MECO Cryogenics- 80 K Heatshield

M. Iarocci
Feb. 27, 2003

PS, TS, DS shield calculations:

	pg..
Thermal radiation basis	2
Cold component length	3
Component diameter	3
Thermal Radiation Estimate	4-8
Thermal Radiation Summary	9
Conduction Load Summary	9
Total 80 K Load	9
Load Summary	10
Comparison of LN2 vs. SC Helium Cooled Shield	11
Heat transfer	12
Helium mass flow requirement, pressure drop	13
Specifics about concentrated loads (conduction)	14-17
Additional compressor requirements and power	18
Differential Cost/ Other Options	18
References	19

I) Approximation of radiation loads 1) PS vacuum jacket to 80 K shield, Inner and Outer, 2) TS vacuum jacket to 80 K shield, Inner and Outer, 3) DS vacuum jacket to 80 K shield, Inner and Outer

1) Calculate the mean apparent thermal conductivity of MLI blanket in appropriate vacuum conditions as a function of spacer conductance, number of reflective layers, thickness, emissivity, and delta-temperature.

$N := 24$ Number of layers of aluminum per cm thickness

$\Delta x := 1\text{cm}$ insulation thickness for 24 layers

$hc := .0851 \frac{W}{m^2 \cdot K}$ Solid conductance of spacer material **(assume fiberglass paper)**

$Cf := 10$ compression factor typical range 10 to 40

$\varepsilon := 0.05$ emmissivity of polished aluminum

$\sigma := 5.669 \cdot 10^{-8} \frac{W}{m^2 \cdot K^4}$ Stefan- Boltzmann constant

$$Ka\_5\_2 := \left(\frac{N}{\Delta x}\right)^{-1} \cdot \left[hc + \frac{\sigma \cdot \varepsilon \cdot \left[(Th)^2 + (Tc)^2\right] \cdot (Th + Tc)}{2 - \varepsilon}\right]$$

MLI equivalent thermal conductivity

I-Calculate Thermal Radiation Exchange

$$Qr := \frac{Th - Tc}{\frac{\ln\left(\frac{Ro}{Ri}\right)}{2 \cdot \pi \cdot K \cdot L}}$$

expression for radial conduction

$Th\_300K := 300K$ Temperature hot plane

$Tc\_80K := 80K$ Temperature cold plane

$$Ka\_300\_80 := \left(\frac{N}{\Delta x}\right)^{-1} \cdot \left[hc + \frac{\sigma \cdot \varepsilon \cdot \left[(Th\_300K)^2 + (Tc\_80K)^2\right] \cdot (Th\_300K + Tc\_80K)}{2 - \varepsilon}\right]$$ [ref 1]

$Ka\_300\_80 = 5.76 \times 10^{-5} \frac{W}{m \cdot K}$

$KaCorrected\_300\_80 := Ka\_300\_80 \cdot Cf$

$KaCorrected\_300\_80 = 5.76 \times 10^{-4} \frac{W}{m \cdot K}$ for temperatures>

$Th\_300K = 300\,K$

$Tc\_80K = 80\,K$

IA) Cold Surface Length [ref 2]:

IA-1 PS, TS, DS Length:

PS_Shield_Length := 5.8m TS_Shield_Length := 13.2m DS_Shield_Length := 11.9m

IB) Shield Nominal Diameter [ref 3]:

IB-1) PS

PS_80K_ID_Heatshield_D := 1.6m

PS_ID_SI_thick := .03m

PS_80K_OD_Heatshield_D := 2.46m

PS_OD_SI_thick := .05m

IB-2) TS

TS_80K_ID_Heatshield_D := 0.596m

TS_ID_SI_thick := .035m

TS_80K_OD_Heatshield_D := 1.2m

TS_OD_SI_thick := .03m

IB-3) DS

DS_80K_ID_Heatshield_D := 2.0m

DS_ID_SI_thick := .04m

DS_80K_OD_Heatshield_D := 2.42m

DS_OD_SI_thick := .05m

IC) Energy Exchange (Thermal Radiation) PS, TS, DS 80 K Heatshields

Recall >

$Th\_300 := 300K$ Temperature hot plane

$Tc\_80 := 80K$ Temperature cold plane

Thermal radiation load is calculated by the radial conduction expression below, using the equivalent "K" value found with the equation from ref 1 above.

$$Qr := \frac{Th - Tc}{\frac{\ln\left(\frac{Ro}{Ri}\right)}{2\cdot\pi\cdot K\cdot L}}$$

IC-1) PS Outer Shield- 300 K to 80 K

$$Ka\_300\_80 := \left(\frac{N}{\Delta x}\right)^{-1}\cdot\left[hc + \frac{\sigma\cdot\varepsilon\cdot\left[(Th\_300K)^2 + (Tc\_80K)^2\right]\cdot(Th\_300K + Tc\_80K)}{2-\varepsilon}\right]$$

$KaCorrected\_300\_80 := Ka\_300\_80\cdot Cf$

$PS\_OD\_SI\_thick = 0.05\,m$

$KaCorrected\_300\_80 = 5.76\times 10^{-4}\,\frac{W}{m\cdot K}$

$$Qr\_PS\_Outer\_Shield\_300\_80K := \frac{Th\_300 - Tc\_80}{\frac{\ln\left(\frac{\frac{PS\_80K\_OD\_Heatshield\_D+PS\_OD\_SI\_thick}{2}}{\frac{PS\_80K\_OD\_Heatshield\_D}{2}}\right)}{2\cdot\pi\cdot KaCorrected\_300\_80\cdot PS\_Shield\_Length}}$$

$Qr\_PS\_Outer\_Shield\_300\_80K = 229.69\,W$

IC-1A) PS Inner Shield- 300 K to 80 K

$$Ka\_300\_80 := \left(\frac{N}{\Delta x}\right)^{-1}\cdot\left[hc + \frac{\sigma\cdot\varepsilon\cdot\left[(Th\_300K)^2 + (Tc\_80K)^2\right]\cdot(Th\_300K + Tc\_80K)}{2-\varepsilon}\right]$$

$$KaCorrected\_300\_80 := Ka\_300\_80\cdot Cf$$

$$PS\_ID\_SI\_thick = 0.03\,m$$

$$KaCorrected\_300\_80 = 5.76\times 10^{-4}\,\frac{W}{m\cdot K}$$

$$Qr\_PS\_Inner\_Shield\_300\_80K := \frac{Th\_300 - Tc\_80}{\dfrac{\ln\left(\dfrac{\frac{PS\_80K\_ID\_Heatshield\_D+PS\_ID\_SI\_thick}{2}}{\frac{PS\_80K\_ID\_Heatshield\_D}{2}}\right)}{2\cdot\pi\cdot KaCorrected\_300\_80\cdot PS\_Shield\_Length}}$$

$$Qr\_PS\_Inner\_Shield\_300\_80K = 248.79\,W$$

IC-2) TS Outer Shield- 300 K to 80 K

$$Ka\_300\_80 := \left(\frac{N}{\Delta x}\right)^{-1}\cdot\left[hc + \frac{\sigma\cdot\varepsilon\cdot\left[(Th\_300K)^2 + (Tc\_80K)^2\right]\cdot(Th\_300K + Tc\_80K)}{2-\varepsilon}\right]$$

$$KaCorrected\_300\_80 := Ka\_300\_80\cdot Cf$$

$$KaCorrected\_300\_80 = 5.76\times 10^{-4}\,\frac{W}{m\cdot K}$$

$$Qr\_TS\_Outer\_Shield\_300\_80K := \frac{Th\_300 - Tc\_80}{\dfrac{\ln\left(\dfrac{\dfrac{TS\_80K\_OD\_Heatshield\_D + TS\_OD\_SI\_thick}{2}}{\dfrac{TS\_80K\_OD\_Heatshield\_D}{2}}\right)}{2\cdot\pi\cdot KaCorrected\_300\_80\cdot TS\_Shield\_Length}}$$

$Qr\_TS\_Outer\_Shield\_300\_80K = 425.96\,W$

IC-2A) TS Inner Shield- 300 K to 80 K

$$Ka\_300\_80 := \left(\frac{N}{\Delta x}\right)^{-1}\cdot\left[hc + \frac{\sigma\cdot\varepsilon\cdot\left[(Th\_300K)^2 + (Tc\_80K)^2\right]\cdot(Th\_300K + Tc\_80K)}{2 - \varepsilon}\right]$$

$KaCorrected\_300\_80 := Ka\_300\_80\cdot Cf$ $PS\_ID\_SI\_thick = 0.03\,m$

$KaCorrected\_300\_80 = 5.76\times10^{-4}\,\frac{W}{m\cdot K}$

$$Qr\_TS\_Inner\_Shield\_300\_80K := \frac{Th\_300 - Tc\_80}{\dfrac{\ln\left(\dfrac{\dfrac{TS\_80K\_ID\_Heatshield\_D + TS\_ID\_SI\_thick}{2}}{\dfrac{TS\_80K\_ID\_Heatshield\_D}{2}}\right)}{2\cdot\pi\cdot KaCorrected\_300\_80\cdot TS\_Shield\_Length}}$$

$Qr\_TS\_Inner\_Shield\_300\_80K = 184.32\,W$

IC-3) DS Outer Shield- 300 K to 80 K

$$Ka\_300\_80 := \left(\frac{N}{\Delta x}\right)^{-1} \cdot \left[hc + \frac{\sigma \cdot \varepsilon \cdot \left[(Th\_300K)^2 + (Tc\_80K)^2 \right] \cdot (Th\_300K + Tc\_80K)}{2 - \varepsilon} \right]$$

$$KaCorrected\_300\_80 := Ka\_300\_80 \cdot Cf$$

$$KaCorrected\_300\_80 = 5.76 \times 10^{-4} \frac{W}{m \cdot K}$$

$$Qr\_DS\_Outer\_Shield\_300\_80K := \frac{Th\_300 - Tc\_80}{\dfrac{\ln\left(\dfrac{\frac{DS\_80K\_OD\_Heatshield\_D + DS\_OD\_SI\_thick}{2}}{\frac{DS\_80K\_OD\_Heatshield\_D}{2}}\right)}{2 \cdot \pi \cdot KaCorrected\_300\_80 \cdot DS\_Shield\_Length}}$$

$$Qr\_DS\_Outer\_Shield\_300\_80K = 463.67\,W$$

IC-3A) DS Inner Shield- 300 K to 80 K

$$Ka\_300\_80 := \left(\frac{N}{\Delta x}\right)^{-1} \cdot \left[hc + \frac{\sigma \cdot \varepsilon \cdot \left[(Th\_300K)^2 + (Tc\_80K)^2\right] \cdot (Th\_300K + Tc\_80K)}{2 - \varepsilon}\right]$$

$$KaCorrected\_300\_80 := Ka\_300\_80 \cdot Cf$$

$$KaCorrected\_300\_80 = 5.76 \times 10^{-4} \frac{W}{m \cdot K}$$

$$Qr\_DS\_Inner\_Shield\_300\_80K := \frac{Th\_300 - Tc\_80}{\dfrac{\ln\left(\dfrac{\frac{DS\_80K\_ID\_Heatshield\_D + DS\_ID\_SI\_thick}{2}}{\frac{DS\_80K\_ID\_Heatshield\_D}{2}}\right)}{2 \cdot \pi \cdot KaCorrected\_300\_80 \cdot DS\_Shield\_Length}}$$

$$Qr\_DS\_Inner\_Shield\_300\_80K = 478.84\,W$$

II) Thermal Radiation Loads PS, TS, DS Summed

Total_Radiation_Load_to_PS_TS_DS_Heatshields := Qr_PS_Outer_Shield_300_80K + Qr_PS_Inner_Shield

$\text{Total\_Radiation\_Load\_to\_PS\_TS\_DS\_Heatshields} = 2.03 \times 10^{3}\ \text{W}$

let > A := Total_Radiation_Load_to_PS_TS_DS_Heatshields

III) Approximation of Thermal Conduction loads from 1) Warm-to-Cold ends, 2) Supports, 3) Etc.

Estimates for conductive loads from ambient to the 80 K temperature level are taken from [ref 2], table 15.4 page 215

conductive_loads_to_80K_sink := 1338W

let > B := conductive_loads_to_80K_sink

IV) Summary of Heatshields and Thermal Conduction loads from 1) Warm-to-Cold ends, 2) Supports, 3) Etc.

Qr_PS_Outer_Shield_300_80K = 229.69 W <PS outer shield

Qr_PS_Inner_Shield_300_80K = 248.79 W <PS inner shield

Qr_TS_Outer_Shield_300_80K = 425.96 W <TS outer shield

Qr_TS_Inner_Shield_300_80K = 184.32 W <TS inner shield

Qr_DS_Outer_Shield_300_80K = 463.67 W <DS outer shield

Qr_DS_Inner_Shield_300_80K = 478.84 W <DS inner shield

conductive_loads_to_80K_sink := 1338W <conductive load summary [ref 2]

Total_Load_from_PS_TS_DS_Heatshields_and_Conductive_Loads := A + B

Total_Load_from_PS_TS_DS_Heatshields_and_Conductive_Loads = 3.37×10^{3} W <total load to 80 K cooling

V) Comparison of LN2 vs. SC Helium Cooled Shield; heat transfer, helium mass flow requirement, pressure drop, additional compressor requirements and power.

Assumptions:

A) 6 parallel tubes along the length of the aluminum shield, cooled with supercritical helium at an average temperature of 70 K or LN2.
B) 1/2" tube OD X 0.035" wall, therefore tube ID= 0.43"
C) A single tube removes 80 W end-to-end (from DS example with 6 parallel tubes)

Assuming 90% wetted tube for the LN2 application and the ID given:

$DS\_Shield\_Length := 11.9m$ $Tube\_ID := 0.43in$ $Q\_wall := 80W$

$$Surface\_Area\_Tube\_ID := DS\_Shield\_Length \cdot \pi \cdot Tube\_ID$$

$$Surface\_Area\_Tube\_ID = 4.08 \times 10^{3}\ cm^{2}$$

$$Active\_Surface\_Area\_Tube\_ID := Surface\_Area\_Tube\_ID \cdot 0.9$$

$$Active\_Surface\_Area\_Tube\_ID = 3.67 \times 10^{3}\ cm^{2}$$

I- For LN2 use:

$$Average\_Tube\_Heat\_Flux := \frac{Q\_wall}{Active\_Surface\_Area\_Tube\_ID}$$

$$Average\_Tube\_Heat\_Flux = 0.022\ \frac{W}{cm^{2}}$$

Comparing this value with experimental and predictive nucleate and film boiling data and calculations, one can see that the temperature difference at the interface between the tube wall and LN2 is << 0.1 K

II- For Helium Cooled Shield:

I- Assume a flow sufficient to limit the end-to-end differential temperature of the shield to 20 K with a nominal shield internal pressure of 15 atm. Calculate heat transfer for LN2 and Helium gas.

$\text{Shield\_dT} := 20\text{K}$ $\quad \text{Average\_Temperature} := 70\text{K}$ $\quad \text{Cp} := 5.2\,\frac{\text{J}}{\text{gm}\cdot\text{K}}$ $\quad \text{Pr} := .7$

$\text{mass\_flow} := \frac{\text{Q\_wall}}{\text{Cp}\cdot\text{Shield\_dT}}$ $\quad \rho\text{\_He\_15atm\_70K} := 0.01015\,\frac{\text{gm}}{\text{cm}^3}$ $\quad \mu\text{\_He} := 0.8046\cdot 10^{-5}\,\text{Pa}\cdot\text{s}$

$\text{mass\_flow} = 0.77\,\frac{\text{gm}}{\text{s}}$ $\quad \text{Section\_Area\_Tube} := \frac{\pi\cdot\text{Tube\_ID}^2}{4}$

$\text{Section\_Area\_Tube} = 0.94\,\text{cm}^2$

$$\text{Flow\_Velocity} := \frac{\text{mass\_flow}}{\text{Section\_Area\_Tube}\cdot\rho\text{\_He\_15atm\_70K}}$$

$$\text{Flow\_Velocity} = 80.89\,\frac{\text{cm}}{\text{s}}$$

$$\text{Red} := \frac{\text{Tube\_ID}\cdot\text{Flow\_Velocity}\cdot\rho\text{\_He\_15atm\_70K}}{\mu\text{\_He}}$$

$\text{Red} = 1.11\times 10^4$ <therefore turbulent flow

so for the calculation of the film coefficient the empirical relationship [ref 4] is used:

$$h := 0.023\cdot\text{Cp}\cdot\frac{\text{mass\_flow}}{\text{Section\_Area\_Tube}}\cdot\text{Red}^{-0.2}\cdot\text{Pr}^{\frac{2}{3}}$$

$$h = 0.012\,\frac{\text{W}}{\text{cm}^2\cdot\text{K}}$$

with the average heat flux ($\text{Average\_Tube\_Heat\_Flux} = 0.022\,\frac{\text{W}}{\text{cm}^2}$) shows that an ~ 2 K gas to tube surface differential is needed to achieve the same heat flux value (Average_Tube_Heat_Flux). So by comparison the helium cooled shield will only differ by its wall temperature temperature increase of ~ 2 K.

$$G := \frac{mass\_flow}{Section\_Area\_Tube} \qquad gc := 1\,\frac{m}{s^2}$$

$$G = 8.21\,\frac{kg}{m^2 s}$$

$$\Delta P := \frac{0.092 \cdot G^2}{Red^{0.2} \cdot gc \cdot Tube\_ID \cdot \rho\_He\_15atm\_70K} \cdot DS\_Shield\_Length$$

$$\Delta P = 0.15\,\frac{lb}{in^2}$$

<Note this does not represent a detailed design, head loss for manifolds, fittings, etc. not included; but considering the low drop through the main section it seems pressure drop is not an issue.

IV- Estimation of 70 K helium flow requirements:

The example above is for the DS and it was found that each of 6 heatstation tubes requires a mass flow of 0.8 g/s. This scales to approximately 5.0 g/s for the total DS magnet shield and thermal intercepts.

Using the flow value of 5.0 g/s, and the ratio of the heat loads, flow for other magnets are estimated:

$$DS\_outer\_flow := 5\,\frac{g}{s}$$

$$DS\_total\_load := 37W + 58W + 65W + Qr\_DS\_Inner\_Shield\_300\_80K + Qr\_DS\_Outer\_Shield\_300\_80K$$

$$TS\_total\_load := 992W + Qr\_TS\_Outer\_Shield\_300\_80K + Qr\_TS\_Inner\_Shield\_300\_80K$$

$$PS\_total\_load := 92W + Qr\_PS\_Outer\_Shield\_300\_80K + Qr\_PS\_Inner\_Shield\_300\_80K$$

$$TS\_70\_flow := \frac{TS\_total\_load}{Qr\_DS\_Outer\_Shield\_300\_80K} \cdot DS\_outer\_flow$$

$$PS\_70\_flow := \frac{PS\_total\_load}{Qr\_DS\_Outer\_Shield\_300\_80K} \cdot DS\_outer\_flow$$

$$DS\_70\_flow := \frac{DS\_total\_load}{Qr\_DS\_Outer\_Shield\_300\_80K} \cdot DS\_outer\_flow$$

$TS\_70\_flow = 17.28 \frac{g}{s}$ $PS\_70\_flow = 6.15 \frac{g}{s}$ $DS\_70\_flow = 11.89 \frac{g}{s}$

$$Total\_Flow\_70\_K := DS\_70\_flow + TS\_70\_flow + PS\_70\_flow$$

$Total\_Flow\_70\_K = 35.32 \frac{g}{s}$

<Estimate of total flow requirement for all magnets

V- Comment about TS support heat stationing.

The total flow requirement for the supports is included in the estimate above. Assuming the worst case is 100 W per station, some design work is needed for these stations. We cannot simply use the 1/2" tubing because the length would be equivalent to the DS OAL. These heat stationing "blocks" will need the proper surface area in a more compact length without sacrificing performance. A general approach could be a short coaxial heatexchanger where helium is diverted through an annular space to maintain velocity (and therefor good heat transfer) and increase the "per length" surface area. This issue is not novel to helium cooling.

V. A- Example of Compacting the Heat Station for Supports (note, this is for proof of principle and does not suggest a design approach. See comments at the end of this section)

As an example let's assume an annular arrangement with the length of about 0.4 meter, and with about the same internal surface convection area:

$\text{Surface\_Area\_Tube\_ID} = 4.08 \times 10^{3}\ \text{cm}^{2}$ $\text{Length\_Annulus} := 0.4\text{m}$

$$\text{Outer\_Tube\_ID} := \frac{\text{Surface\_Area\_Tube\_ID}}{\text{Length\_Annulus}\cdot\pi}$$

$\text{Outer\_Tube\_ID} = 32.49\ \text{cm}$

The hydraulic diameter for annular flow is the ID of the outer tube - the OD of the inner tube. As a starting point, let the hydraulic diameter = the 1/2" tube ID. So Diameter_Hydraulic= $\text{Tube\_ID} := 0.43\text{in}$

Replace the original tube diameter with the hydraulic diameter for the annular arrangement:

$\text{OD\_Inner\_Tube} := \text{Outer\_Tube\_ID} - \text{Tube\_ID}$

$\text{OD\_Inner\_Tube} = 31.4\ \text{cm}$

$\text{OD\_Inner\_Tube} := 32.3\text{cm}$ <Change the inner tube OD to increase the flow velocity

$\text{Dh} := \text{Outer\_Tube\_ID} - (\text{OD\_Inner\_Tube})$

$\text{Dh} = 0.08\ \text{in}$

$$\text{Sectional\_Area\_Annulus} := \pi\cdot\frac{\left(\text{Outer\_Tube\_ID}^{2} - \text{OD\_Inner\_Tube}^{2}\right)}{4}$$

$Sectional\_Area\_Annulus = 9.82\,cm^2$

$Section\_Area\_Tube = 0.94\,cm^2$

<sectional area of the annular tube arrangement. Note that matching the hydraulic diameter with the 1/2" tube produces much more flow area, reduces the velocity and therefor reduces the Reynolds number. See following.

$$Flow\_Velocity\_Annulus := \frac{mass\_flow}{Sectional\_Area\_Annulus \cdot \rho\_He\_15atm\_70K}$$

$$Flow\_Velocity\_Annulus = 7.72\,\frac{cm}{s}$$

$$Red\_annulus := \frac{Dh \cdot Flow\_Velocity\_Annulus \cdot \rho\_He\_15atm\_70K}{\mu\_He}$$

$Red\_annulus = 187.87$ <therefore laminar flow

Pressure drop at support heat station with annulus flow arrangement:

$$G := \frac{mass\_flow}{Sectional\_Area\_Annulus} \qquad gc := 1\,\frac{m}{s^2}$$

$$G = 0.78\,\frac{kg}{m^2 s}$$

$$\Delta P\_Annulus := \frac{32 \cdot G^2}{Red \cdot gc \cdot Dh \cdot \rho\_He\_15atm\_70K} \cdot Length\_Annulus$$

$$\Delta P\_Annulus = 5.12 \times 10^{-5}\,\frac{lb}{in^2}$$

Convection coefficient at support heat station with annulus flow arrangement:

so for the calculation of the laminar flow film coefficient the empirical relationship [ref 4] is used:

$$k\_Helium := 0.05996\frac{W}{m\cdot K}$$

$$h\_annulus := \left[(3.658) + \frac{0.0668\cdot\left(\frac{Dh}{.25\cdot m}\right)\cdot Red\_annulus\cdot Pr}{1 + (0.04)\cdot\frac{Dh}{.25\cdot m}\cdot Red\_annulus\cdot Pr^{\frac{2}{3}}}\right]\cdot\frac{k\_Helium}{Dh}$$

$$h\_annulus = 0.0116\frac{W}{cm^2\cdot K}$$

<This is equivalent to the coefficient obtained for the flow through heat station tubes along the MLI shield.

The above example is a simplified approach to cooling MECO 70 K level conduction loads and is used **to illustrate the concept only**. The final heat exchanger, positioned at each conduction station, would incorporate more traditional heat transfer enhancements like extended transfer area via extended surfaces or heat transfer fins. **Using proper heat exchanger design will reduce the volume of this heat sink considerably.**

VI- Additional Power for 70 K helium flow requirements:

The additional flow requirement for the 70 K system would represent approximately an 36 % flow increase based upon the overall flow requirements of a 700 W 4.5 K system. In terms of electrical power it would be the equivalent of about 150 HP or 112 kW. In terms of present BNL power cost ($ .06/ kW-hr), about $6.80 per hour. This estimate does not consider reintroduction of the high pressure cold return gas into the refrigerator process cycle to drive turbines, so the actual figure associated with the compressor flow is also related to the refrigerator process cycle design. For example, the power required to refrigerate at 70 K is only about 4% of the equivalent power at 4.5 K. Considering the nominal % Carnot efficiency for typical refrigerators the power required to produce 4.5 K refrigeration is ~ 300 We/Wr (Watts electrical per Watts of refrigeration). For a 3 kW shield at 70 K, 36 kW of electrical power is needed.

VII- Capital cost summary for modified refrigerator and other options for the production of cold helium gas for shield cooling, and reasons for discounting them

A - a budgetary estimate for adding the 70 K option, to a standard refrigerator that covers MECO's 4.5 K and lead requirements, was obtained from Linde. The cost is ~ $125K.

B - a separate dual heat exchanger (he/LN2 with economizer) in a separate cold box could be used. It would require the same additional compressor flow. It would cost several $100K.

C - a closed loop he/LN2 exchanger with dedicated cold compressor could be used. This type of system does not fully utilize the N2 gas specific heat component, but reduces compressor HP requirements. It would also cost several $100K.

References

1- Randall F. Barron, "Cryogenic Systems," 1985

2- MIT MECO CDR

3- Discussions with Brad Smith

4- Thomas M. Flynn, "Cryogenic Engineering," 1997