DS Solenoid Helium Relief Simulation Loss of Vacuum and Simultaneous Magnet Quench

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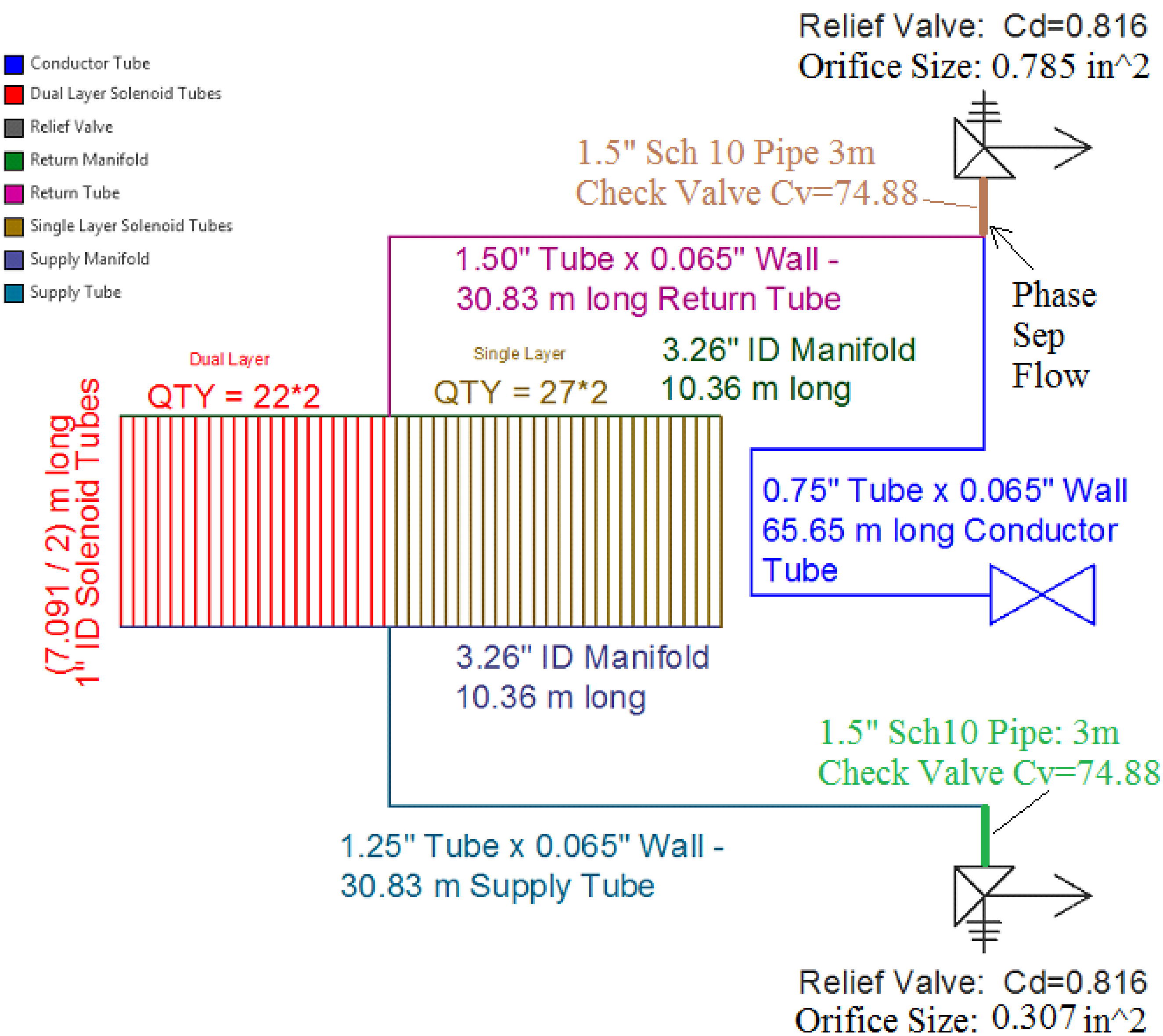
We Perform a Transient Thermal Analysis of the DS Solenoid (Design Pressure = 285 psid) with loss of vacuum and simultaneous magnet quench. We use the heat load to the helium in the solenoid cooling tubes from this thermal model as an input heat load in a fluid simulation of the relieving event, which includes the tubing to the two 100 psi relief valves, and their flow resistance and heat load from loss of vacuum and quench. The Fluid Simulation, done in ANSYS CFX, has been verified by running a test case from "Thermal Hydraulic Simulation of Helium Expulsion" [Source 4] where results are in agreement. For the DS case, we must perform the CFD simulation instead of using literature values, as literature case is too constrained (Its equation requires constant heat load, rupture disks, one tube size, and 2.5K Initial Temperature, none of which we have). Schematic of the Helium/Relief Circuit is shown below:



Material Properties of Aluminum Solenoid

Source: NIST Cryogenic Materials Database

$$Al_{5.k} := \begin{pmatrix} -0.90933 \\ 5.751 \\ -11.112 \\ 13.612 \\ -9.3977 \\ 3.6873 \\ -0.77295 \\ 0.067336 \\ 0 \end{pmatrix} \qquad Al_{Cp} := \begin{pmatrix} 46.6467 \\ -314.292 \\ 866.662 \\ -1298.3 \\ 1162.27 \\ -637.795 \\ 210.351 \\ -38.3094 \\ 2.96344 \end{pmatrix}$$

Mandrel is Al 5083, Superconductor is Combination of Pure Aluminum, and epoxy/glass wrapping. The bulk properties for the coils were calculated by Nandani Dhanaraj for the Mu2e TS cool down analysis (Mu2e DocDB #5217).

$$k_{5083}(Temp) := \left| \begin{array}{l} \text{for } i \in 0..8 \\ \quad expon_i \leftarrow Al_{5.k_i} \cdot \log\left(\frac{Temp}{K}\right)^i \\ value \leftarrow 10^{\left(\sum_{i=0}^{8} expon_i\right)} \cdot \frac{W}{m \cdot K} \\ \text{return } value \end{array} \right.$$

$$Cp_{Al}(Temp) := \left| \begin{array}{l} \text{for } i \in 0..8 \\ \quad expon_i \leftarrow Al_{Cp_i} \cdot \log\left(\frac{Temp}{K}\right)^i \\ value \leftarrow 10^{\left(\sum_{i=0}^{8} expon_i\right)} \cdot \frac{J}{kg \cdot K} \\ \text{return } value \end{array} \right.$$

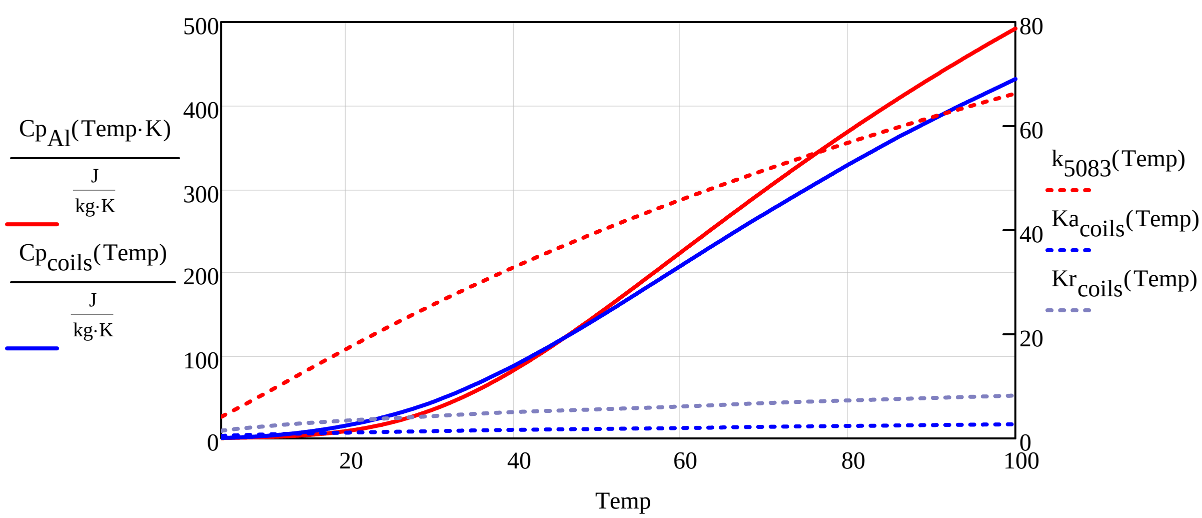
Coil Thermal Properties:

Specific Heat $\quad Cp_{coils}(Temp) := \text{linterp}\left(prop_{coils}^{\langle 0 \rangle}, prop_{coils}^{\langle 4 \rangle}, \frac{Temp}{K}\right) \cdot \frac{J}{kg \cdot K}$

Axial Cond. $\quad Ka_{coils}(Temp) := \text{linterp}\left(prop_{coils}^{\langle 0 \rangle}, prop_{coils}^{\langle 2 \rangle}, \frac{Temp}{K}\right) \cdot \frac{W}{m \cdot K}$

Radial Cond. $\quad Kr_{coils}(Temp) := \text{linterp}\left(prop_{coils}^{\langle 0 \rangle}, prop_{coils}^{\langle 1 \rangle}, \frac{Temp}{K}\right) \cdot \frac{W}{m \cdot K}$

Tangential Cond. $\quad Kt_{coils}(Temp) := \text{linterp}\left(prop_{coils}^{\langle 0 \rangle}, prop_{coils}^{\langle 3 \rangle}, \frac{Temp}{K}\right) \cdot \frac{W}{m \cdot K}$ *No Tangential Heat Transfer*



Helium Properties: Source: NIST RefProp v9.1

Average Helium in lines will be Saturated Mixture @ 4.7K: Vapor Quality 5%

$$\rho_{He} := 97.805 \frac{kg}{m^3}$$

Enthalpy at Constant Density:

$$Enth_{He}(Temp) := linterp\left(He_{props}^{\langle 0\rangle}, He_{props}^{\langle 3\rangle}, \frac{Temp}{K}\right)\cdot\frac{kJ}{kg}$$

Pressure WRT Enthalpy:

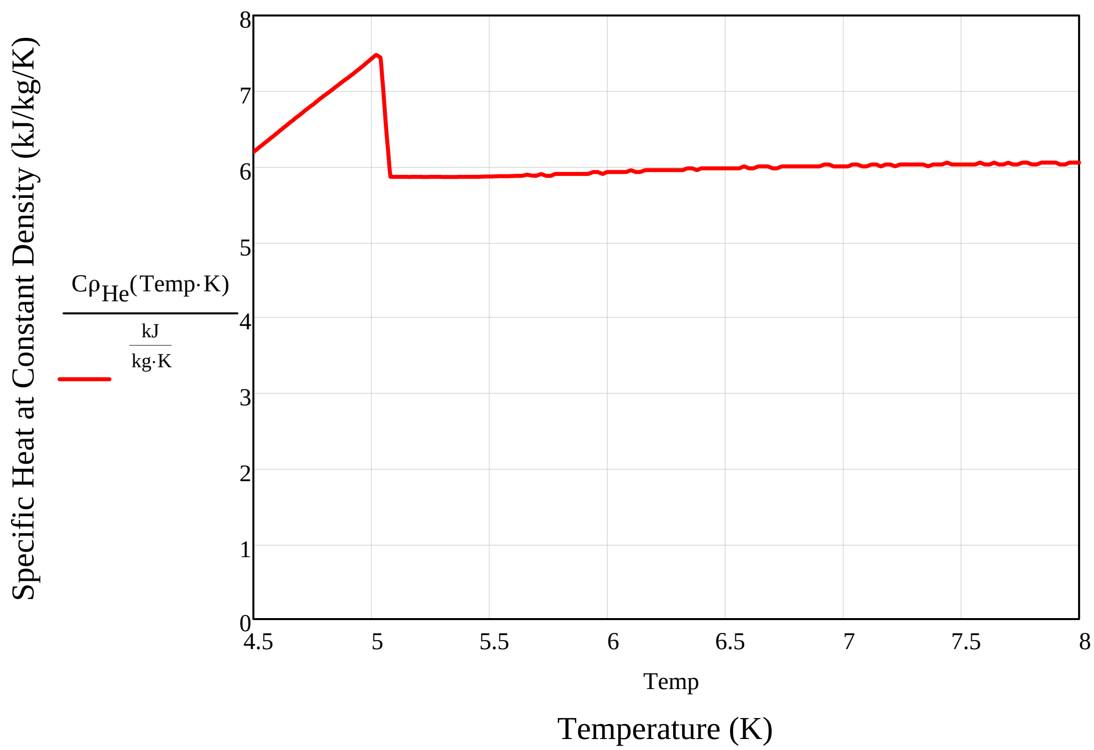
$$Press_{He}(Enth) := linterp\left(He_{props}^{\langle 3\rangle}, He_{props}^{\langle 1\rangle}, \frac{Enth}{\frac{kJ}{kg}}\right) psi$$

Temp WRT Pressure

$$Temp_{He}(Press) := linterp\left(He_{props}^{\langle 1\rangle}, He_{props}^{\langle 0\rangle}, \frac{Press}{psi}\right) K$$

Specific Heat at Constant Density for helium saturated mixture being heated and pressurized and converting to supercritical helium :

$$C\rho_{He}(Temp) := linterp\left(He_{props}^{\langle 0\rangle}, He_{props}^{\langle 4\rangle}, \frac{Temp}{K}\right)\frac{kJ}{kg\cdot K}$$



Dimensions of Solenoid Tubes and Manifolds

Parts of solenoid with two (dual) rows of superconductor, and single rows of superconductor

$Length_{DualCoil} := 408.73cm + 42.48cm = 451.21 \cdot cm$

$Length_{SingleCoil} := 584.95cm$

$num_{tubes\_DualCoil} := 22$

$num_{tubes\_SingleCoil} := 27$

$width_{averageDual} := \frac{Length_{DualCoil}}{num_{tubes\_DualCoil}} = 20.51 \cdot cm$

$width_{averageSingle} := \frac{Length_{SingleCoil}}{num_{tubes\_SingleCoil}} = 21.665 \cdot cm$

$r_{innerWall} := 104.85cm$

$r_{tubeCenter} := r_{innerWall} + 8cm$

$OD_{solenoidTube} := 3.175cm$

$ID_{solenoidTube} := 1in$

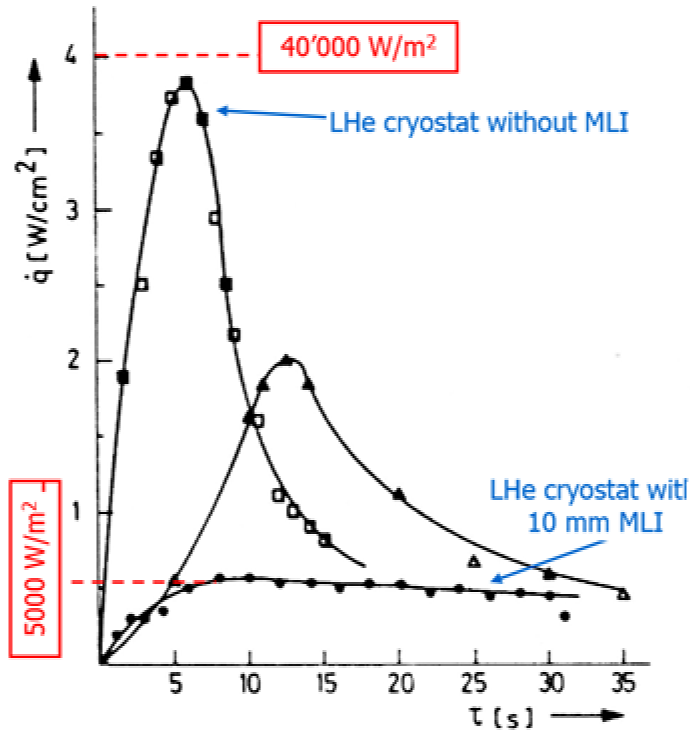
$CS_{tube} := \frac{\pi}{4} \cdot ID_{solenoidTube}^{2}$

$length_{solenoidTubes} := r_{tubeCenter} \cdot \pi = 3.545 \cdot m$

$Vol_{solenoidTubes} := \left(num_{tubes\_DualCoil} + num_{tubes\_SingleCoil}\right) \cdot length_{solenoidTubes} \cdot CS_{tube} \cdot 2$

$Length_{manifold} := Length_{DualCoil} + Length_{SingleCoil} = 10.362\,m$

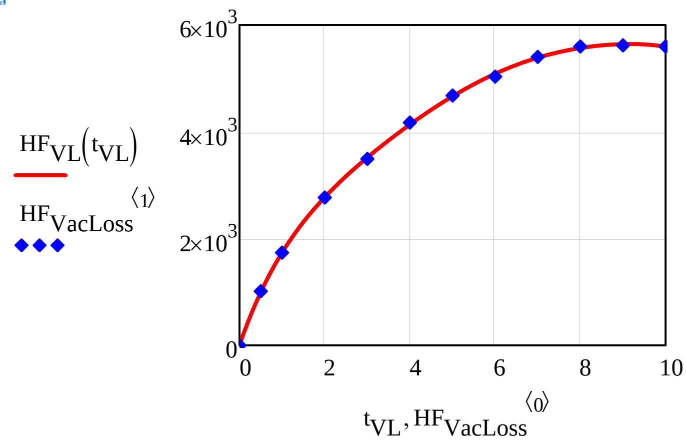
Heat Load to Helium due to Loss of vacuum [Source 1]



W. Lehmann & G. Zahn, *Safety aspects for LHe cryostats*, Proc. ICEC7, IPC Science & Technology (1978) 569-579

$HF_{VacLoss} :=$

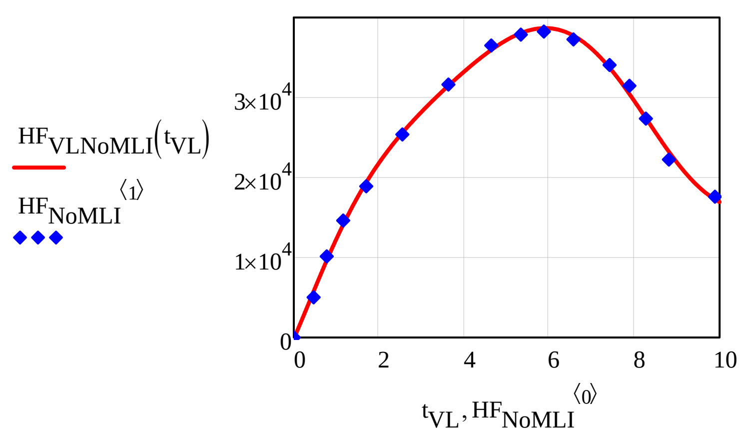
Time (s)	*Heat Flux W/m²*
0	0
0.5	1014
1	1736
2	2770
3	3492
4	4174
5	4681
6	5033
7	5403
8	5598
9	5620
10	5598



$HF_{NoMLI} :=$

0.000	0
0.464	5029
0.773	10133
1.159	14629
1.700	18895
2.550	25371
3.631	31619
4.636	36495
5.331	37867
5.872	38248
6.567	37257
7.417	34057
7.881	31467
8.267	27352
8.808	22248
9.890	17600
10.585	15695
11.049	14248

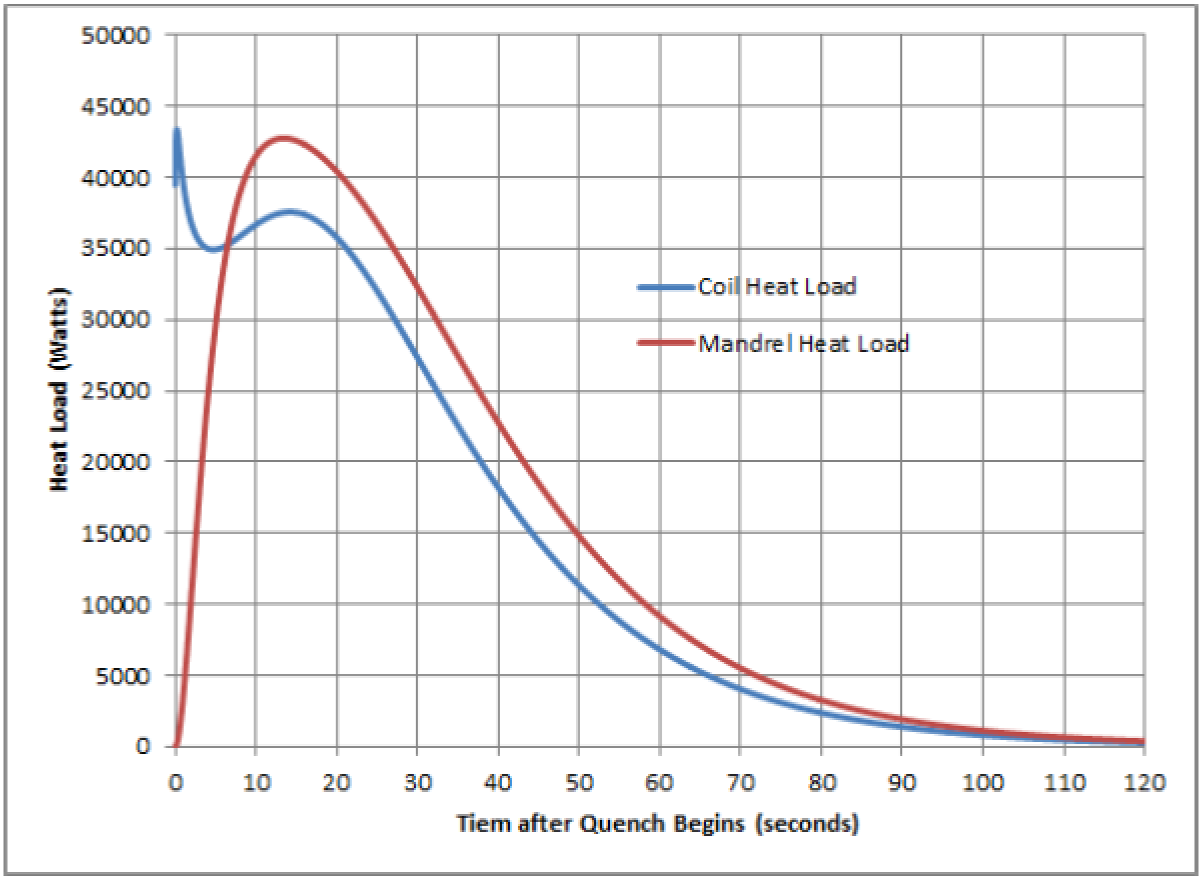
This Heat Flux is used for Loss of vacuum on all exterior surfaces of piping, and the outside of the solenoid. All of these surfaces are covered in MLI, so that curve is used in the simulations. The inner surface of the solenoid has No MLI against it, so we use the higher heat flux curve: (7th order Poly Fit)



Quench Energy: 26.1 MJ total Energy to be released during quench.
Since we were not given the heat load as a function of time, we assume the time constant is similar to the g-2 quench heat load. We make conservative assumptions while doing this:

The g-2 power functions are shown below. Total Energy in the g-2 Coil alone was 2.2 MJ, as opposed to the 26.1 MJ of the DS solenoid. We scale the heat load over the first 10 seconds up by the ratio of stored energy in the solenoids. We also deposit all the heat into the coils without the time delay of the mandrel energy.

Quench Heat Load is Calculated in g-2 DocDB 2226-v2. It is added into the model as a volumetric heat source in the mandrel and coil:



$Quench_{Energy} := 26.1MJ$ $\quad Quench_{Energy\_g2} := 2.2MJ$ $\quad Heat10sec_{g2} := 37.5kW$

$$InitialHeatLoad := \frac{Heat10sec_{g2}}{Quench_{Energy\_g2}} \cdot Quench_{Energy} = 444.9 \cdot kW$$

We put a constant 445 kW into DS coils for the quench energy. Also 33.74 W/meter heat load to conductor tube helium.

This is only our estimate based off the g-2 magnet time constant. We will need to re-do the calculation if the heat load (time constant) if quicker than the g-2 magnet. or it gets deposited differently. We tried to be conservative with our estimate. The Loss of vacuum is the dominant heat load anyway, not so much the quench energy, but it should be noted this is just an estimate based of quench energy and another magnets time constant.

Calculate Volumetric Coil Heat load for solid model

$$AxialLength_{Coils} := Length_{DualCoil} \cdot 2 + Length_{SingleCoil} = 14.874\,m$$

$$QuenchHeatPerRadialLayer := \frac{InitialHeatLoad}{AxialLength_{Coils}} = 29.911 \cdot \frac{kW}{m}$$

$$Vol_{DualCoils} := Length_{DualCoil} \cdot \pi \cdot \left[(109.3847cm)^2 - (105.35cm)^2\right] = 1228.124\,L$$

$$Vol_{SingleCoils} := Length_{SingleCoil} \cdot \pi \cdot \left[(107.154cm)^2 - (105.35cm)^2\right] = 704.486\,L$$

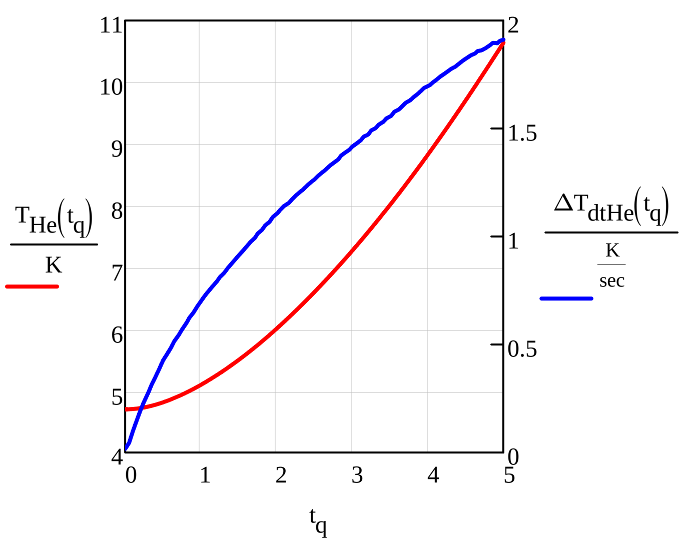
$$HeatGen_{DualLayer} := \frac{QuenchHeatPerRadialLayer \cdot 2 \cdot Length_{DualCoil}}{Vol_{DualCoils}} = 0.22 \cdot \frac{MW}{m^3}$$

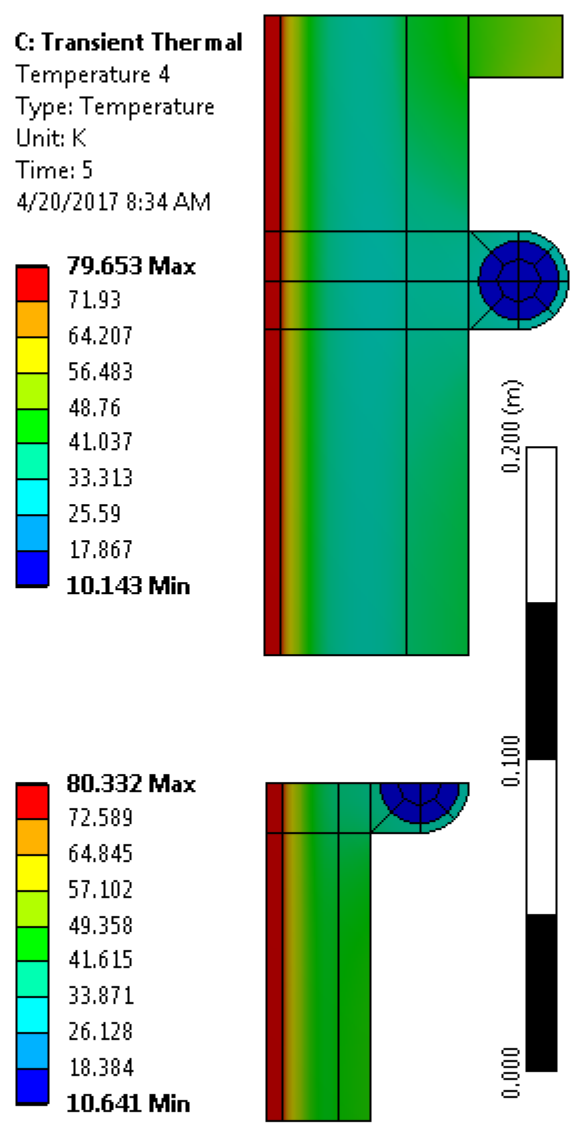
$$HeatGen_{SingleLayer} := \frac{QuenchHeatPerRadialLayer \cdot Length_{SingleCoil}}{Vol_{SingleCoils}} = 0.248 \cdot \frac{MW}{m^3}$$

Import ANSYS Transient Thermal Model Data: Below is temperature and dT/dt for the first 4 seconds of the event. This is the temperature of a single layer solenoid tube section, as its heat load was higher than the Dual Layer Solenoid tube section. We look at the helium temperature throughout the simulation, and calculate the heat energy deposited into the helium.

$$T_{He}(t_q) := linterp\left(Temp_{Hel}^{\langle 0 \rangle}, Temp_{Hel}^{\langle 1 \rangle}, \frac{t_q}{sec}\right) \cdot K$$

$$\Delta T_{dtHe}(t_q) := linterp\left(Temp_{Hel}^{\langle 0 \rangle}, Temp_{Hel}^{\langle 2 \rangle}, \frac{t_q}{sec}\right) \cdot \frac{K}{s}$$





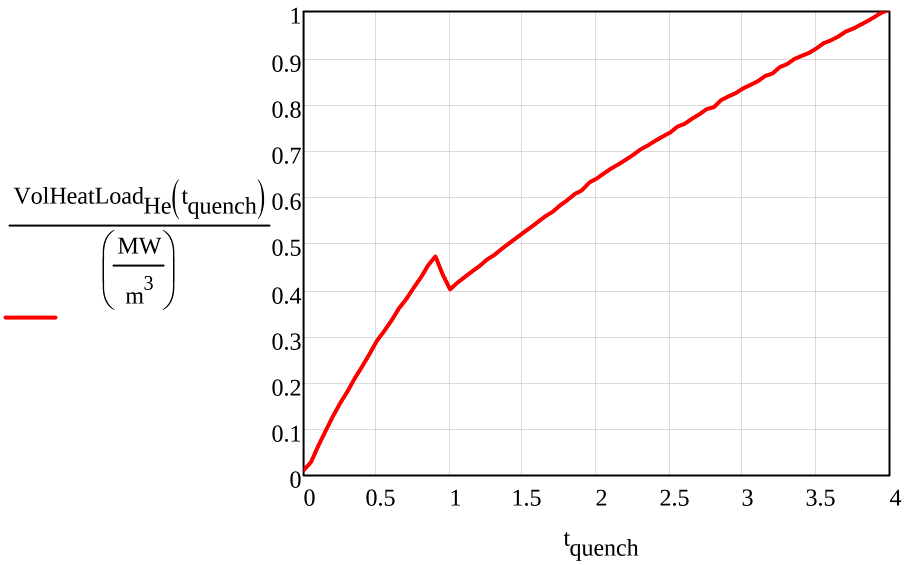
Calculate Volumetric Heat Load to the Single Layer Helium Tubes.

$time_{quench} := 5s \qquad num_{steps} := 100 \qquad time_{step} := \dfrac{time_{quench}}{num_{steps}} = 0.05\,s$

$$Vol_{HeatLoadHe} := \left| \begin{array}{l} \text{for } i \in 0..num_{steps} \\ \quad VHL_{S_i} \leftarrow \Delta T_{dtHe}(time_{step} \cdot i) \cdot C\rho_{He}(T_{He}(time_{step} \cdot i)) \cdot \rho_{He} \\ \text{return } VHL_S \end{array} \right.$$

$$t_{qn} := \left| \begin{array}{l} \text{for } i \in 0..num_{steps} \\ \quad t_{qn_i} \leftarrow i \cdot time_{step} \\ \text{return } t_{qn} \end{array} \right.$$

$VolHeatLoad_{He}(t_{quench}) := linterp(t_{qn}, Vol_{HeatLoadHe}, t_{quench})$



Pipe sizes, and Heat Loads for Supply, Return, Manifold and Conductor Piping. these are covered in MLI and we use [Source 1] for the heat load due to loss of vacuum

Manifolds

$OD_{manifold} := 3.5in \qquad t_{wall} := 0.120in \qquad Vol_{HeatLoad}(t_{VL}, OD, ID) := \dfrac{HF_{VL}(t_{VL}) \cdot OD \cdot 4}{ID^2}$

$ID_{manifold} := OD_{manifold} - 2 \cdot t_{wall} = 3.26 \cdot in \qquad A_{manifold} := \dfrac{\pi}{4} \cdot ID_{manifold}^{\;2}$

$Manifold_{Heat}(t_{VL}) := Vol_{HeatLoad}(t_{VL}, OD_{manifold}, ID_{manifold})$

Supply Tube

$Length_{TransferLine} := 30.826m = 30.826\,m \qquad Length_{Supply} := Length_{TransferLine}$

$OD_{Supply} := 1.25in \qquad t_{wall} := 0.065in$

$ID_{Supply} := OD_{Supply} - 2 \cdot t_{wall} = 1.12 \cdot in \qquad A_{supply} := \dfrac{\pi}{4} \cdot ID_{Supply}^{\;2} = 6.356 \cdot cm^2$

$Supply_{Heat}(t_{VL}) := Vol_{HeatLoad}(t_{VL}, OD_{Supply}, ID_{Supply})$

Return Tube

$OD_{Return} := 1.5in \quad t_{wall} := 0.065in \quad Length_{Return} := Length_{TransferLine}$

$ID_{Return} := OD_{Return} - 2 \cdot t_{wall} = 1.37 \cdot in \quad A_{Return} := \frac{\pi}{4} \cdot ID_{Return}^{2} = 9.51 \cdot cm^{2}$

$Return_{Heat}(t_{VL}) := Vol_{HeatLoad}(t_{VL}, OD_{Return}, ID_{Return})$

Conductor Tube

$OD_{Cond} := 0.75in \quad t_{wall} := 0.065in \quad Length_{Conductor} := 67.653m$

$ID_{Cond} := OD_{Cond} - 2 \cdot t_{wall} = 0.62 \cdot in \quad A_{Conductor} := \frac{\pi}{4} \cdot ID_{Cond}^{2} = 1.948 \cdot cm^{2}$

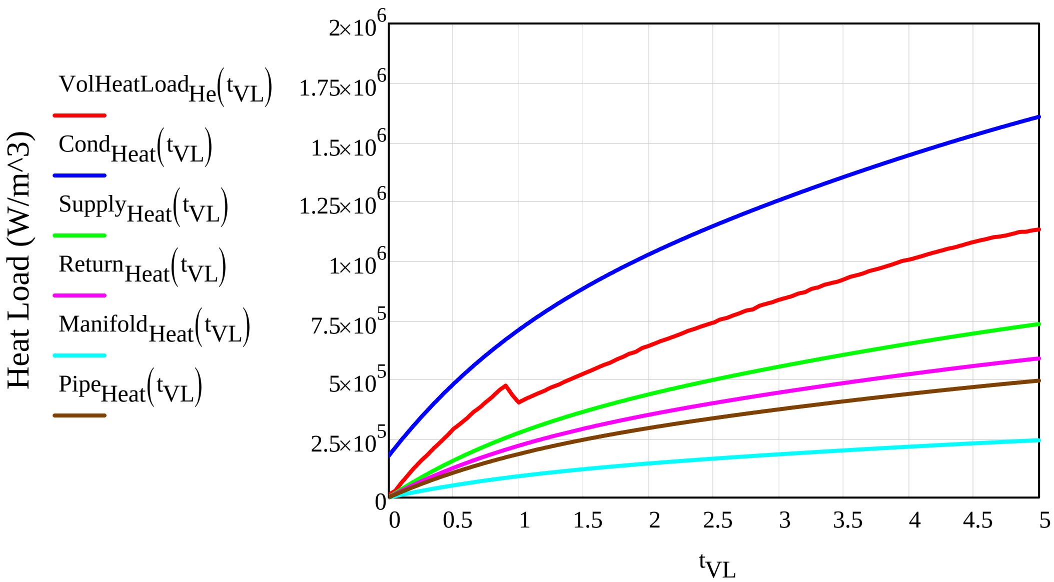
$Cond_{Heat}(t_{VL}) := Vol_{HeatLoad}(t_{VL}, OD_{Cond}, ID_{Cond}) + \frac{33.74W}{A_{Conductor} \cdot 1m}$

Relief Pipes (last 3 meters before supply and return relief valves)

$OD_{Pipes} := 1.9in \quad t_{wall} := 0.109in \quad Length_{Pipes} := 3m \cdot 2$

$ID_{Pipes} := OD_{Pipes} - 2 \cdot t_{wall} = 1.682 \cdot in \quad A_{Pipes} := \frac{\pi}{4} \cdot ID_{Return}^{2} = 9.51 \cdot cm^{2}$

$Pipe_{Heat}(t_{VL}) := Vol_{HeatLoad}(t_{VL}, OD_{Pipes}, ID_{Pipes})$



Volume of All Helium Tubes:

$Vol_{solenoidTubes} = 176.05\,L$

$Vol_{Manifolds} := A_{manifold} \cdot (Length_{SingleCoil} + Length_{DualCoil}) \cdot 2 = 111.596\,L$

$Vol_{Supply} := A_{supply} \cdot Length_{Supply} = 19.593\,L$

$Vol_{Return} := A_{Return} \cdot Length_{Return} = 29.317\,L$

$Vol_{conductor} := A_{Conductor} \cdot Length_{Conductor} = 13.177\,L$

$Vol_{PSVPipes} := A_{Pipes} \cdot Length_{Pipes} = 5.706\,L$

$$Volume_{Tubes} := \begin{pmatrix} Vol_{solenoidTubes} \\ Vol_{Manifolds} \\ Vol_{Supply} \\ Vol_{Return} \\ Vol_{conductor} \\ Vol_{PSVPipes} \end{pmatrix} = \begin{pmatrix} 176.05 \\ 111.596 \\ 19.593 \\ 29.317 \\ 13.177 \\ 5.706 \end{pmatrix} L$$

$$Mass_{Tubes} := Volume_{Tubes} \cdot \rho_{He} = \begin{pmatrix} 17.219 \\ 10.915 \\ 1.916 \\ 2.867 \\ 1.289 \\ 0.558 \end{pmatrix} kg$$

$$Total_{HeMass} := \sum_{n=0}^{5} Mass_{Tubes_n} = 34.764\,kg$$

Relief valve Set Point and Relief Info

$P_{relief} := 100psig + 1atm = 114.696 \cdot psia$

$Press_{He}(EnthalpyRelief) = P_{relief}$

$EnthalpyRelief := Find(EnthalpyRelief) = 14.658 \cdot \frac{kJ}{kg}$

$Energy_{ToRelief} := EnthalpyRelief \cdot Total_{HeMass} = 509.554 \cdot kJ$

Initial Temperature Condition when relief Valve Opens

$Temp_{He}(P_{relief}) = 7.099\,K$

Relief Will open after this much energy has been deposited into helium (pressure will be 100 psig)

Heat Loads with respect to time after loss of vacuum and quench

$HL_{Solenoid}(t_q) := VolHeatLoad_{He}(t_q) \cdot Vol_{solenoidTubes}$

$HL_{Manifolds}(t_q) := Manifold_{Heat}(t_q) \cdot Vol_{Manifolds}$

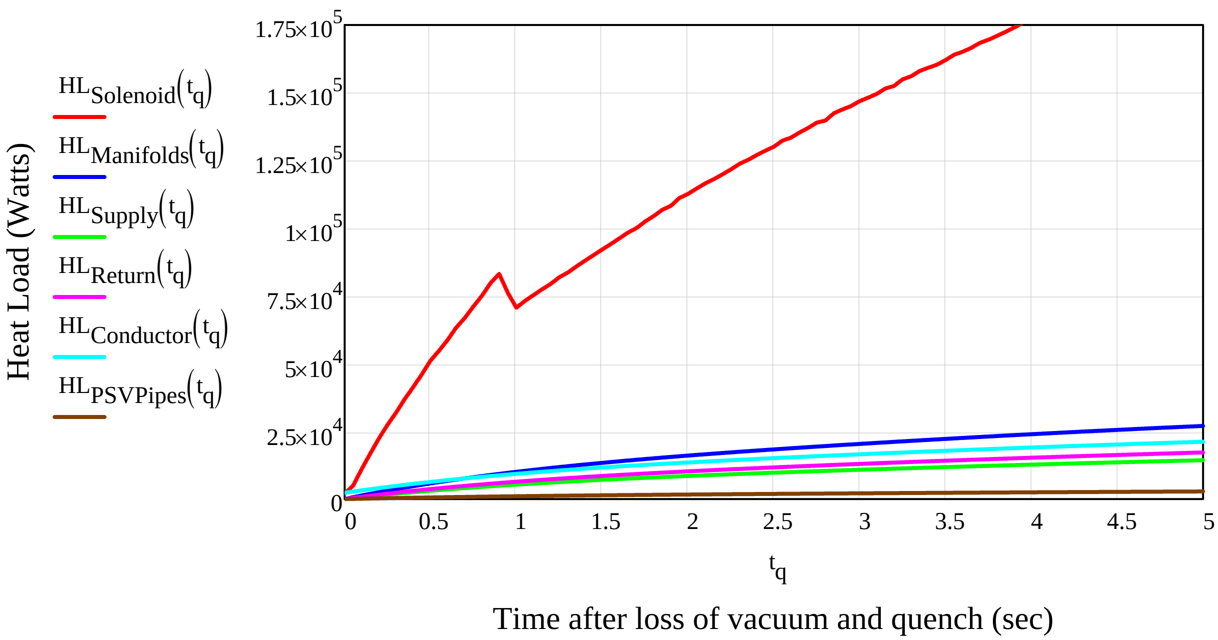
$HL_{Supply}(t_q) := Supply_{Heat}(t_q) \cdot Vol_{Supply}$

$HL_{Return}(t_q) := Return_{Heat}(t_q) \cdot Vol_{Return}$

$HL_{Conductor}(t_q) := Cond_{Heat}(t_q) \cdot Vol_{conductor}$

$HL_{PSVPipes}(t_q) := Pipe_{Heat}(t_q) \cdot Vol_{PSVPipes}$

$Total_{HeatLoad}(t_q) := HL_{Solenoid}(t_q) + HL_{Manifolds}(t_q) + HL_{Supply}(t_q) + HL_{Return}(t_q) + HL_{Conductor}(t_q) + HL_{PSVPipes}(t_q)$



We can see most of the heat is deposited into the solenoids, due to the large surface area of the solenoid, as well as all the quench energy being deposited there. It is also where half of the helium in the piping system is held. The dominating heat source in the solenoids is the loss of vacuum heat load, not the quench heat load.

Calculate when relief Valve Opens: when has 509.5 kJ been deposited into Helium, and pressure reaches the relief set point:

$time_{quench} := 5s \qquad num_{steps} := 100 \qquad time_{step} := \frac{time_{quench}}{num_{steps}} = 0.05\,s$

$$Integrated_{EnergyHeat} := \left| \begin{array}{l} IE_0 \leftarrow 0J \\ \text{for } i \in 1 .. num_{steps} \\ \quad \left| \begin{array}{l} Energy_{step_i} \leftarrow Total_{HeatLoad}(time_{step} \cdot i) \cdot time_{step} \\ IE_i \leftarrow IE_{i-1} + Energy_{step_i} \end{array} \right. \\ \text{return } IE \end{array} \right.$$

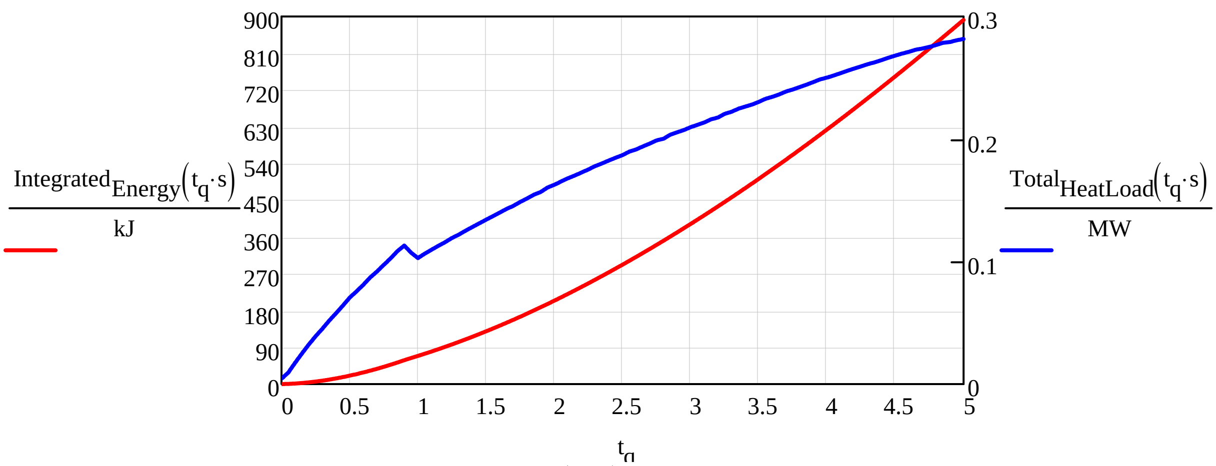
$Integrated_{Energy}(t_{quench}) := linterp(t_{qn}, Integrated_{EnergyHeat}, t_{quench})$

$Integrated_{Energy}(time_{relief}) = Energy_{ToRelief}$

$time_{relief} := Find(time_{relief}) = 3.529\,s$

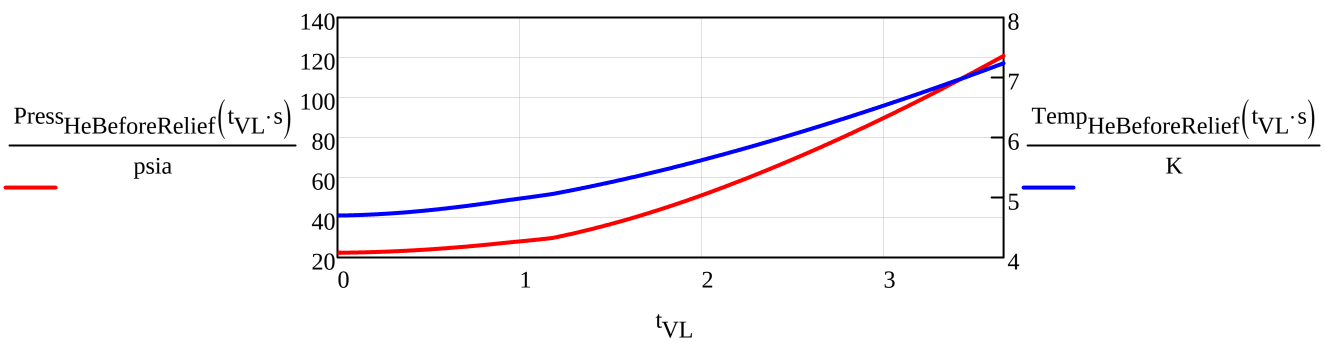
The Relief Valves will open 3.529 seconds after the Loss of vacuum and simultaneous quench event.

Total Energy Transferred to Helium and Total Heat Load W.R.T. Time



$$Press_{HeBeforeRelief}(t_{VL}) := Press_{He}\left(\frac{Integrated_{Energy}(t_{VL})}{Total_{HeMass}}\right)$$

$$Temp_{HeBeforeRelief}(t_{VL}) := Temp_{He}(Press_{HeBeforeRelief}(t_{VL}))$$



K factor for simulating piping pressure drop

$$\Delta P_{kloss} = K_{loss} \cdot \frac{\rho}{2} \cdot Vel^2 \qquad K_{\Delta P} = \frac{friction_{factor}}{ID}$$

$$\mu := 2.9194\mu Pa \cdot s \qquad \rho_{He} = 97.805 \frac{kg}{m^3} \qquad \varepsilon_f := 0.015mm = 4.921 \times 10^{-5} \cdot ft$$

$$friction_{factor}(ff, mass_{flow}, d_{pipe}) := -2 \cdot \sqrt{ff} \cdot \log\left[\frac{\varepsilon_f}{3.7 \cdot d_{pipe}} + \frac{2.51}{\frac{mass_{flow}}{\frac{\pi}{4} \cdot d_{pipe} \cdot (\mu)} \cdot \sqrt{ff}}\right] - 1$$

$$pipe_f(mass_{flow}, d_{pipe}) := root(friction_{factor}(ff, mass_{flow}, d_{pipe}), ff, 0.008, 0.09)$$

$$MF_{ave} := 2 \frac{kg}{sec}$$

K factors for 5 different pipe sizes:

$$K_{solenoid} := \frac{pipe_f(MF_{ave}, ID_{solenoidTube})}{ID_{solenoidTube}} = 0.683 \frac{1}{m} \qquad Re := \frac{MF_{ave}}{\frac{\pi}{4} \cdot ID_{solenoidTube} \cdot (\mu)} = 3.434 \times 10^7$$

$$K_{manifold} := \frac{pipe_f(MF_{ave}, ID_{manifold})}{ID_{manifold}} = 0.164 \frac{1}{m} \qquad Re := \frac{MF_{ave}}{\frac{\pi}{4} \cdot ID_{manifold} \cdot (\mu)} = 1.053 \times 10^7$$

$$K_{Return} := \frac{pipe_f(MF_{ave}, ID_{Return})}{ID_{Return}} = 0.465 \frac{1}{m} \qquad Re := \frac{MF_{ave}}{\frac{\pi}{4} \cdot ID_{Return} \cdot (\mu)} = 2.507 \times 10^7$$

$$K_{Supply} := \frac{pipe_f(MF_{ave}, ID_{Supply})}{ID_{Supply}} = 0.595 \frac{1}{m} \qquad Re := \frac{MF_{ave}}{\frac{\pi}{4} \cdot ID_{Supply} \cdot (\mu)} = 3.066 \times 10^7$$

$$K_{Conductor} := \frac{pipe_f(MF_{ave}, ID_{Cond})}{ID_{Cond}} = 1.233 \frac{1}{m} \qquad Re := \frac{MF_{ave}}{\frac{\pi}{4} \cdot ID_{Cond} \cdot (\mu)} = 5.539 \times 10^7$$

$$K_{Pipes} := \frac{pipe_f(MF_{ave}, ID_{Pipes})}{ID_{Pipes}} = 0.362 \frac{1}{m} \qquad Re := \frac{MF_{ave}}{\frac{\pi}{4} \cdot ID_{Pipes} \cdot (\mu)} = 2.042 \times 10^7$$

Pressure Drop is simulated using a quadratic loss model as: $\Delta P = K_{loss} \cdot \frac{\rho}{2} \cdot Velocity^2$

Relief Valves: There are two relief valves, each is an Anderson greenwood series 81, 1.5" valves. the supply has a 0.307in^2 orifice, and the return side has a 0.785in^2 orifice. The return side also vents the phase separator flow. which is added as a mass source in the fluid simulation

$C_d := 0.816 \qquad Area_{Return} := 0.785\,in^2 \qquad Area_{Supply} := 0.307\,in^2$

Flow out the two Relief Valves is simulated according to the equations below, where Cp/Cv, Pressure, and Density are all evaluated locally at the inlet of the relief valves during the simulation. We use local real gas Cp/Cv as it is a much more accurate for actual mass flow than using the ideal gas Cp/Cv as stated in some codes. This has been demonstrated for supercritical helium in previous CFD models where sonic flow through an orifice was simulated using helium with both ideal gas and real gas properties.

$$Relief_{FlowR}(k_{PSV}, P_{PSV}, \rho_{PSV}) := C_d \cdot Area_{Return} \cdot \sqrt{k_{PSV} \cdot \rho_{PSV} \cdot P_{PSV} \cdot \left(\frac{2}{k_{PSV} + 1}\right)^{\frac{k_{PSV}+1}{k_{PSV}-1}}}$$

$$Relief_{FlowS}(k_{PSV}, P_{PSV}, \rho_{PSV}) := C_d \cdot Area_{Supply} \cdot \sqrt{k_{PSV} \cdot \rho_{PSV} \cdot P_{PSV} \cdot \left(\frac{2}{k_{PSV} + 1}\right)^{\frac{k_{PSV}+1}{k_{PSV}-1}}}$$

Just for an example, we show the relief capacity at 10% overpressure using the initial density of the Helium.

$k_{He} := 1.666 \qquad Press_{PSV} := P_{relief} \cdot 110\%$

$Relief_{FlowS}(k_{He}, Press_{PSV}, \rho_{He}) = 1.082\,\frac{kg}{s} \qquad Relief_{FlowR}(k_{He}, Press_{PSV}, \rho_{He}) = 2.768\,\frac{kg}{s}$

SIMULATION VALIDATION: Compare to HeDump Code Literature

We will use this combined heat load case and find the helium pressure during the relief process. Source 4 gives a nice correlation for maximum pressure rise in a helium tube during a relief process which uses a computer code "HEDUMP" to simulate fluid flow and develop the correlation, given here:

Unfortunately this is for constant heat input. It also only works for initial conditions of 2.5 atm and 2K Helium. Which we will not be at. We will then solve for the max pressure in our own scenario by using ANSYS CFX as the numerical solver to solve the energy and momentum equations. We will validate our simulation by comparing against a HEDUMP case example:

A formula has been derived to calculate the peak pressure in a quenching internally-cooled conductor for the case of an entire section going normal.[2] The maximum pressure is given by (in mks units):

$$p_{max} = k_f \left(\frac{Q^2 L^3}{d_h} \right)^{0.36} \qquad (7)$$

in which d_h is the hydraulic diameter, L is the half-distance between exit ports, Q is a constant heat input rate per unit volume of helium, and k_f is a constant which depends on the friction coefficient. k_f = 0.1 for f = 0.018 and k_f = 0.14 for f = 0.052. (It should be noted that the Darcy friction coefficient, f, is used in this work, while References 1 through 8 use the Fanning friction coefficient c_f, with f = $4c_f$.)

Simulation Validation: Compare results from our simulation with case from Source 4 computer code "HEDUMP":

$fric_{test} := 0.016 \qquad C_{fTest} := 0.097 \qquad D_{htest} := 1.25\text{cm}$

$Length_{flowPathTest} := 50\text{m} \qquad E_{inTest} := 3 \cdot 10^7 \qquad K_{lossTest} := \frac{fric_{test}}{D_{htest}} = 1.28 \frac{1}{\text{m}}$

$DeltaP(\rho_{fluid}, Vel_{fluid}) := K_{lossTest} \cdot \frac{\rho_{fluid}}{2} \cdot Vel_{fluid}^2$ *function of density and velocity*

$FrictionalHeating(\rho_{fluid}, Vel_{fluid}) := K_{lossTest} \cdot \frac{\rho_{fluid}}{2} \cdot Vel_{fluid}^3$ *function of density and Velocity*

$$\Delta P := C_{fTest} \cdot \left[\frac{(E_{inTest})^2 \cdot \left(\frac{Length_{flowPathTest}}{\text{m}} \right)^3}{\frac{D_{htest}}{\text{m}}} \right]^{0.36} \cdot \text{Pa} = 7.768 \cdot \text{MPa}$$ *eq. 7 [Source 4]*

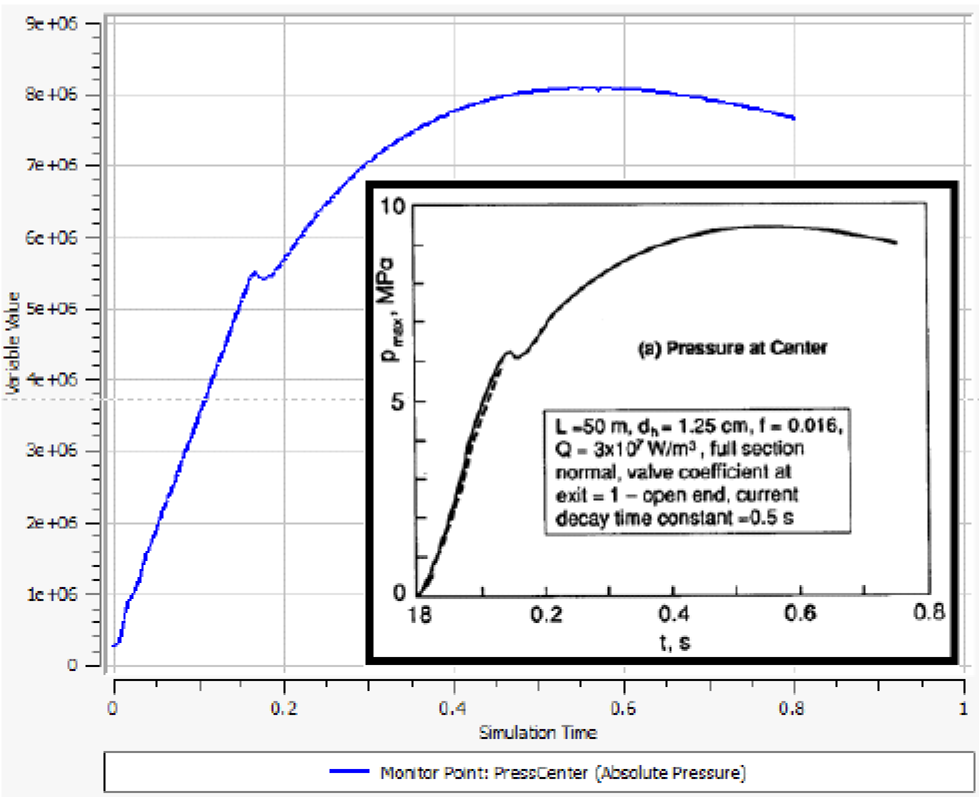
Result from Equation 7 in Source 4 matches very closely with our simulation:

$Max_{PressureEquation} := \Delta P + 2.5\text{atm} = 8.021 \cdot \text{MPa} \qquad MaxPressure_{OurSimulation} := 8.0986\text{MPa}$

$$Percent_{Difference} := \frac{MaxPressure_{OurSimulation} - Max_{PressureEquation}}{(MaxPressure_{OurSimulation} + Max_{PressureEquation}) \cdot 0.5} = 0.961 \cdot \%$$

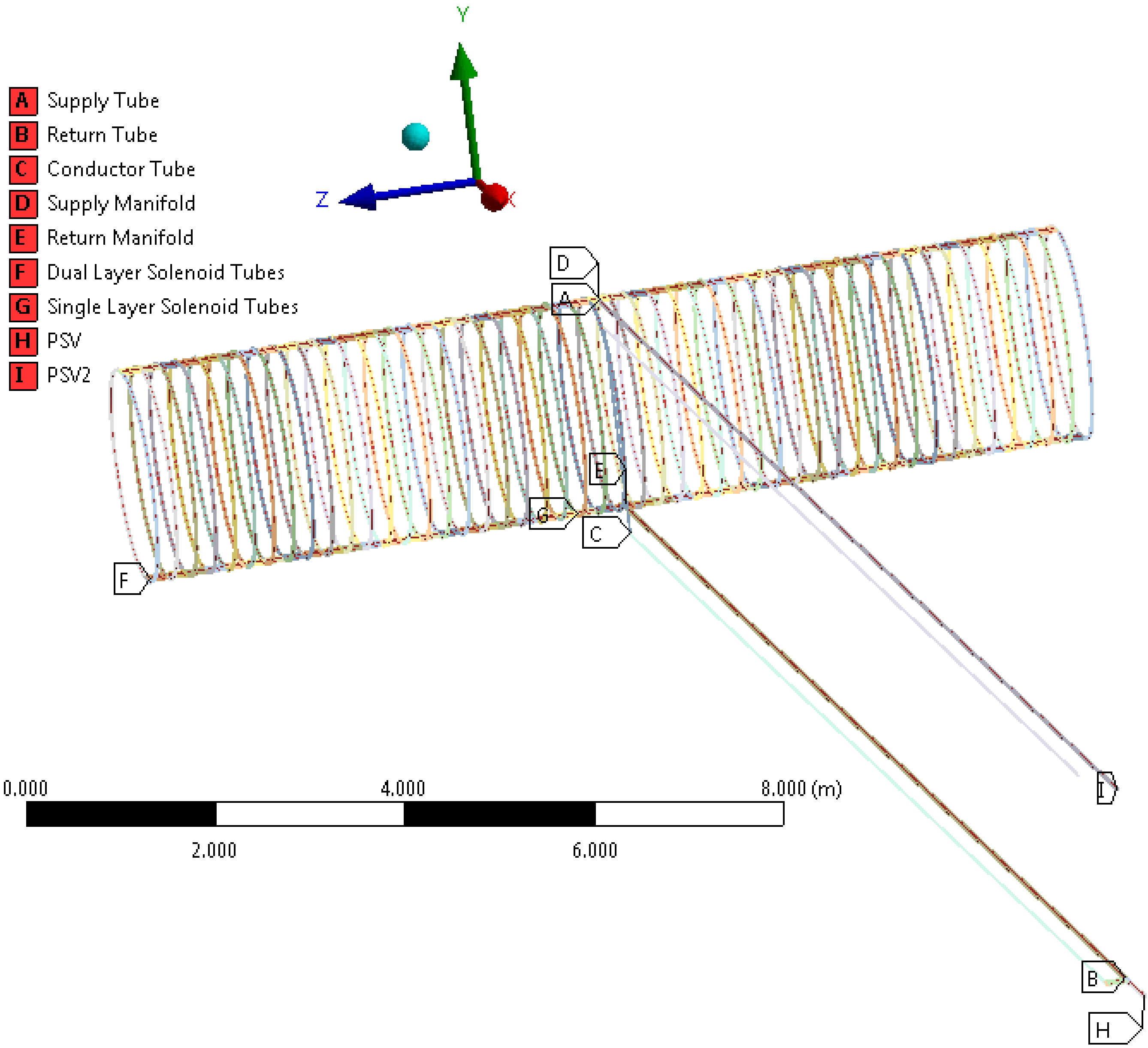
Comparison of our CFX Simulation (blue line) of Center Pressure and Figure 6(a) for Source 4: The Blue line is the output of absolute pressure at the symmetry boundary condition from our CFX simulation. (Units in MPa)

****We have validated our simulation method, and can now use it with confidence for our cases.****



CFD Simulation Setup:

A representation of the Helium Geometry is shown below, the schematic view is on the cover page.



Simulation Conditions:

Several Changes were made to our simulation techniques to make the calculations more accurate (to take out some conservatism), and make a more realistic simulation:

1.) The solid model which solves for the heat transfer to the helium in the solenoid uses 300 W/m^2/K as the thermal conductance at the interface of the helium and the tube. Once Helium reaches relief pressure of 100 psig, we switch to solving the solid model (mandrel, coils and helium in solenoid) and fluid models (fluid flow through all piping including relief valves) simultaneously, a 2 way Fluid Structure Interaction, with results from each simulation used as variables in the other:

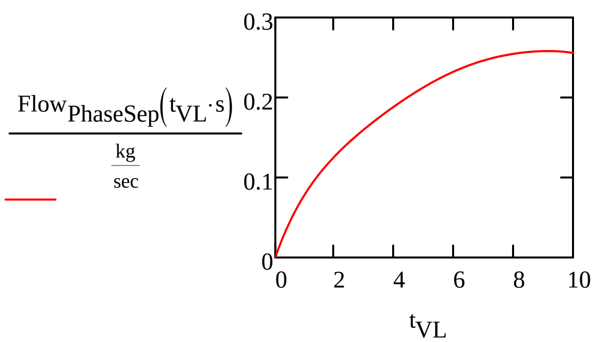
- *Heat Transfer Coefficient from the Fluid simulation was used at the interface of the Fluid and Tube in the Solid Model. This is Calculated using the Dittus Boelter coefficient multiplied by 1.25 to be conservative.*
- *Heat Load to the Solid Model Helium used as Volumetric Heat Load to solenoid helium in the fluid model.*
- *Mass Source/Sink in the solid model helium keeps the density of helium equal to the density of helium in the fluid model, as to accurately predict the heat transfer to the fluid.*

2.) Volumetric Heat loads added to all tubing and piping.
3.) Check Valves are included in model, simulating their pressure drop using local flow, density, and their own DP as inputs to their general momentum source terms which cause pressure drop.
4.) Phase Separator mass flow added as mass source into fluid model @ Return Pipe before check valve.
5.) Quench Heat Load added to Conductor tubing which is connected to superconductor. 33.74 W/meter estimated, all transferred directly to helium, which is conservative.
6.) Aungier-redlich-Kwong equation of state used in previous models under predicted the initial density of the helium, which is not conservative. Helium properties are now obtained using an RGP (Real Gas Properties) table with dimensions 400x400: Tmin=6.1[K]; Tmax=320[K]; Pmin=100[psia]; Pmax=325[psia]. The table was generated using NIST_to_RGP Fortran code and NIST RefProp helium.fld property data was used as the input. Initial Density and all fluid properties now match the RefProp values.

Phase Separator Flow: Inserted directly into model before return Check Valve

$$\nu := 0.0084033\,\frac{m^3}{kg} \qquad dh_{dv} := \frac{(17.385 - 16.747)\frac{kJ}{kg}}{(0.008466 - 0.0083421)\frac{m^3}{kg}} = 5149.314\cdot\frac{kJ}{m^3} \qquad Surface_{Area} := 3066in^2$$

$$Cp_{HeliumPhaseSeperator} := \nu\cdot dh_{dv} = 43.271\cdot\frac{kJ}{kg} \qquad Flow_{PhaseSep}(t_{VL}) := \frac{HF_{VL}(t_{VL})\cdot Surface_{Area}}{Cp_{HeliumPhaseSeperator}}$$



Check Valve Pressure Drop: Calculate function to use in simulation. This test calculation uses arbitrary variables for density and mass flow.

$C_v := 74.88$

Ideal gas k

$k_{He} := 1.666$ $\quad M_{air} := 28.965\,\frac{gm}{mol}$

$P_1 := 200psi$ $\quad \Delta P_{CV} := 4psi$ $\quad T_1 := 20K$

$F_k := \frac{k_{He}}{1.4} = 1.19$ $\quad x_T := 0.72$ $\quad x_R := \frac{\Delta P_{CV}}{P_1} = 0.02$ $\quad Y_1 := 1 - \frac{\Delta P_{CV}}{3\cdot\frac{k_{He}}{1.4}\cdot 0.72\cdot P_1} = 0.992$

$$q_{PRVBKFILL} := 1360\cdot SCFH\cdot Y_1\cdot C_v\cdot\sqrt{\frac{\frac{\Delta P_{CV}}{psi}\cdot\frac{P_1}{psi}}{\left(\frac{T_1}{R}\right)\cdot\frac{M_{He}}{M_{air}}}} = 2.136\times 10^4\cdot SCFM$$

$$MassFlowCV := q_{PRVBKFILL}\cdot\rho_{HeGas}(1atm, 60\,°F) = 1.703\,\frac{kg}{s}$$

Check Our Formula for pressure drop:

$P_2 := P_1 - \Delta P_{CV}$

$$\Delta P_{CheckValve} := \frac{0.00025048402034559\cdot\left(\frac{MassFlowCV}{\frac{lb}{hr}}\right)^2}{C_v^{\,2}\cdot\frac{\rho_{HeGas}(P_1, T_1)}{\frac{lb}{ft^3}}\cdot\left(1 - \frac{P_1 - P_2}{k_{He}\cdot 1.543\cdot P_1}\right)^2}\cdot psi = 4\cdot psi$$

We use This formula in our CFD model. It is a function of: Local Density, Inlet Pressure, Outlet Pressure, and mass flow through the check valve.

*Check Valve Delta P Function = ((0.00025048402034559 * ((2.2219888[in^2] * (ave(Velocity)@REGION:RCVin) * (ave(Density)@REGION:RCVin)) / (1[lb/hr])) ^2) / ((CvCheckValve^2)*ReturnCVDensity*(1-((ReturnCVP1-ReturnCVP2)/(2.5704* ReturnCVP1)))^2))*1[psi]*

Density Equalizer Function for Mass Source/Sink in Solid model Helium to match Average Density in Solenoid Helium Tube, and accurately calculate heat transfer to the helium.

$Area_{solenoidTube} := \frac{\pi}{4} \cdot (1in)^2 = 0.785 \cdot in^2$ $\quad radius := 1.0974m \quad$ $depth := radius \cdot 2 \cdot \pi \cdot \frac{0.1deg}{360deg} = 1.915 \cdot mm$

$Volume_{2Dmodel} := \frac{Area_{solenoidTube} \cdot depth}{2} = 0.48525 \cdot cm^3 \quad time_{stepMax} := 1 \cdot 10^{-3} s$

Test Function to see if it does what we want it to:

$Density_{2D} := 80 \frac{kg}{m^3} \quad Density_{Solenoid} := 79 \frac{kg}{m^3}$

$MassSource := \frac{(Density_{2D} - Density_{Solenoid}) \cdot Volume_{2Dmodel}}{time_{stepMax}}$

$Mass_1 := Density_{2D} \cdot Volume_{2Dmodel} = 3.882 \times 10^{-5} kg$

$MassSource \cdot time_{stepMax} = 4.853 \times 10^{-7} kg$

$Mass_2 := Mass_1 - MassSource \cdot time_{stepMax} = 3.834 \times 10^{-5} kg \quad \rho_2 := \frac{Mass_2}{Volume_{2Dmodel}} = 79 \frac{kg}{m^3}$

This will work and be numerically stable with our maximum time step.

*Density Equalizer Function = -(((volumeAve(Density)@SolidHelium - ave(Density)@SolenoidTubes) * 0.48525[cm^3]) / (0.001[s]))*

Decrease Biot Number in solid model helium so thermal resistance is only at interface, and not through fluid.

$k_{HeHighK} := 1000 \frac{W}{m \cdot K} \quad HTC := 250 \frac{W}{m^2 \cdot K} \quad length := \frac{1m^2}{\pi \cdot 1in} = 12.532\,m$

$L_c := \frac{\frac{\pi}{4} \cdot ID^2}{\pi \cdot ID} = 0.36 \cdot in \quad Bi := \frac{L_c \cdot HTC}{k_{HeHighK}} = 0.0023$

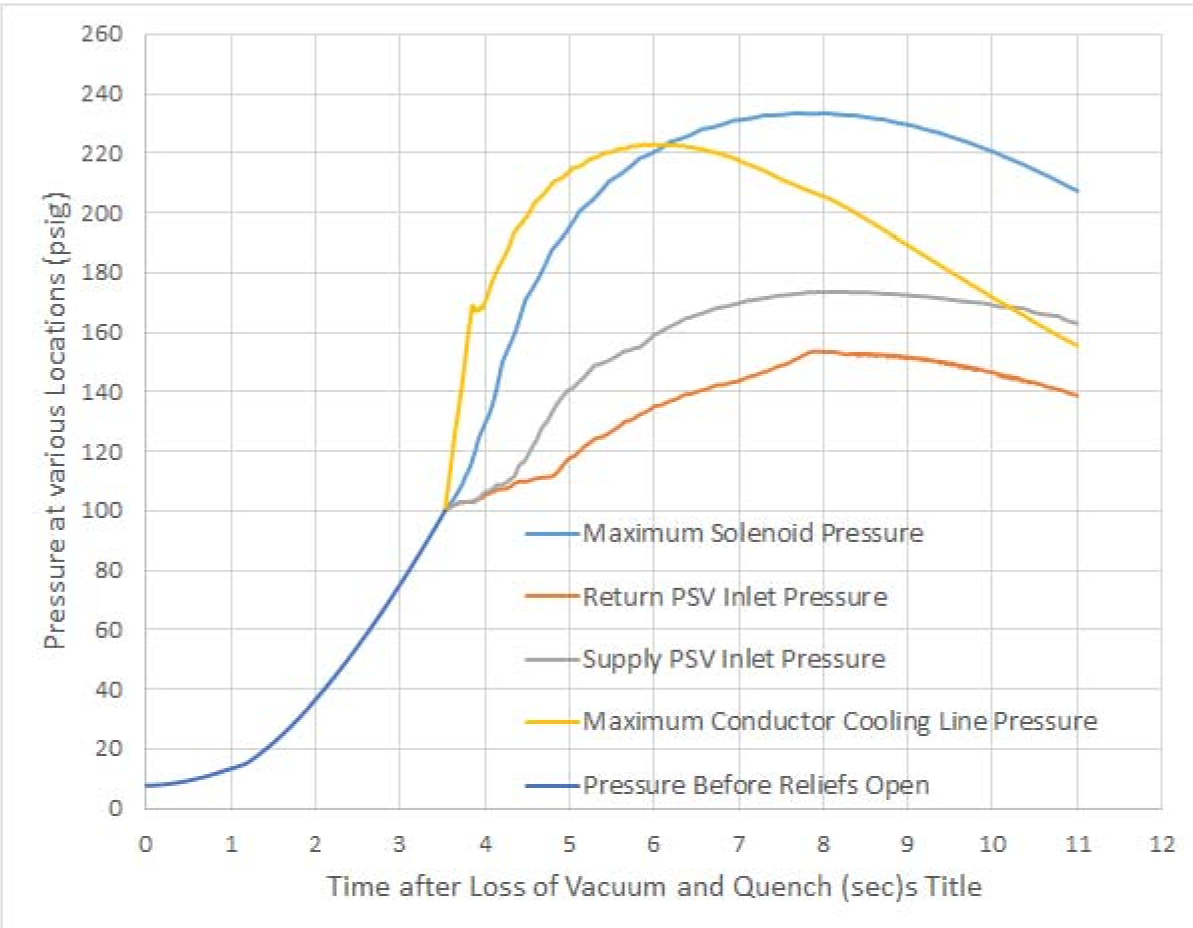
Bi is << 1, so the Helium will be isothermal in the solid model.

Mathmatical Expressions Used in Helium Relief Simulation			
#	**Expression**	**Formula**	**Description of Expression**
1	AreaReturnPSV	0.785[in^2]	Relief Valve Orifice Area
2	AreaSupplyPSV	0.307 [in^2]	Relief Valve Orifice Area
3	CvCheckValve	74.88	Cv of Check Valve
4	DPReturnCheckValve	((0.00025048402034559 * ReturnCVMassFlow ^2) / ((CvCheckValve^2)*ReturnCVDensity*(1-((ReturnCVP1-ReturnCVP2)/(2.5704*ReturnCVP1)))^2	Pressure Drop Across Check Valve in Return Line
5	DPSupplyCheckValve	((0.00025048402034559 * SupplyCVMassFlow^2) / ((CvCheckValve^2)*SupplyCVDensity*(1-((SupplyCVP1-SupplyCVP2)/(2.5704*SupplyCVP1)))^2	Pressure Drop Across Check Valve in Supply Line
6	DischargeCoeff	0.816	Relief Valve Discharge Coeff
7	EqualizationMassFlow	-(((volumeAve(Density)@SolidHelium - ave(Density)@SolenoidTubes) * 0.48525[cm^3]) / (0.001[s]))	Mass Sink in the Solid model helium Domain which removes (or adds) fluid to match the density of helium in the solenoids in the fluid
8	InterfaceResistance	(1/(if(SolenoidHTC>80[W/m^2/K],SolenoidHTC,((80[W/m^2/K] + SolenoidHTC)/2)))) / 1.25	Interface Thermal Resistance for Solid Model Heat Transfer to Helium - with minimum of 1/100[W/m^2/K] and reduced by
9	MassFlowPhaseSeperator	LOVHeatFlux(t) * SurfaceAreaPhaseSeperator /	Simulated Mass Flow of the Phase seperator inserted into Return Pipe
10	PhaseSepTemp	7.1[K]	Constant Temperature of Phase Seperator Flow
11	Pinit	114.696[psi]	Initial Fluid Simulation Pressure when reliefs open
12	ReturnCVDensity	(ave(Density)@REGION:RCVin) / 1[lb/ft^3]	Density at Return Check Valve Inlet
13	ReturnCVMassFlow	(2.2219888[in^2] * (ave(Velocity)@REGION:RCVin) * (ave(Density)@REGION:RCVin)) /	Mass Flow through Return Check Valve for DP calculation inserted as general momentum source.
14	ReturnCVP1	ave(Absolute Pressure)@REGION:RCVin	Pressure at inlet of Return Check Valve - used in DP calculation
15	ReturnCVP2	ave(Absolute Pressure)@REGION:RCVout	Pressure at Outlet of Return Check Valve - used in DP calculation
16	ReturnPSVMassFlow	(DischargeCoeff*AreaReturnPSV*sqrt(kValReturn*(probe(Density)@ReturnPSV)*(probe(Absolute Pressure)@ReturnPSV) * ((2/(kValReturn+1))^((kValReturn+1)/(kValReturn-1))))) * RampFunction((probe(Absolute	Mass Flow out the Return Relief Valve

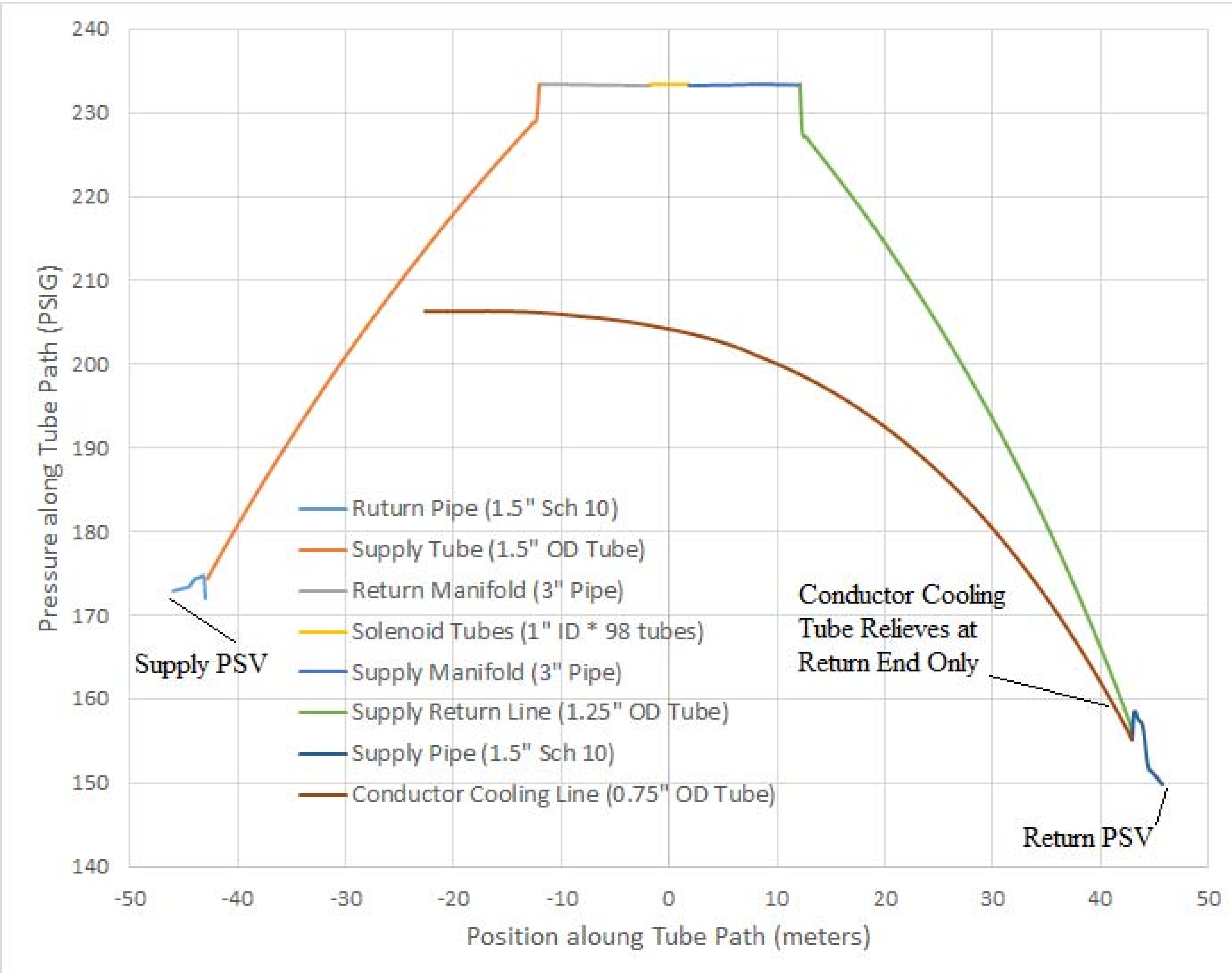
17	SolenoidHTC	max(((0.023* ((volumeAve(Density)@SolenoidTubes)*(volumeAve(Velocity)@SolenoidTubes)*(1 [in]) / (volumeAve(Dynamic Viscosity)@SolenoidTubes)) ^0.8) * (((volumeAve(Specific Heat Capacity at Constant Pressure)@SolenoidTubes) * (volumeAve(Dynamic Viscosity)@SolenoidTubes) / (volumeAve(Thermal Conductivity)@SolenoidTubes))^0.4) * (volumeAve(Thermal Conductivity)@SolenoidTubes) / (1[in])),20[W/m^2/K])	Average Heat Transfer Coefficient inside the Solenoid Tubes - used as part of the Thermal resistance function in the solid model. Based off Dittus-Boelter Correlation.
18	SolenoidHeatFlux	areaAve(Wall Heat Flux)@Default Fluid Solid Interface Side 1 1	Average Heat Flux to helium in solid model - Used as Volumetric Heat input in Fluid Simulation
19	SolenoidVolHeat	(SolenoidHeatFlux * 1[in] * 4) / (1[in])^2	Volumetric Heat Load to Solenoid Helium in Fluid Simulation
20	SpecificHeatInputHelium	43.271[kJ/kg]	Specific Heat Input for Phase Seperator Helium
21	SupplyCVDensity	(ave(Density)@REGION:SCVin) / 1[lb/ft^3]	Density at Supply Check Valve Inlet
22	SupplyCVMassFlow	(2.2219888[in^2] * (ave(Velocity)@REGION:SCVin) * (ave(Density)@REGION:SCVin)) /	Mass Flow through Supply Check Valve for DP calculation inserted as general momentum source.
23	SupplyCVP1	ave(Absolute Pressure)@REGION:SCVin	Pressure at inlet of Supply Check Valve - used in DP calculation
24	SupplyCVP2	ave(Absolute Pressure)@REGION:SCVout	Pressure at Outlet of Supply Check Valve - used in DP calculation
25	SupplyPSVMassFlow	(DischargeCoeff*AreaSupplyPSV*sqrt(kValSupply*(ave(Density)@SupplyPSV)*(ave(Absolute Pressure)@SupplyPSV) * ((2/(kValSupply+1))^((kValSupply+1)/(kValSupply-1))))) * RampFunction((ave(Absolute	Mass Flow out the Supply Relief Valve
26	SurfaceAreaPhaseSeperator	3066[in^2]	Wetted Area of Phase Seperator
27	Tinit	7.099[K]	Initial Temperature of Helium when relief valves open @ 100 psig
28	kValReturn	(probe(Specific Heat Capacity at Constant Pressure)@ReturnPSV) / (probe(Specific Heat Capacity at Constant	Real Gas Cp/Cv @ Return relief valve inlet
29	kValSupply	(ave(Specific Heat Capacity at Constant Pressure)@SupplyPSV) / (ave(Specific Heat Capacity at Constant	Real Gas Cp/Cv @ Supply relief valve inlet
30	ConductorQuenchHeatLoad	173207.7 [W/m^3]	Volumetric Energy to Conductor Helium from Quenching

CFD Simulation Results:

Maximum Pressure in the solenoids reaches 233.5 psig @ 7.7 sec



Pressure along tube path @ time of highest solenoid pressure (7.7 sec)

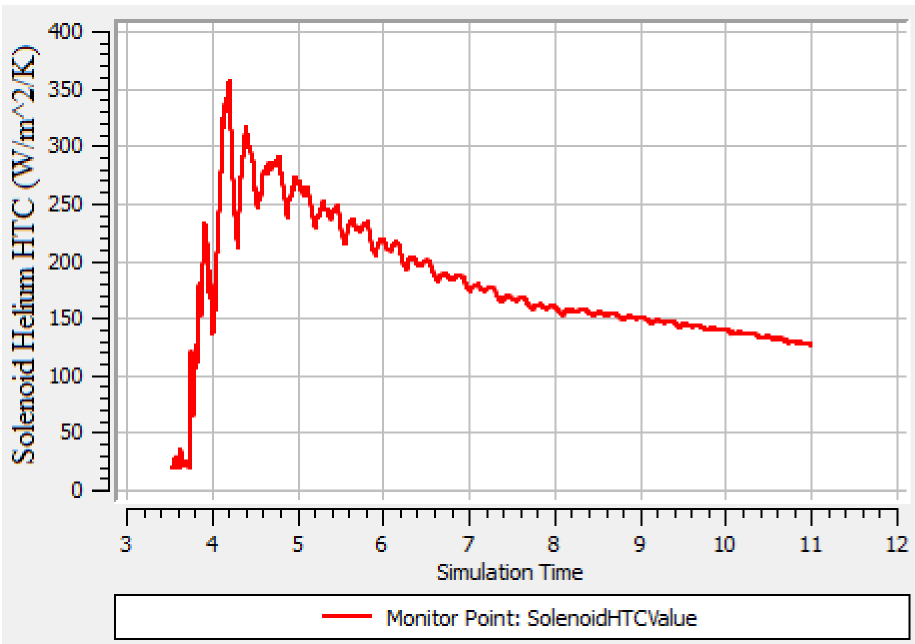


This Pressure displayed in this graph is static Pressure, not total pressure, it does not include dynamic head, so we see static pressure increase in enlarging Pipes before relief valves, and a reduction in static pressure upon entering the supply and return tubes due to higher velocity in smaller tubes.

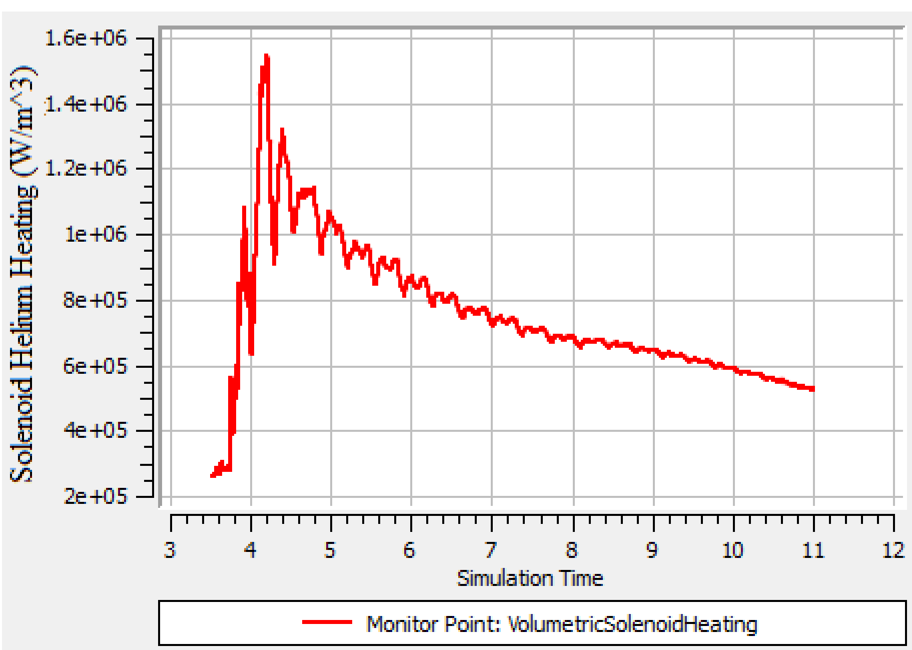
*Heat Transfer coefficient of Helium in solenoid tube (Dittus Boelter * 1.25)*

Average Heat Transfer Coefficient of Helium flowing in solenoid tubes. There are 98 tubes in parallel, and fluid flows both ways in the solenoid tube out to the relief valves, so the velocity is very low (zero at some intermediate point in each tube). This translates to a very low film coefficient. This is the helium HTC according to the Dittus-Boelter relationship:

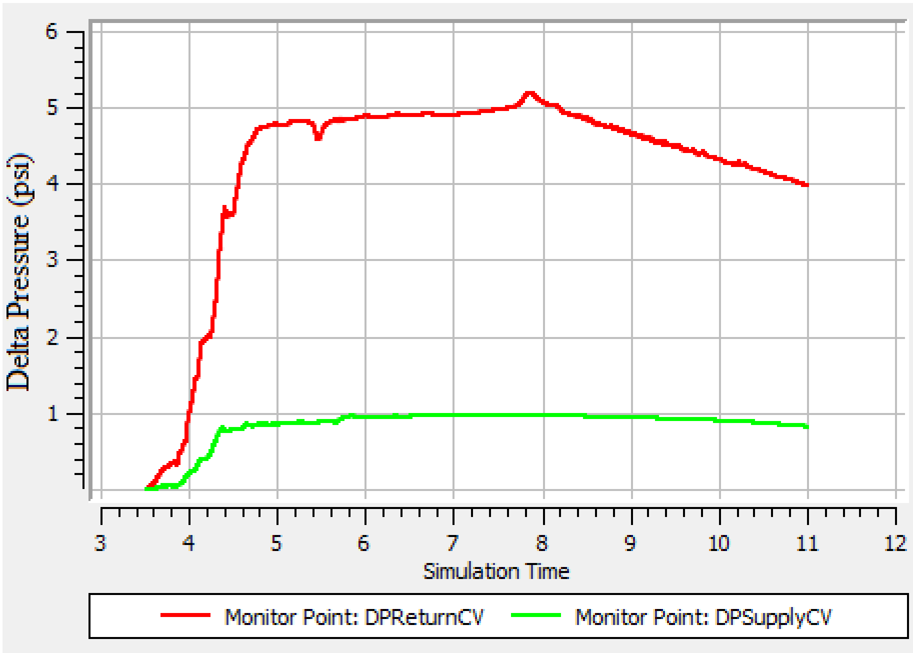
HTC:= (0.023 ((volumeAve(Density)@SolDomain)*(volumeAve(Velocity)@SolDomain)*(1[in]) / (volumeAve(Dynamic Viscosity)@SolDomain)) ^0.8) * (((volumeAve(Specific Heat Capacity at Constant Pressure)@SolDomain) * (volumeAve(Dynamic Viscosity)@SolDomain) / (volumeAve(Thermal Conductivity)@SolDomain))^0.4) * (volumeAve(Thermal Conductivity)@SolDomain) / (1[in]) * (1.25)*



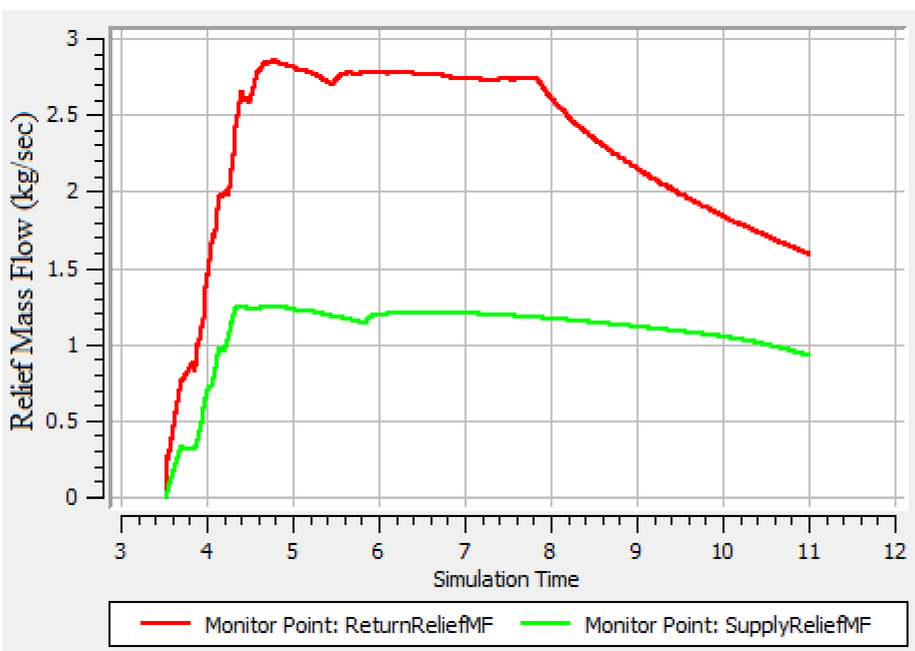
Volumetric Heating of Helium in Solenoid Tube



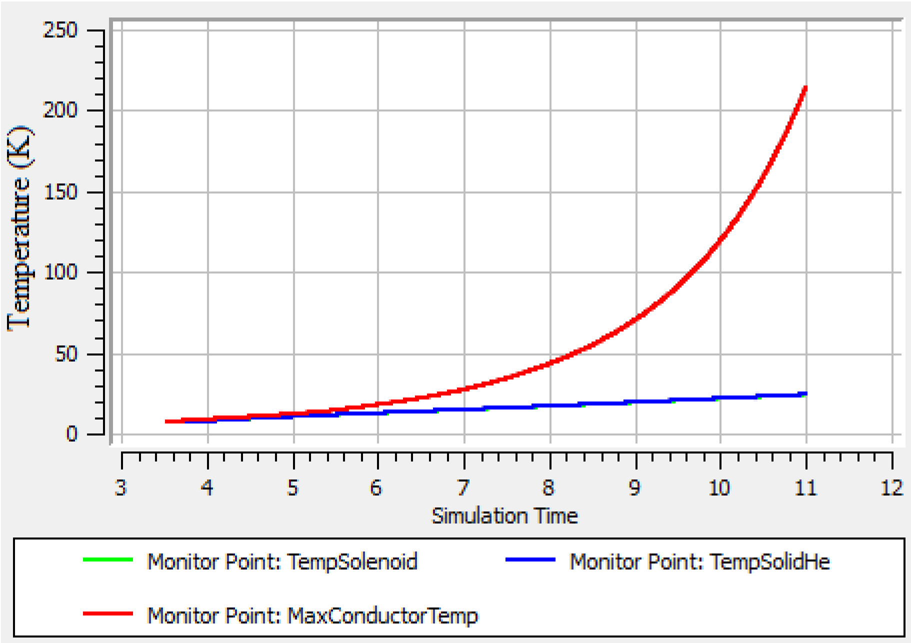
Pressure Drop of Check Valves with Cv = 74.88



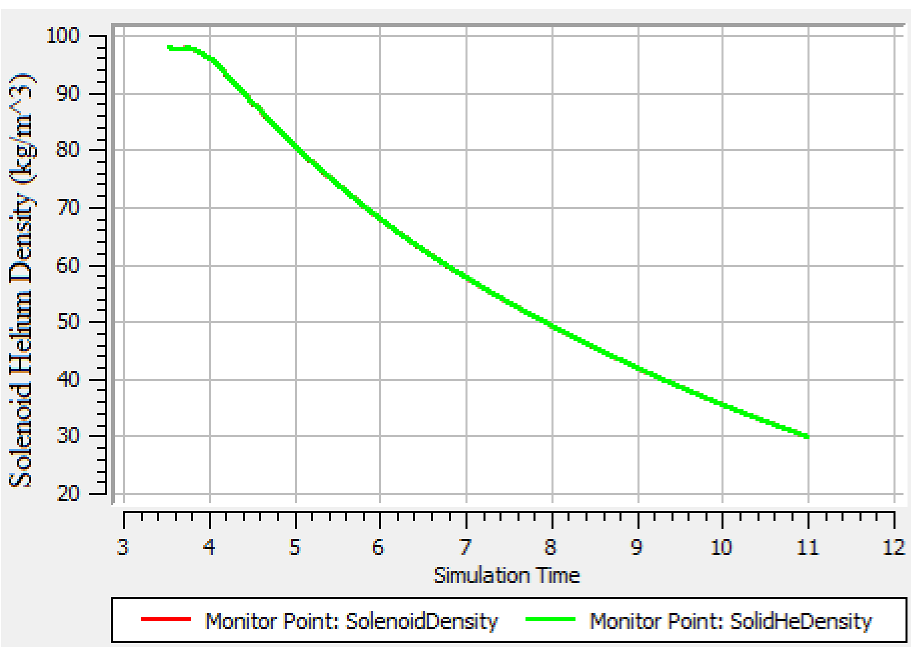
Mass Flow Out Relief Valves

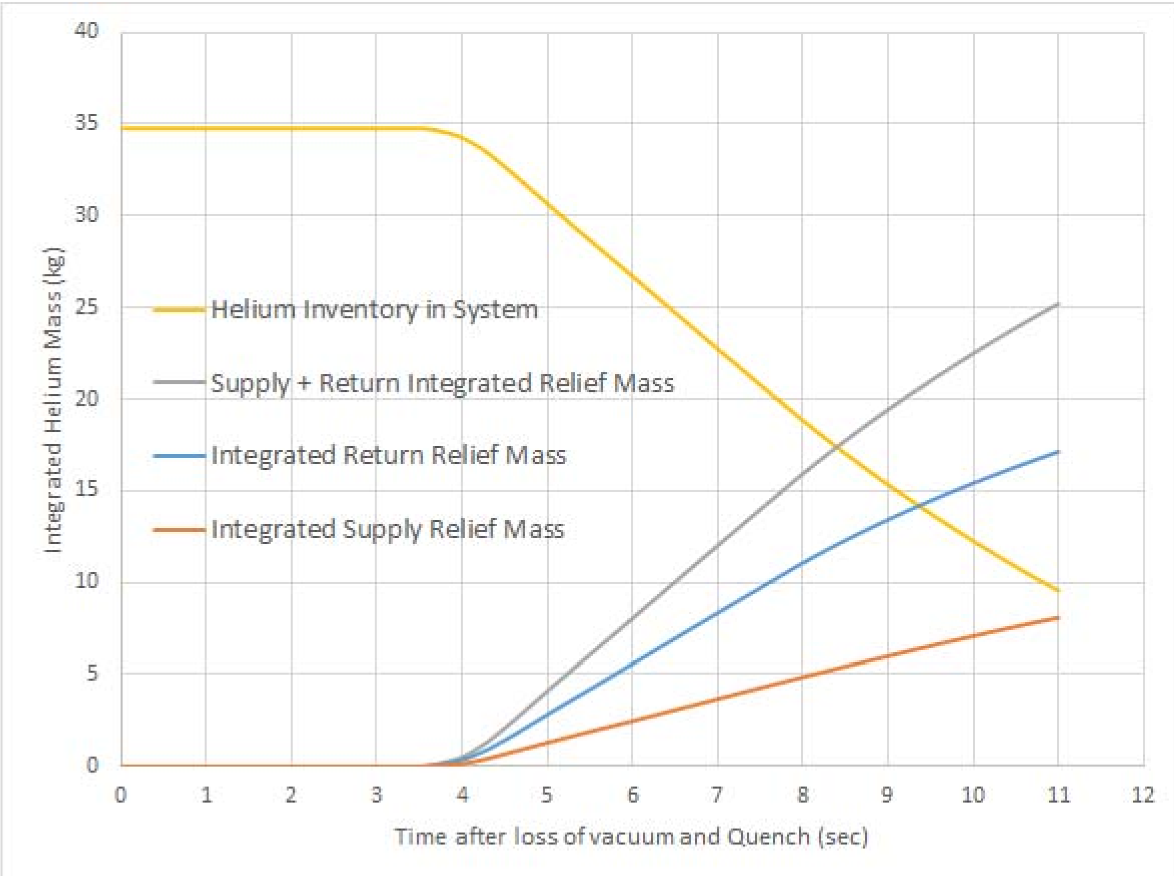


Helium Temperature in Solenoid and Conductor tube.
Solenoid helium from fluid model and Solid model helium are both shown and match each other. Conductor tube gets the hottest and would reach greater than 300K in 12 seconds



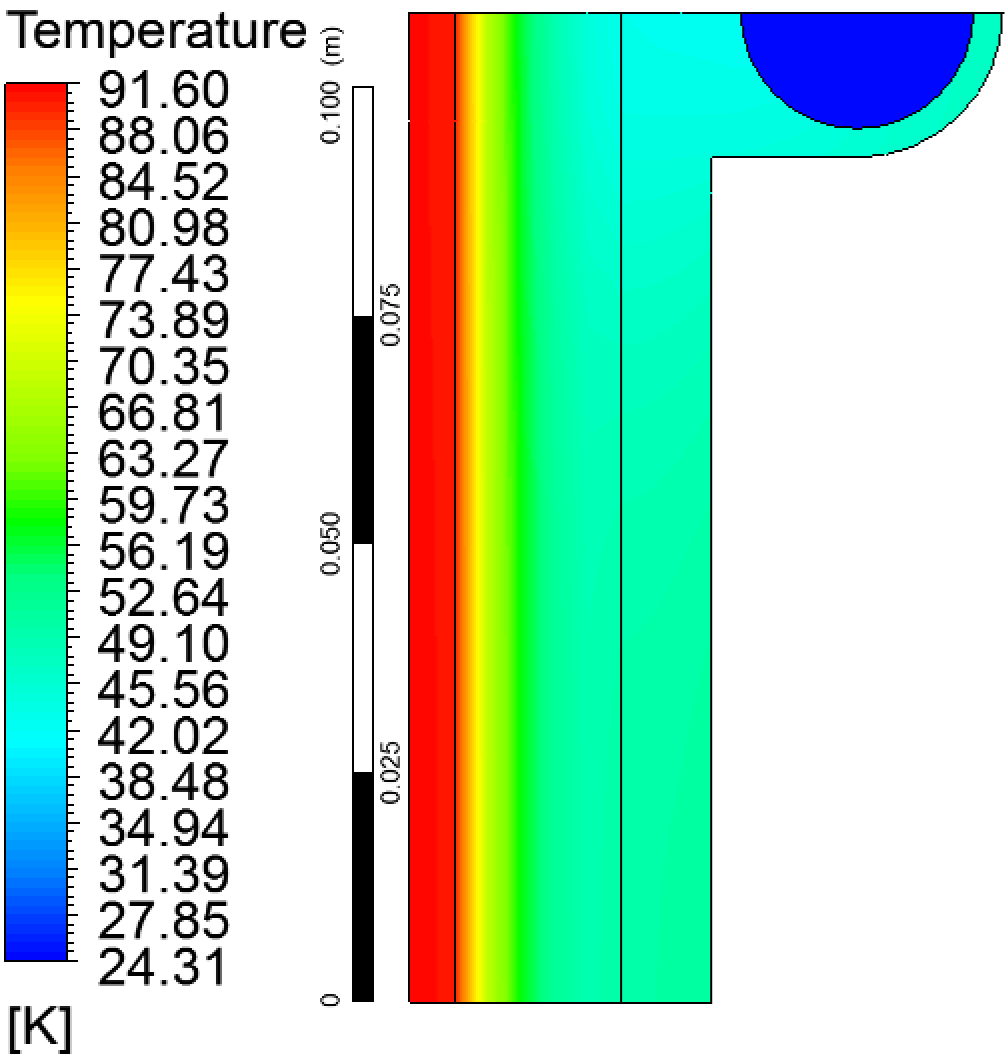
Average Helium Density in Solenoid Tubes:
(Initial Value matches RefProp value of 97.8 kg/m^3)
Solenoid helium from fluid model and Solid model helium are both shown and match each other. which is a great double check.



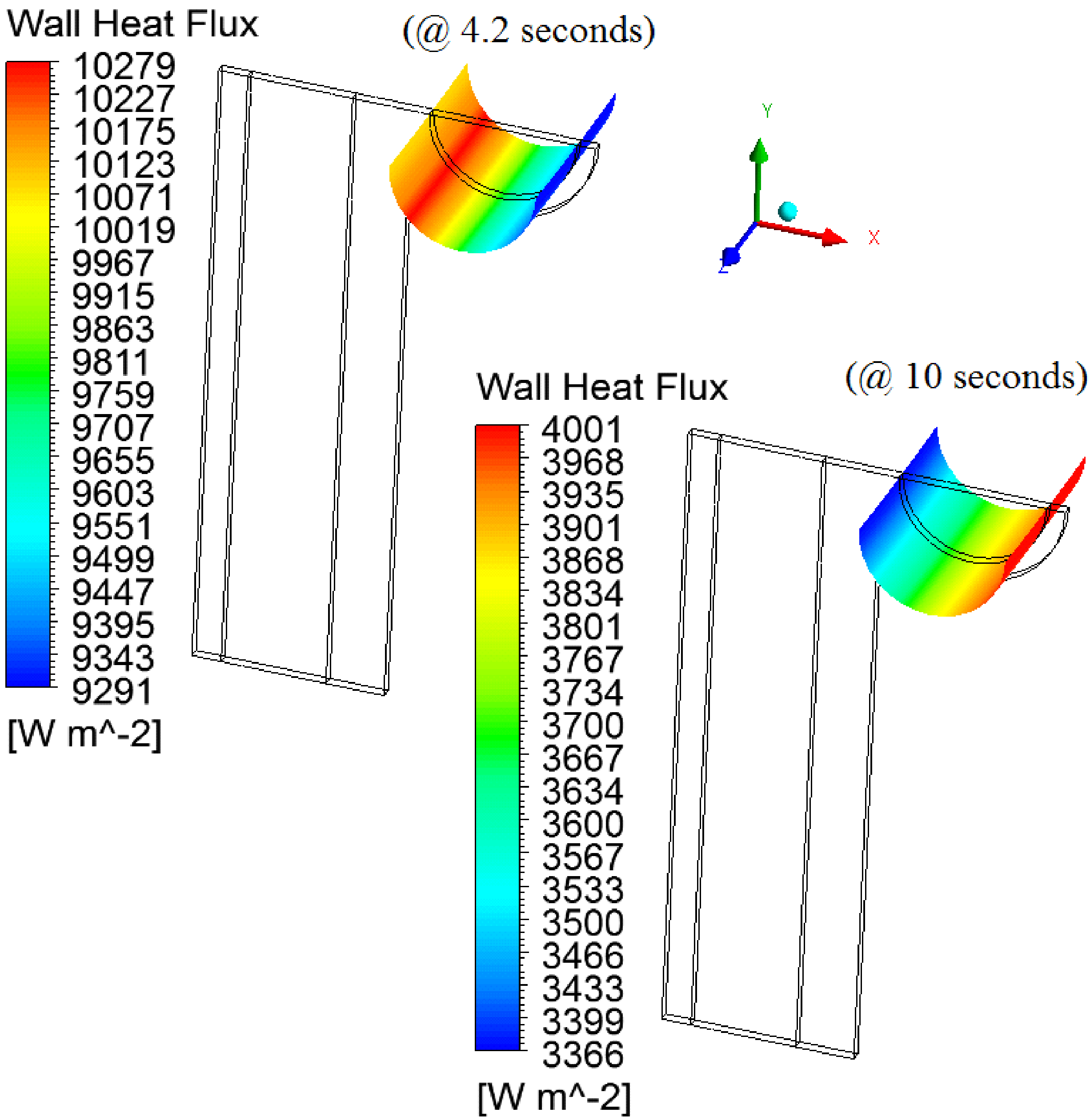


Still some built in conservatism in model:
The heat loads for loss of vacuum from Lehmann and Zahn are heat loads to liquid Helium filled cryostats, where cold liquid helium is boiling with a high thermal conductance to the vessel wall, and a very high ratio of thermal mass for the Helium vs the vessel. In our tubing, with a much higher surface area to volume ratio, the liquid is heated to the supercritical state relatively quickly, and heat load would decrease below the Lehmann and Zahn values because of the increased thermal resistance of the supercritical helium flowing in the tube, and the higher ratio of tube material vs helium. We omit the thermal mass of the tubing in our calculations, and use the full heat load values regardless of temperature. For example, in the small conductor tubes, the helium temperature reaches ~300K after 12 seconds, and this continues to rise sharply as the helium density keeps decreasing.

Temperature of the representative section of the Single Layer solenoid @ 11 seconds



Heat Flux to Helium in solenoid Tubes @ 4.2 and 10 seconds.



References

1. W.Lehman & G Zahn, *Safety Aspects for LHe cryostats,* Proc. ICEC7, IPC Science and Technology (1978) 569 – 579

2. NIST Material Measurement Laboratories; Cryogenic Material Properties. June 21, 2014 <http://www.cryogenics.nist.gov/MPropsMAY/material%20properties.htm>

3. g-2 document # 1586 – v1, June 21, 2014. < http://gm2-docdb.fnal.gov:8080/cgi-bin/RetrieveFile?docid=1586&filename=309%20Jia.pdf&version=1>

4. C. A. Luongo, R. J. Loyd, F. K. Chen. "THERMAL-HYDRAULIC SIMULATION OF HELIUM EXPULSION." IEEE TRANSACTIONS ON MAGNETICS, VOL. 25, NO. 2, MARCH 1989, n.d. Web. < http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=92602>

5. "Absolute Pipe Roughness." *Enggcyclopedia*. N.p., n.d. Web. 25 June 2014. <http://www.enggcyclopedia.com/2011/09/absolute-roughness/>

6. "Micro Blog For Chemical & Process Technology." *: Absolute & Relative Roughness for Piping Material*. N.p., n.d. Web. 25 June 2014. <http://wwcpt-microblog.blogspot.com/2008/10/absolute-relative-roughness-for-piping.html>