug.pdf
- Manual Valve on cold box heat exchanger. (MV-600)
  - Ultra-Precision Needle Valve 1/8" NPT Female, 0.063" Orifice, Brass
  - Purchased from McMaster-Carr; Item 7832K22
    - http://www.mcmaster.com/#flow-control-needle-valves/=eqbzsk