#8

CRYOGENIC CONSULTANTS, INC.

1176 NORTH IRVING STREET • ALLENTOWN, PA. 18103 • (215) 439-0419

December 12, 1985

Mr. Kelley D. Dixon
Fermilab
P.O. Box 500
Batavia, Illinois 60510

Dear Kelley:

Enclosed please find the calculations I promised a few weeks ago. It took sometime, because we had to redo them.

The repeat was caused by a change in the vapor return line from coils to N_2 vessel, which was not checked through our organization.

However, we believe that cooldown can be accomplished in a week or so.

If you have any questions, please call.

Sincerely,

CRYOGENIC CONSULTANTS, INC.

Peter C. Vander Arend
President

PCV/eaj

Encls: Calculations

12/6/82

LIQUID ARGON DEWAR COOLDOWN - SUMMARY

COOLDOWN COILS

3 - Parallel finned tubes, headered, single LN_2 feed and single N_2 gas return to vessel
Height of liquid head ≐ 8' - 8"

STEADY STATE COIL

1 - Parallel finned tube, headered, single LN_2 feed and N_2 gas return to vessel.
Height of liquid head ≐ 8' - 8"

Finned Tubing - 7/8" OD x 0.045" wall w/ 2" OD x 0.030" thick fins, 6 fins/inch
- Each circuit ~ 52 ft long.

LN_2 Feed lines - 1" OD x 0.12" wall

N_2 Gas Return Lines - 1" OD x 0.12" wall

Maximum Cooldown Rates as a Function of LN_2 Pressure

LN_2 Pressure psia	Max. LN_2 Flowrates Steady State Coil gms/sec	Cooldown Coil gms/sec	Cooldown Time hrs	LN_2 Consumed Liters
15.0	37	79	175	90500
20.0	42	91	155	93000
30.0	51	109	132	98000

LAr DEWAR COOLDOWN

LN_2 – $P = 15$ psia
$T = 139.5°R = -320.5°F = 77.5°K$
$\rho_L = 50.43$ lbs/ft^3
$\rho_V = 0.2934$ lbs/ft^3
$\mu_L = 0.396$ lbs/ft·hr. $\mu_V = 0.01307$
$k_L = 0.0785$ BTU/ft·HR·°R $k_V = 0.00441$
$C_{pL} = 0.4932$ BTU/lb·°R $C_{pV} = 0.2686$

Calc. Pressure drop Through vapor return line, cooldown coil

Cooldown Coil

$\dot{m} = 147$ gm/sec $= 1166$ lbs/hr
$A = \frac{\pi}{4}\left(\frac{0.76}{12}\right)^2 = 0.00315$ ft^2 $d_h = 0.76" = .0633$ ft
$G = 3.701 \times 10^5$ lbs/hr·ft^2
$N_{Re} = 1.793 \times 10^6$
$f = .00258$
$\Delta P/L = 0.635$ psi/ft (too high)

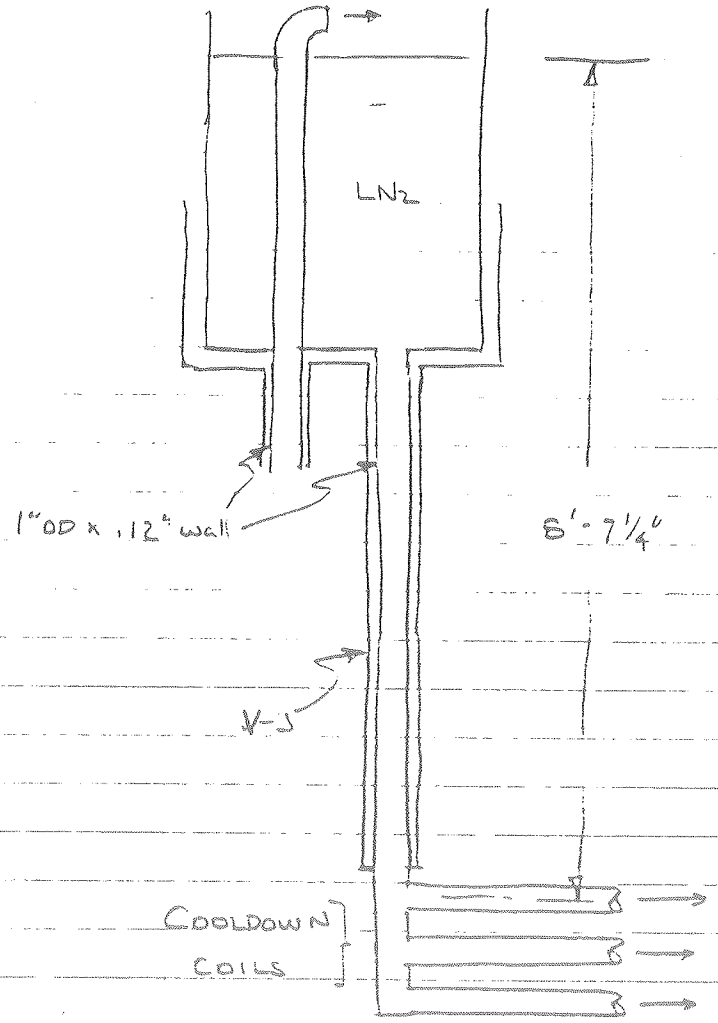
Pressure head available, $\Delta P_H = \frac{\cancel{5.504}\ 8.35}{144}(50.43 - 0.29) = \cancel{3.0}\ 2.9$ psi

Steady State Coil

$\dot{m} = 49$ gm/sec $= 388.5$ lbs/ft^3

$G = 1.233 \times 10^5$ lbs/hr·ft^2
$N_{Re} = 5.974 \times 10^5$
$f = 0.00322$
$\Delta P/L = 0.0878$ psi/ft

$\Delta P = 0.0878 \times 9$ ft $= 0.79$ psia pressure loss in the vertical vapor return to the pot.



5' - ~~4.5"~~ 1.5
+ - 2.5"
+ 3' - 3.25"
9' - 0.25
- 5.25"
8' - 7.25"

8' - 4.25"

Vapor Head ~ 4" less than Liquid head

Tubing, finned — 7/8" OD x 0.045" wall w/ 2" OD x 0.030" Thick fins
6 fins/inch x 19'-6" long — Reqd 3 lengths
Copper CCI Dwg 7490-D
CCI Dwg 7483-E

Two-Phase Flow ΔP in finned tube HX.

$L = 20' + 20' + 11'-10'' = 51'-10'' \sim 52$ ft long

Calculate ΔP_L at 50 g/sec. through finned tube,

$\dot{m} = 50$ g/sec $= 396.5$ lbs/hr

$d_H = 0.875 - 0.09 = 0.785$ in $= 0.0654$ ft

$A = 0.00336$ ft^2

$G = 118{,}031$ lbs/hr·ft^2

$N_{Re} = \dfrac{(118{,}031)(0.0654)}{0.396} = 19{,}493$

$f = 0.00638$

$\left(\dfrac{\Delta P}{L}\right)_L = \dfrac{0.00638\,(118{,}031/3600)^2}{193\,(50.43)(0.785)} = 0.000596$ psi/ft

Calc. ΔP_V at 50 g/sec Thru finned tube,

$G = 118{,}031$ lbs/hr·ft^2

$N_{Re} = \dfrac{(118{,}031)(0.0654)}{0.01307} = 590{,}607$

$f = 0.00322$

$\left(\dfrac{\Delta P}{L}\right)_V = \dfrac{0.00322\,(118{,}031/3600)^2}{193\,(0.2934)(0.785)} = 0.0787$ psi/ft

∴ Too high Through single steady state coil

Argon B.P. @ 14.7 psia $= -302.6$ °F $= 157.4$ °R $= 87.4$ °K

As pressure of LN_2 pot is increased, ΔT avail. for condensing LAr is reduced;
at 35 psia, T_{sat} (N_2) $= 154$ °R

$\Delta T = 3.4$ °R

ESTIMATE ΔP IN COILS (Account for 2ϕ flow)

$$\left(\frac{\Delta P}{L}\right) = \frac{(2.37 \times 10^{-12})(F^{1.8})(\mu^{0.2})}{\rho\, D^{4.8}}$$

Solving for F, flowrate, in lbs/hr

$$F^{1.8} = \frac{(\Delta P/L)(\rho)(D^{4.8})}{(2.37 \times 10^{-12})(\mu^{0.2})}$$

$$F = \left[\frac{(\Delta P/L)(\rho)(D^{4.8})}{(2.37 \times 10^{-12})(\mu^{0.2})}\right]^{0.556}$$

Check $F = \left[\frac{(0.0767)(0.2934)(0.0654)^{4.8}}{(2.37 \times 10^{-12})(0.01307)^{0.2}}\right]^{0.556} = 400$ lbs/hr

Used 396.5 lbs/hr. – ok check

For Steady state single coil,

ΔP_T (available) = 3.0 psi.

Assume $\frac{\Delta P}{L}$ in vertical return tube is same $\Delta P/L$ in the condenser tube.

$\therefore L = \underset{\text{coil}}{52\text{ ft}} + \underset{\text{vertical}}{9\text{ ft}} + \underset{\text{bends, fittings}}{5\text{ ft}} = 66\text{ ft.}$

$\Delta P/L$ (allowable) $= \frac{3.0}{66} = 0.0455$ psi/ft

Also assume average $\Delta P/L = (\Delta P/L)_{\text{vap}}$ through coil.

$$F = \dot{m} = \left[\frac{(0.0455)(0.2934)(0.0654)^{4.8}}{(2.37 \times 10^{-12})(0.01307)^{0.2}}\right]^{0.556}$$

$= 295$ lbs/hr. $= 37.2$ gms/sec.

For Cooldown coil,
3 - finned tube coils (52 ft each)
1 - Vapor return line (9 ft)

$\Delta P/L$ in Vapor return line carries 3x's the mass flow of each of the finned tubes and will be

$$\left(\frac{\Delta P}{L}\right)_{VR} = (3)^{1.8}\left(\frac{\Delta P}{L}\right)_{F.T.} = 7.22\left(\frac{\Delta P}{L}\right)_{F.T.}$$

$$\Delta P_T = \left[9(7.22) + 52 + 5\right]\left(\frac{\Delta P}{L}\right)_{F.T.}$$

$$3.0 = 122\left(\frac{\Delta P}{L}\right)_{F.T.}$$

$$\left(\frac{\Delta P}{L}\right)_{F.T.} = 0.0246 \text{ psi/ft.}$$

$$F\,(\text{per finned circuit}) = \left[\frac{(0.0246)(0.2934)(0.0654)^{4.8}}{(2.37\times10^{-12})(0.01307)^{0.2}}\right]^{0.556}$$

$$= 209.6 \text{ lbs/hr} = 26.43 \text{ gm/sec}$$

Check -
1) Finned tube circuit.

$\dot{m} = 209.6$ lbs/hr.
$G = 62{,}381$ lbs/hr.ft^2
$N_{Re} = 312{,}143$
$f = 0.00366$

$$\Delta P/L = \frac{0.00366\left(62{,}381/3600\right)^2}{193(0.2934)(0.785)} = 0.0247 \text{ psi/ft}$$

$L = 52 + 5 = 57$ ft.

$\Delta P = 1.409$ psi

2) Vapor return line

$\dot{m} = 3 \times 209.6 = 628.8$ lbs/hr

$G = 199619$ lbm/hr·ft²

$N_{Re} = 966{,}785$

$f = 0.00292$

$$\Delta P/L = \frac{(0.00292)(199619/3600)^2}{193\,(0.2939)(0.76)} = 0.209 \text{ psi}$$

$\Delta P = 9 \times 0.209 = 1.88$ psi

$\Delta P_T = 1.88 + 1.409 = 3.29$ psi (10% above 3 psi avail)

<u>COOLDOWN</u> <u>LN2</u> <u>FLOW</u> (maximum)

$\dot{m} = 37.2 + 3(26.4) = 116.4$ gms/sec

Use $\dot{m} = 110$ gm/sec for cooldown time calcs.

COOLDOWN TIME

			BTU's
Stainless Steel Shell	45,000 lbs (33.27 BTU/lb)	=	1.50×10^6
Hadron Detector			
G-10	60,000 lbs $(0.134 \frac{BTU}{lb \cdot °F})(70 + 300)$	=	2.98×10^6
Steel	260,000 lbs (33.27 BTU/lb)	=	8.65×10^6
Photon Shield (Lead)	50,000 lbs $(.03 \frac{BTU}{lb \cdot °F})(70 + 300)$	=	0.56×10^6
	Total Q to be removed	=	13.69×10^6 Btu
		=	1.444×10^{10} J.

N_2 @ 15 psia, $\Delta H_{vap} = (33.28 + 52.08) = 85.36$ BTU/lb $= 198.4$ J/gm

$\rho_L = 50.43$ lbs/ft^3 $= 0.808$ gm/cc

At $\dot{m}_{LN_2} = 110$ gm/sec, q @ 116 gm/sec

q, cooling rate, $= (198.4)(110) = 21.8$ KW (w/o Heat leak

Cooldown Time $= \frac{(1.444 \times 10^{10})}{(110)(198.4)} \times \frac{1}{3600} = 184$ hrs 174.5 hrs
$= 7.7$ days 7.3 days

LN_2 Consumed during Cooldown,

$$m = \frac{1.444 \times 10^{10}}{198.4} = 7.256 \times 10^7 \text{ gms}$$

$$= 1.599 \times 10^5 \text{ lbs}$$

$$\text{Vol } LN_2 = \frac{1.599 \times 10^5}{50.43} \times 28.32 = 9047 \text{ liters}$$

HEAT FLUX FROM FINNED TUBES

$Q = 21.8$ KW

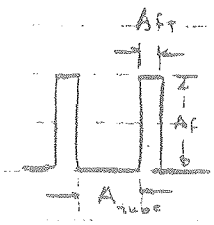
Calc. fin area for 4 parallel finned tubes.

Tubes 0.875" OD

Fins 2" OD, 6 fins/inch, 0.03" thick

Heat Transfer surface Area, A_s

$$A_f = \frac{\pi}{4}(2.0^2 - 0.875^2) \times 2 = 5.081 \text{ in}^2/\text{fin}$$
$$= 30.48 \text{ in}^2/\text{in of tube}$$



$$A_{fT} = 4 \times 52 \times \frac{30.48 \times 12}{144} = 528.3 \text{ ft}^2$$

$$A_{tube} = \pi\left(\frac{0.875}{12}\right)\left[\frac{1.0 - (0.03 \times 6)}{} \times 4 \times 52\right] = 39.1 \text{ ft}^2$$

$$A_{fin\ edge} = \pi\left(\frac{2}{12}\right)\left(6 \times 12 \times 52 \times 4\right)\left(\frac{.03}{12}\right) = 19.6 \text{ ft}^2$$

Total Heat Transfer Surface Area,

$A_T = 587 \text{ ft}^2$ in 4 finned coils

$\therefore$ Heat Flux, Required $\frac{Q}{A} = \frac{21{,}800 \text{ watts}}{587 \times 929} = 0.04$ watts/cm^2

For Condensing N_2, (which should be similar to A_T)

ΔT, (°K)	Q/A (watts/cm^2)
1.0	0.3
5.0	1.3
10.0	1.7

For LN_2 at 15 psia

$\Delta T = 87.4 - 77.5 = 9.9$ °K

$\therefore$ Cooldown limited by capacity of coils for N_2 flow.

INSIDE TUBE COEFFICIENT

7/8" OD × 0.045 WL ID = 0.785 in. = 0.0654 ft
= 1.994 cm.

From UCRL-3421, Boiling N_2 Coeff vs Temp graph.

ΔT, °K	Q, watts/cm²	h_i watts/cm²·°K	Btu/hr·ft²·°F
1.0	0.053	.0530	93.4
1.6	0.100	.0625	110.0
2.0	0.145	.0725	127.7
3.0	0.340	.1133	199.6
4.0	0.750	.1875	330.3
5.0	1.60	.320	563.7
6.0	3.00	.500	880.7

× 1761.4

Calc. inside heat transfer coefficient

$$A = \frac{\pi}{2}(.0654)^2 = 0.00336 \text{ ft}^2$$

$$\dot{m} = 26.43 \text{ gms/sec} = 209.6 \text{ lbs/hr}$$

$$G = 62381 \text{ lbs/hr·ft}^2$$

As liquid —

$$N_{Re} = \frac{(0.0654)(62381)}{0.396} = 10302$$

$$f = 0.00725$$

$$j = 0.00362$$

$$h_{iL} = \frac{(0.4932)(0.00362)(62381)}{1.836} = 60.6 \text{ Btu/hr·ft}^2\text{·°F}$$

As Vapor —

$$N_{Re} = \frac{(0.0654)(62381)}{(0.1307)} = 312,144$$

$$j = 0.001832$$

$$h_{iv} = \frac{(0.2686)(0.001832)(62381)}{0.5589} = 35.74 \text{ Btu/hr·ft}^2\text{·°F}$$

Assume Lower value, $h_i = 35.7$ Btu/hr·ft²·°F

Area available, $A_i = \pi\left(\frac{0.785}{12}\right)(52 \times 4) = 42.75$ ft²

If $q = 21.8$ kwatts.

$$\Delta T_{req'd} = \frac{21{,}800 \text{ watts}}{35.7 \text{ Btu/hr·ft}^2\cdot{}^\circ F} \times \frac{1}{42.75 \text{ ft}^2} \times 3.4129 \frac{\text{Btu/hr}}{\text{watt}} = 48.8^\circ F$$
$$= 27.1^\circ K$$

Not possible – need boiling coefficients shown on page 9.

At $\Delta T = 4.0^\circ K$, $h_i = 330$ Btu/hr·ft²·°R

$$\therefore Q_i = 330(42.75)(4.0)(1.8) = 101{,}574 \text{ Btu/hr}$$
$$= 29.8 \text{ kW}$$

∴ Maintain ΔT_i between N_2 in tubes and Tube wall at 4.0°K or greater.

ΔT_o between tube wall and Ar must be,

$$\left(\frac{Q}{A}\right)_{max} = \frac{21{,}800 \text{ watts}}{567 \text{ ft}^2 \times 929 \text{ cm}^2/\text{ft}^2} = 0.04 \frac{\text{watts}}{\text{cm}^2}$$

ΔT_o can be 1.0°K or less – practically, Let $\Delta T_o = 1.0^\circ K$.

$$\therefore \Sigma \Delta T = 4.0 + 1.0 = 5.0^\circ K$$

What pressure can LN_2 be at?

Boiling T LN_2 = 87.4 − 5.0 = 84.4 °K
= 151.9 °R

@ P = 30 psia, $\overline{T}_{sat} = 151.1$ °R

Calc. Max Flowrate Possible at LN_2 Pressure = 30 psia

Properties

	Vapor	Liquid
P, psia	30	30
T, °R	151.1	151.1
ρ, lbs/ft^3	0.5579	48.51
μ, lbs/ft·hr.	.01426	0.321
k, Btu/ft·hr·°R	.00487	0.0714
C_p, Btu/lb·°R	0.2621	0.4992
$Pr^{1/3}$	0.880	1.715

Assume average $\Delta P/L$ in coils and risers is equal to $(\Delta P/L)$ for all vapor.

$$\Delta P_{AVAIL} = \frac{(48.51 - 0.5579)(8.6\,ft)}{144} = 2.86 \text{ psi}$$

For Steady State Single Coil:

$$\Delta P/L = \frac{2.86}{66\,ft} = 0.0434 \text{ psi/ft}$$

$$\dot{m}_{LN_2} = F = \left[\frac{(0.0434)(0.5579)(0.0654)^{4.8}}{(2.37\times10^{-12})(0.01426)^{0.2}}\right]^{0.556} \quad (Pg.\ 4)$$

$$= 406.9 \text{ lbs/hr.}$$

$$= 51.3 \text{ gms/sec}$$

For Cooldown Coil:

$$(\Delta P/L)_{Fill} = \frac{2.86}{122} = 0.0234 \text{ psi/ft}$$

$$\dot{m}_{LN_2} = F = \left[\frac{(0.0234)(0.5579)(0.0654)^{4.8}}{(2.37\times10^{-12})(0.01426)^{0.2}}\right]^{0.556}$$

$$= 285.6 \text{ lbs/hr}$$

$$= 36.4 \text{ gms/sec.}$$

$$\therefore \sum \dot{m}_{LN_2} = 3(36.4) + 51.3 = 160.5 \text{ gms/sec}$$

COOLDOWN TIME @ 150 gms/sec LN_2 @ 160 gm/sec

$$\Theta = \frac{1.444 \times 10^{10}}{(150)(189.4)(3600)} = 141.2 \text{ hrs} = 5.9 \text{ days.}$$

132.4 hrs
5.5 days.

$$\text{Liters consumed} = \frac{1.444 \times 10^{10} \times 28.32}{(189.4)(454)(48.51)} = 9804 \text{ liters}$$

Calc. Max Flowrate at 20 psia LN_2 Pressure

	Vapor	Liquid
P_1 psia	20	20
T_1 °R	144.1	144.1
ρ	0.3828	49.69
μ	0.0135	0.360
k	0.00458	0.0757
C_p	0.2733	0.4950
$Pr^{2/3}$	0.866	1.77

$$\Delta P_{avail} = \frac{(49.69 - 0.3828)(8.6)}{144} = 2.94 \text{ psi}$$

For steady state single coil:

$$\Delta P/L = \frac{2.94}{66} = 0.0445 \text{ psi/ft}$$

$$\dot{m} = F = \left[\frac{(0.0445)(0.3828)(0.0654)^{4.8}}{(2.37 \times 10^{-12})(0.0135)^{0.2}}\right]^{0.556}$$

$$= 336.7 \text{ lbs/hr}$$
$$= 42.5 \text{ gms/sec}$$

For cooldown coils

$$\Delta P/L = \frac{2.94}{122} = 0.0241 \text{ psi/ft.}$$

$$\dot{m} = F = \left[\frac{(0.0241)(0.3625)(0.0654)^{4.8}}{(2.37\times10^{-12})(0.0135)^{0.2}}\right]^{.556}$$

$$= 239.4 \text{ lbs/hr}$$

$$= 30.2 \text{ gms/sec.}$$

$$\Sigma \dot{m}_{LN_2} = 3(30.2) + 42.5 = 133.1 \text{ gm/sec.}$$

COOLDOWN TIME @ 125 gm/sec @ 133 gm/sec

$$\Theta = \frac{1.444\times10^{10}}{(125)(194.9)(3600)} = 164.6 \text{ hours} = 6.9 \text{ days.}$$

154.7 hrs
6.4 days.

LN_2 Consumed during cooldown

$$V = \frac{1.444\times10^{10}}{(194.9)(49.69)(454)} \times 28.32 = 9301 \text{ liters}$$