Fermilab

SSC DETECTOR SOLENOID DESIGN NOTE # 130

TITLE: Cooldown and Quench Recovery

AUTHOR: A. M. Stefanik

DATE: January 22, 1991

ABSTRACT: This design note contains the first set of calculations for cooldown and quench recovery.

SUMMARY: The calculations indicate that a 1000 W refrigerator can cool a 24,000 kg cold mass down to liquid helium temperature in 248 hours. Helium supply pressure must be above 10 ATM at times to achieve this cooldown rate. The cooldown rate will increase if helium supply pressure is limited to a low value because of the relief valves on the solenoid's LHe cooling circuit. These relief valves may have a relatively low set point to limit quench pressure in the circuit.

The calculations indicate that a 1500 W refrigerator can provide a quench recovery time of about 14 hours from a temperature of 77.5 K. The 77.5 K quench temperature assumes that all of the solenoid's stored energy, 190 MJ, is deposited in the cold mass. Quench recovery can be achieved in under 4 hours with 6,000 liters of stored LHe. The gaseous helium returning from the solenoid must be compressed, stored and reliquefied at a later time.

A quench temperature of 50 K is calculated for the CDF cold mass from data recorded for a September 1988 quench.

CONCLUSION: The cooldown and quench recovery requirements must be included in the specification for the refrigerator.

SUBJECT: COOLDOWN AND QUENCH RECOVERY

NAME: A.M. STEFANIK

DATE: 1/22/91 | REVISION DATE:

INDEX

No.	SUBJECT	PAGE
3.1	COOLDOWN	2-26
3.2	QUENCH RECOVERY	27-42
3.3	EXAMINE CDF QUENCH RECOVERY DATA	43-44

SUBJECT: SOLENOID COOLDOWN

NAME: AMS

DATE: 12/11/90

REVISION DATE:

PROCEDURE: ASSUME A COOLDOWN RATE AND ESTIMATE THE HELIUM FLOW RATES REQUIRED TO ACHIEVE THAT RATE.

CDF COOLDOWN TAKES ABOUT 10 DAYS.

$$\frac{\Delta T}{t} = \frac{300\ K}{10\ days \times \frac{24\ hrs}{day}} = 1.25 \frac{K}{hr}$$

USE THIS VALUE FOR THIS CALCULATION.

TYPE U SOLENOID COLD MASS $\doteq$ 24 tonnes = 24,000 kg

$\doteq$ 52,910 Lbm

THE COLD MASS IS PREDOMINANTLY ALUMINUM.

THE SPECIFIC HEAT AND ENTHALPY OF ALUMINUM ARE TABULATED ON PAGE 3.

BASE THE CALCULATION ON COOLDOWN TEMPERATURE INTERVALS OF 50 K DOWN TO 50 K, THEN USE 25 K INTERVAL

CALCULATE THE COOLING POWER FOR EACH TEMP INTERVAL.

USE A CONSTANT HEAT LEAK OF:

145 W	- SUPPLY LINE	FROM DN 123
5 W	- CHIMNEY LINE	
20 W	- SOLENOID	
170 W	- Σ	

THE REQUIRED COOLING POWER FOR EACH TEMPERATURE LEVEL IS TABULATED ON PAGE 4.

AMS 12/11/90

SPECIFIC HEAT, ENTHALPY of ALUMINUM

Sources of Data:

Giauque, W. F. and Meads, P. F., J. Am. Chem. Soc. 63, 1897-1901 (1941)
Maier, C. G. and Anderson, C. T., J. Chem. Phys. 2, 513-27 (1934)
Phillips, N. E., Low Temperature Physics and Chemistry, Univ. Wisconsin Press (1958)

Other References:

Behn, U., Ann. Physik Beiblätter 25, 178 (1901)
Goodman, B. B., Compt. rend. 244, 2899 (1957)
Griffiths, E. G. and Griffiths, E., Phil. Trans. Roy. Soc. London A90, 557 (1914)
Kok, J. A. and Keesom, W. H., Physica 4, 835 (1937)
Koref, F., Ann. Physik (4) 36, 49 (1911)
Nernst, W., Ann. Physik (4) 36, 395 (1911)
Nernst, W. and Lindemann, F. A., Z. Elektrochem. 17, 817 (1911)
Nernst, W. and Schwers, F., Sitzber. kgl. preuss. Akad. Wiss. 355 (1914)
Richards, T. W. and Jackson, F. G., Z. physik. Chem. 70, 414 (1910)
Schmitz, H. E., Proc. Roy. Soc. (London) 72, 177 (1903)
Tilden, W. A., Proc. Roy. Soc. (London) 71, 220 (1903)

Table of Selected Values

	Temp. °K	C_p j/gm-°K	H j/gm	Temp. °K	C_p j/gm-°K	H j/gm	
	1	0.000 10*		60	0.214	3.64	0.22
	1	.000 051	0.000 025	70	.287	6.15	
	2	.000 108	.000 105	80	.357	9.37	
	3	.000 176	.000 246	90	.422	13.25	
0.00026	4	.000 261	.000 463	100	.481	17.76	0.49
	6	.000 50	.001 21	120	.580	28.4	
	8	.000 88	.002 6	140	.654	40.7	
	10	.001 4	.004 9	160	.713	54.4	
	15	.004 0	.018	180	.760	69.2	
0.0085	20	.008 9	.048	200	.797	84.8	0.8
	25	.017 5	.112	220	.826	101.0	
	30	.031 5	.232	240	.849	117.8	
	35	.051 5	.436	260	.869	135.0	
	40	.077 5	.755	280	.886	152.5	
	50	.142	1.85	300	.902	170.4	0.9

* Superconducting

↑ Cp for 3003, 5083, 6061

RJC Issued: 6/15/59

REF: WADD TECH REPORT 60-56 OCT. 1960

522703

INTERVAL NO.	SOLENOID TEMPERATURE INITIAL (K)	SOLENOID TEMPERATURE FINAL (K)	SOLENOID ENTHALPY INITIAL (J/g)	SOLENOID ENTHALPY FINAL (J/g)	TOTAL HEAT LOAD (MJ)	INTERVAL TIME (HR)	REQUIRED COOLING POWER W/O HEAT LEAK (KW)	REQUIRED COOLING POWER W/HEAT LEAK (KW)
1	300	250	170.4	126.4	1,056	40	7.3	7.5
2	250	200	126.4	84.8	998	40	6.9	7.1
3	200	150	84.8	47.5	895	40	6.2	6.4
4	150	100	47.5	17.8	713	40	5	5.1
5	100	50	17.8	1.9	382	40	2.7	2.8
6	50	25	1.9	0.1	43	20	0.6	0.8
7	25	4	0.1	0.000463	2.4	20	0.033	0.203

SUBJECT

NAME AMS

DATE 12/11/90 | REVISION DATE

ESTIMATE HELIUM FLOW RATES —

COMPRESSOR CAPACITY FOR A FERMI 600 W HELIUM REFRIGERATOR IS 58 g/s.

ASSUME COMPRESSOR CAPACITY FOR THE 1500 W HELIUM REFRIGERATOR IS AT LEAST (1500/600) 58 = 145 g/s.

RATIO THE SSC MTL COMPRESSOR CAPACITY AS A CHECK:

(1500/3530) 345 g/s = 147 g/s ≐ 145 g/s

PROCEDURE TO CALCULATE THE HELIUM FLOW RATE FOR EACH TEMPERATURE INTERVAL:

1) $Q = \dot{m}(h_2 - h_1)$

WHERE: 2 ≡ OUTLET AND 1 ≡ INLET

2) ΔT DEFINITIONS

SOLENOID ΔT FOR EACH INTERVAL = $T_{INITIAL} - T_{FINAL}$

APPROACH ΔT = 10 K (GHe TO SOLENOID)

3) GAS INLET TEMP = AVERAGE SOLENOID TEMP − 100 K
MAXIMUM GAS ΔT AT CDF = 100 K

4) COOLDOWN CAPACITY ABOVE 100 K IS PROVIDED SOLELY BY COOLING THE HELIUM FLOW WITH LN_2. LOWEST HELIUM TEMP IN THIS CASE IS 90 K.

5) COOLDOWN CAPACITY BELOW 100 K IS PROVIDED BY THE HELIUM REFRIGERATOR. WHEN COOLING WITH HELIUM GAS, THE LOWEST TEMP IS 10 K AND THE MAXIMUM PRESSURE IS 3.5 ATM (ENGINE EXHAUST PRESSURE).

6) ASSUME THE HELIUM REFRIGERATOR CAN NOT RECOVER THE REFRIGERATION IN THE LOW PRESSURE GHe RETURN STREAM.

7) LEAD FLOW SUPPLY POINT IS DOWNSTREAM OF SOLENOID.

522703

SUBJECT

NAME Ams

DATE 12/12/90 | REVISION DATE

INTERVAL NO 1 ASSUME: $P_{IN} = 10$ ATM & $P_{OUT} = 2$ ATM

SOLENOID AVERAGE TEMP = (300 + 250)/2 = 275 K

GAS OUTLET TEMP = 275 − 10 = 265 K
GAS INLET TEMP = 275 − 100 = 175 K
} $\Delta T = 90$ K

$Q = \dot{m}(h_2 - h_1) = \dot{m}\, c_p \Delta T$ $P_{AVE} = (10+2)/2 = 6$ ATM

$c_p = 5.2 \frac{J}{gK}$ BETWEEN 275 K AND 175 K AT 6 ATM.

SOLVE FOR $\dot{m}$ –

$7{,}500 \frac{J}{s} = \dot{m}\, g/s\, (5.2\, J/gK)(90\, K)$

$16\ g/s = \dot{m}$

CALCULATE THE PRESSURE DROP.

THE ASSUMED PRESSURE DROP IS 10 − 2 = 8 ATM = 118 psi

FROM DN 123, THE EQUIVALENT LENGTH FROM THE REFRIGERATOR THROUGH THE SOLENOID IS ABOUT 1,874 ft BASED ON A 1" INNER DIAMETER PIPE. THIS LENGTH IS CALCULATED AS FOLLOWS

	Le (ft)	d (in)	f	DN 123 PG NO
SUPPLY LINE	484	1.097	0.023	13
CHIMNEY LINES	45+44	1	0.023	41, 52
SOLENOID COIL	1480	1	0.023	46, 50

CONVERT THE SUPPLY LINE TO 1" BASIS.

$$K_{1''} = K_{1.097''}\left(\frac{d_{1''}}{d_{1.097''}}\right)^4 = \frac{0.023(484)}{1.097}\left(\frac{1}{1.097}\right)^4$$

PER REF 1 PG 3-5 EQ 3-24

$$= 7 = \frac{f\,Le}{d} = \frac{0.023\,Le}{1} \Rightarrow Le = 305 \text{ ft}$$

$$\Sigma = 305 + 45 + 44 + 1480 = 1{,}874 \text{ ft}$$

$$W = 16\,\frac{g}{s} \times 3600\,\frac{s}{hr} \times 2.204623\,\frac{Lbm}{1000g} = 127 \text{ Lbm/hr}$$

AVE GAS TEMP = (265 + 175)/2 = 220 K

μ = 0.016 cp AT 220 K AND 6 ATM

$$Re = 6.31\,\frac{W}{d\mu} = \frac{6.31(127)}{1(0.016)} = 5\times10^4 \Rightarrow f = 0.026$$

$$K = \frac{fL}{D} = \frac{0.026\,(1{,}874\text{ ft})}{(1/12)\text{ ft}} = 585$$

BASE THE ΔP OF THE EXIT SPECIFIC VOLUME. THIS IS A SIMPLIFYING, CONSERVATIVE ASSUMPTION.

$v_2 = 43\ ft^3/Lbm$

$$A = \frac{\pi d^2}{4} = \frac{\pi 1^2}{4} = 0.7854\ in^2 = 0.0054\ ft^2$$

$$\Delta P_f = \frac{fL}{D}\left(\frac{\dot{m}}{A}\right)^2 \frac{v_m}{2g_c}$$

$$= 585\left(\frac{127^2\ Lbm^2}{3600^2\ sec^2} \times \frac{1}{0.0054^2\ ft^4}\right) 43\ \frac{ft^3}{Lbm} \times \frac{Lbf\text{-}sec^2}{2(32.2\ ft\text{-}Lbm)} \times \frac{ft^2}{144\ in^2}$$

$$= 116\ psi \doteq 118\ psi \quad \underline{OK}$$

THE MASS FLOW RATE COULD BE INCREASED TO DECREASE THE COOLDOWN TIME FOR THIS TEMPERATURE INTERVAL.

INTERVAL NO. 2 ASSUME: $P_{IN} = 8$ ATM & $P_{OUT} = 2$ ATM

SOLENOID AVERAGE TEMP = $(250+200)/2 = 225$ K

GAS OUTLET TEMP = $225 - 10 = 215$ K
GAS INLET TEMP = $225 - 100 = 125$ K } $\Delta T = 90$ K

$Q = \dot{m}(h_2 - h_1) = \dot{m} C_p \Delta T$ $P_{AVE} = (8+2)/2 = 5$ ATM

$C_p = 5.2$ J/gK BETWEEN 125 K AND 225 K AT 5 ATM

SOLVE FOR $\dot{m}$ –

$$7{,}100 \text{ J/s} = \dot{m} \text{ g/s} \left(5.2 \text{ J/gK}\right)(90 \text{ K})$$

$$\dot{m} = 15.2 \text{ g/s}$$

CALCULATE THE PRESSURE DROP.

THE ASSUMED PRESSURE DROP IS $8-2 = 6$ ATM $= 88$ psi

$$W = 15.2 \text{ g/s} * 3600 \text{ s/hr} * 2.2046 \frac{\text{Lbm}}{1000 \text{ g}} = 120.6 \text{ Lbm/hr}$$

AVE GAS TEMP = $(215+125)/2 = 170$ K

$\mu = 0.014$ cp AT 170 K AND 5 ATM

$$Re = \frac{6.31\,(120.6 \text{ Lbm/hr})}{(1 \text{ in})(0.014 \text{ cp})} = 5.4 \times 10^4 \Rightarrow f = 0.026$$

K = 585 (PAGE 7)

$v_2 = 34.8$ ft^3/Lbm

$$\Delta P_f = \frac{fL}{D}\left(\frac{\dot{m}}{A}\right)^2 \frac{v_m}{2g_c}$$

$$= 585\left[\frac{120.6}{3600(0.0054)}\right]^2 \frac{(34.8)}{2(32.2)(144)} = 85\,psi \doteq 88\,psi$$

OK

THE MASS FLOW RATE COULD BE INCREASED TO DECREASE THE COOLDOWN TIME FOR THIS TEMPERATURE INTERVAL.

INTERVAL NO 3 ASSUME $P_{IN} = 7$ ATM & $P_{OUT} = 2$ ATM

SOLENOID AVERAGE TEMP = (200 + 150)/2 = 175 K

GAS OUTLET TEMP = 175 − 10 = 165 K
GAS INLET TEMP = 175 − 100 = ~~75~~ K
= 90 K (LOW LIMIT)
} $\Delta T = 75$ K

$Q = \dot{m}(h_2 - h_1) = \dot{m} c_p \Delta T$ $P_{AVE} = (7+2)/2 = 4.5$ ATM

$C_p = 5.2$ J/gK BETWEEN 90K AND 175 K AT 4.5 ATM

SOLVE FOR $\dot{m}$ —

$6{,}400 \text{ J/s} = \dot{m} \text{ g/s} (5.2 \text{ J/gK})(75 \text{ K})$

$\dot{m} = 16.4$ g/s

CALCULATE THE PRESSURE DROP.

THE ASSUMED PRESSURE DROP IS 7 − 2 = 5 ATM = 74 psi

$W = 16.4 \frac{g}{s} * 3600 \frac{s}{hr} * 2.2046 \frac{Lbm}{1000 g} = 130$ Lbm/hr

AVE GAS TEMP = (165 + 90)/2 = 128 K

$\mu = 0.011$ cp AT 128 K AND 4.5 ATM

$$Re = \frac{6.31(130)}{1(0.011)} = 7.5 \times 10^4 \Rightarrow f = 0.025$$

$$K = \frac{fL}{D} = \frac{0.025(1874 \text{ ft})}{(1/12) \text{ ft}} = 563$$

$v_2 = 26.6$ ft³/Lbm

522703

$$\Delta P_f = \frac{fL}{D}\left(\frac{\dot{m}}{A}\right)^2 \frac{v_m}{2 g_c}$$

$$= 563\left[\frac{130}{3600(0.0054)}\right]^2 \frac{26.6}{2(32.2)(144)} = 72 \text{ psi} \doteq 74 \text{ psi}$$

OK

THE MASS FLOW RATE COULD BE INCREASED TO DECREASE THE COOLDOWN TIME FOR THIS TEMPERATURE INTERVAL.

INTERVAL NO 4 ASSUME: $P_{IN} = 15$ ATM & $P_{OUT} = 2$ ATM

SOLENOID AVERAGE TEMP = (150 + 100)/2 = 125 K

GAS OUTLET TEMP = 125 − 10 = 115 K
GAS INLET TEMP = 125 − 100 = ~~25~~ K
= 90 K (LOW LIMIT)
$\Delta T = 25$ K

$Q = \dot{m}(h_2 - h_1) = \dot{m} c_p \Delta T$ $P_{AVE} = (15+2)/2 = 8.5$ ATM

$c_p = 5.2$ J/gK BETWEEN 90 K AND 125 K AT 8.5 ATM

SOLVE FOR $\dot{m}$ —

$$5{,}100 \text{ J/s} = \dot{m} \text{ g/s} (5.2 \text{ J/gK})(25 \text{ K})$$

$$\dot{m} = 39.2 \text{ g/s}$$

CALCULATE THE PRESSURE DROP.

THE ASSUMED PRESSURE DROP IS 15 − 2 = 13 ATM = 191 psi

NOTE: 15 ATM IS ASSUMED TO BE THE MAXIMUM SUPPLY PRESSURE, SO THE MAXIMUM ΔP IS 191 psi.

$$W = 39.2 \text{ g/s} * 3600 \text{ s/hr} * 2.2046 \frac{\text{Lbm}}{1000 \text{g}} = 311 \text{ Lbm/hr}$$

AVE GAS TEMP = (115 + 90)/2 = 102.5 K

$\mu = 0.01$ cp AT 100 K AND 8.5 ATM

$$Re = \frac{6.31(311)}{1(0.01)} = 2 \times 10^5 \Rightarrow f = 0.024$$

$$K = \frac{fL}{D} = \frac{0.024(1{,}874 \text{ ft})}{(1/12) \text{ ft}} = 540$$

$v_2 = 18.3$ ft³/Lbm

$$\Delta P_f = \frac{fL}{D}\left(\frac{\dot{m}}{A}\right)^2 \frac{v_m}{2g_c}$$

$$= 540\left[\frac{311}{(3600)(0.0054)}\right]^2 \frac{18.3}{2(32.2)(144)} = 273 \text{ psi} > 191 \text{ psi}$$

NG

∴ THE MASS FLOW RATE MUST BE REDUCED:

$$\dot{m} = 311\sqrt{\frac{191}{273}} = 260 \frac{\text{Lbm}}{\text{hr}} = 32.8 \text{ g/s}$$

CALCULATE THE COOLDOWN TIME FOR THIS INTERVAL:

$$\text{COOLING POWER AVAILABLE} = 32.8 \text{ g/s}\left(5.2 \text{ J/gK}\right)(25 \text{ K})$$

$$= 4{,}264 \text{ W}$$

$$\text{COOLDOWN TIME} = \frac{5{,}100}{4{,}264}(40 \text{ hrs}) = 48 \text{ hrs}$$

522703

THE HELIUM HAS BEEN COOLED SOLELY WITH LN_2 FOR INTERVALS 1 THROUGH 4. THE HELIUM WILL BE COOLED WITH THE REFRIGERATOR FOR INTERVALS 5 THROUGH 7.

THE COOLING NEEDED FOR EACH INTERVAL MUST BE COMPARED TO THE COOLDOWN CAPACITY OF THE PROPOSED 1500 W REFRIGERATOR.

ESTIMATE COMPRESSOR POWER FOR THE 1500 W REFR:

$W \equiv$ COMPRESSOR POWER

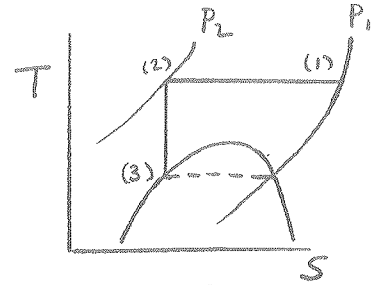
$Q \equiv$ COOLING POWER $= 1{,}500$ W

$$\left.\begin{aligned} T_H &= 308 \text{ K} \\ T_C &= 4.334 \text{ K} \\ \eta &= 25\% \text{ OF CARNOT} \end{aligned}\right\} \text{DATA FOR SSC MTL FACILITY}$$

$$\left.\frac{W}{Q}\right|_{IDEAL} = \frac{T_H}{T_C} - 1 = \frac{308}{4.334} - 1 = 70.07$$

$$W_{SHAFT} = \frac{70.07\,(1.5\text{ kW})}{0.25} = 420 \text{ kW}$$

CALCULATE THE LIQUEFACTION RATE THAT CAN BE ACHIEVED WITH 420 KW.



$$W_{IDEAL} = T_H\,(s_1 - s_3) - (h_1 - h_3)$$

$s_1 = 31.538$ J/g-K $\quad h_1 = 1614.6$ J/g

$s_3 = 3.568$ J/g-K $\quad h_3 = 10.28$ J/g

$$W_{IDEAL} = 308\text{ K}\,(31.538 - 3.568)\,\text{J/g-K} - (1614.6 - 10.28)\,\text{J/g}$$
$$= 7{,}010.44 \text{ J/g}$$

$$W_{SHAFT} = \frac{7{,}010.44}{0.25} = 28{,}042 \text{ J/g}$$

LIQUEFACTION RATE $= 420{,}000$ J/s $/ 28{,}042$ J/g $= 15$ g/s

$$15\ \text{g/s} * 3600\ \text{s/hr} * 0.123\ \text{cc/g} * \frac{1\ \ell}{1000\text{ cc}} = 439\ \ell/\text{hr}$$

522703

INTERVAL NO. 5 ASSUME: $P_{IN} = 2.4$ ATM & $P_{OUT} = 2$ ATM

SOLENOID AVERAGE TEMP $= (100+50)/2 = 75$ K

GAS OUTLET TEMP $= 75 - 10 = 65$ K
GAS INLET TEMP $= 10$ K
$\Delta T = 55$ K

$Q = \dot{m}(h_2 - h_1)$

$2{,}800 \ \cancel{J/s} = \dot{m} \ \cancel{g/s} \ (352.5 - 62.53) \ J/g$

$\dot{m} = 9.7 \ g/s$

CALCULATE THE PRESSURE DROP.

THE ASSUMED PRESSURE DROP IS $2.4 - 2 = 0.4$ ATM $= 5.9$ psi

$W = 9.7 \ \cancel{g/s} * 3600 \ \cancel{s}/hr * 2.2046 \ \frac{Lbm}{1000 \cancel{g}} = 77 \ Lbm/hr$

AVERAGE GAS TEMP $= (65+10)/2 = 38$ K

$\mu = 0.0054$ cp AT 38 K AND 2.3 ATM.

$Re = \frac{6.31 \ (77)}{1 \ (0.0054)} = 9 \times 10^4 \Rightarrow f = 0.025$

$K = 563$ (PAGE 11)

$v_2 = 10.7 \ ft^3/Lbm$

$v_1 = 1.3 \ ft^3/Lbm$

$v_m = (10.7 + 1.3)/2 = 6 \ ft^3/Lbm$

522703

$$\Delta P_f = \frac{fL}{D}\left(\frac{\dot{m}}{A}\right)^2 \frac{v_m}{2g_c}$$

$$= 563\left[\frac{77}{(3600)(0.0054)}\right]^2 \frac{6}{2(32.2)(144)} = 5.7 \text{ psi} \doteq 5.9 \text{ psi}$$

ok

THE 1500 W REFRIGERATOR CAN PRODUCE THE COOLING POWER REQUIRED FOR THIS TEMPERATURE INTERVAL BECAUSE THE REQUIRED FLOW OF 9.7 g/s IS LESS THAN THE LIQUEFACTION RATE OF 15 g/s.

INTERVAL NO. 6 ASSUME: $P_{IN} = 2.2$ ATM & $P_{OUT} = 2$ ATM

SOLENOID AVERAGE TEMP = $(50+25)/2 = 37.5$ K

GAS OUTLET TEMP = $37.5 - 10 = 27.5$ K
GAS INLET TEMP = 10 K
$\Delta T = 17.5$ K

$Q = \dot{m}(h_2 - h_1)$

$800 \text{ J/s} = \dot{m}\ \text{g/s}\,(156.88 - 62.88)\ \text{J/g}$

$\dot{m} = 8.5$ g/s

CALCULATE THE PRESSURE DROP.

THE ASSUMED PRESSURE DROP IS $2.2 - 2 = 0.2$ ATM $= 2.9$ psi

$W\ 8.5\ \text{g/s} * 3600\ \frac{\text{s}}{\text{hr}} * 2.2046\ \frac{\text{Lbm}}{1000\ \text{g}} = 67.5$ Lbm/hr

AVERAGE GAS TEMP $= (27.5 + 10)/2 = 18.75$ K

$\mu = 0.0035$ cp AT 19 K AND 2.1 ATM

$Re = \frac{6.31\,(67.5)}{1\,(0.0035)} = 1.2 \times 10^5 \Rightarrow f = 0.025$

$K = 563$ (PAGE 11)

$v_2 = 4.5$ ft^3/Lbm

$v_1 = 1.4$ ft^3/Lbm

$v_m = (4.5 + 1.4)/2 = 2.95$ ft^3/Lbm

$$\Delta P_f = \frac{fL}{D}\left(\frac{\dot{m}}{A}\right)^2 \frac{v_m}{2g_c}$$

$$= 563\left[\frac{67.5}{3600(0.0054)}\right]^2 \frac{2.95}{2(32.2)(144)} = 2.2 \text{ psi} \doteq 2.9 \text{ psi}$$

OK

THE REQUIRED FLOW OF 8.5 g/s IS LESS THAN THE LIQUEFACTION RATE OF 15 g/s. OK

CALCULATE THE PRESSURE DROP FOR 15 g/s FOR P_{OUT} = 1 ATM AND T_{AVE} = 18.75 K.

$W = 15\,(3600)(2.2046)/1000 = 119$ Lbm/hr

$\mu \doteq 0.0035$ cp AT 19 K

$$Re = \frac{6.31\,(119)}{1\,(0.0035)} = 2.15\times10^5 \Rightarrow f = 0.024$$

K = 540 (PAGE 13)

$v_m = v_2 = 9.04$ ft^3/Lbm (TO SIMPLIFY THE CALC)

$$\Delta P_f = 540\left[\frac{119}{3600(0.0054)}\right]^2 \frac{9.04}{2(32.2)(144)} = 19.7 \text{ psi} = 1.34 \text{ ATM}$$

{FOR T_2 = 50 K, μ = 0.00636, $Re = 1.2\times10^5$, f = 0.025, K = 563, v_m = 16.5

CONCLUSION OF THE ΔP CALC FOR 15 g/s: ΔP_f = 37.5 psi = 2.6 ATM

USE A SPECIFIC HEAT VALUE AT ONE ATM TO CALCULATE m FOR TEMPERATURES ≤ 50 K AND ≥ 10 K. THE SPECIFIC HEAT DOESN'T VARY MUCH FOR THE COOLDOWN FLOW CONDITIONS. A VALUE OF 5.2 J/g K CAN BE USED BETWEEN 50 AND 300 K BECAUSE THE SPECIFIC HEAT DOESN'T VARY SIGNIFICANTLY FROM 1 TO 12 ATM IN THIS TEMPERATURE RANGE.

INTERVAL NO. 7

SOLENOID AVERAGE TEMP = (25 + 4)/2 = 14.5 K

ASSUME THE COOLING POWER IN THIS TEMPERATURE INTERVAL IS PROVIDED BY LIQUID HELIUM BOILING AT 4.4 K.

REFRIGERATOR OUTPUT TEMP IS 4.334 K.

$h_{f_{4.334K}} = 10.3$ J/g AT 4.334 K WHERE $h_f \equiv$ ENTHALPY OF SATURATED LIQUID

HEAT LEAK = 145 + 5 = 150 W (PAGE 2) $\equiv Q_{HL}$

LHe ENTHALPY AT ENTRANCE TO SOLENOID COOLING COIL $\equiv h_c$

LHe FLOW RATE FROM REFRIGERATOR AT 4.334 K $\equiv \dot{m}_s$

QUALITY $\equiv$ FRACTION OF THE TOTAL MASS WHICH IS SATURATED VAPOR $\equiv X$

COOLING POWER $\equiv Q_c = 53$ W LATENT HEAT $\equiv h_{fg}$

$$Q_c = (1-X)\,\dot{m}_s\, h_{fg_{4.4K}}$$

$$h_c = h_{f_{4.334K}} + Q_{HL}/\dot{m}_s$$

$$X = \frac{h_c - h_{f4.4K}}{h_{fg4.4K}}$$

$$\dot{m}_s = Q_c/(1-X)\,h_{fg_{4.4}}$$

$$\dot{m}_s = \frac{Q_c}{\left[1-\left(\frac{h_c - h_{f4.4}}{h_{fg4.4}}\right)\right]h_{fg4.4}} = \frac{Q_c}{h_{fg4.4} - h_c + h_{f4.4}}$$

$$= \frac{Q_c}{h_{fg4.4} - (h_{f_{4.334}} + Q_{HL}/\dot{m}_s) + h_{f4.4}}$$

522703

$$\dot{m}_s = \frac{Q_c}{h_{fg4.4} - h_{f4.334} - \frac{Q_{HL}}{\dot{m}_s} + h_{f4.4}}$$

$$\dot{m}_s\left(h_{fg4.4} - h_{f4.334} - \frac{Q_{HL}}{\dot{m}_s} + h_{f4.4}\right) = Q_c$$

$$\dot{m}_s\left(h_{fg4.4} - h_{f4.334} + h_{f4.4}\right) - \cancel{\dot{m}_s}\left(\frac{Q_{HL}}{\cancel{\dot{m}_s}}\right) = Q_c$$

$$\dot{m}_s = \frac{Q_c + Q_{HL}}{(h_{fg4.4} - h_{f4.334} + h_{f4.4})} = \frac{Q_c + Q_{HL}}{h_{g4.4} - h_{f4.334}}$$

$$\dot{m}_s = \frac{53 + 150\ \cancel{J}/s}{(29.98 - 10.3)\ \cancel{J}/g} = 10.3\ g/s$$

THE REQUIRED FLOW RATE IS LESS THAN THE LIQUEFACTION RATE OF 15 g/s. OK

THE 10.3 g/s FLOW RATE IS CONSERVATIVE BECAUSE THE SENSIBLE HEAT CHANGE FOR THE GAS PHASE HAS NOT BEEN INCLUDED. RECALCULATE THE FLOW RATE FOR THIS INTERVAL CONSIDERING THE COOLING POWER OF THE GAS PHASE.

SUBDIVIDE INTERVAL NO. 7 AND CALCULATE THE COOLING POWER REQUIRED FOR EACH INTERVAL.

522703

INTERVAL NO.	SOLENOID TEMPERATURE INITIAL (K)	SOLENOID TEMPERATURE FINAL (K)	SOLENOID ENTHALPY INITIAL (J/g)	SOLENOID ENTHALPY FINAL (J/g)	TOTAL HEAT LOAD (MJ)	INTERVAL TIME (HR)	REQUIRED COOLING POWER W/O HEAT LEAK (KW)	REQUIRED COOLING POWER W/HEAT LEAK (KW)
7.1	25	15	0.112	0.018	2.256	5	0.125	0.295
7.2	15	10	0.018	0.0049	0.314	5	0.018	0.188
7.3	10	5	0.0049	0.00084	0.097	5	0.006	0.176
7.4	5	4	0.00084	0.000463	0.009	5	0.0005	0.1705

FERMILAB ENGINEERING NOTE

SUBJECT

SECTION 3.1

PROJECT SDC

SERIAL-CATEGORY

PAGE 22

NAME RMS

DATE 12/19/90

REVISION DATE

MODIFY THE EQUATION DERIVED ON PAGES 20 AND 21 TO INCLUDE GAS COOLING.

$$Q_c = (1-X)\dot{m}_s h_{fg4.4} + \dot{m}_s(h_{gT} - h_{g4.4})$$

$$= \cancel{\dot{m}_s h_{g4.4}} - \dot{m}_s h_{f4.4} - X\dot{m}_s(h_{fg4.4} + \dot{m}_s h_{gT} - \cancel{\dot{m}_s h_{g4.4}}$$

$$= \dot{m}_s(h_{gT} - h_{f4.4} - X h_{fg4.4})$$

$$= \dot{m}_s \Delta h$$

$$h_c = h_{f4.334} + Q_{HL}/\dot{m}_s$$

$$X = \frac{h_c - h_{f4.4}}{h_{fg4.4}}$$

$$\dot{m}_s = Q_c/\Delta h = \frac{Q_c}{h_{gT} - h_{f4.4} - \left(\frac{h_c - h_{f4.4}}{\cancel{h_{fg}}}\right)\cancel{h_{fg}}}$$

$$= \frac{Q_c}{h_{gT} - \cancel{h_{f4.4}} - \left(h_{f4.334} + \frac{Q_{HL}}{\dot{m}_s}\right) + \cancel{h_{f4.4}}}$$

$$\dot{m}_s\left(h_{gT} - h_{f4.334} - \frac{Q_{HL}}{\dot{m}_s}\right) = Q_c$$

$$\dot{m}_s(h_{gT} - h_{f4.334}) = Q_c + Q_{HL}$$

$$\dot{m}_s = \frac{Q_c + Q_{HL}}{h_{gT} - h_{f4.334}}$$

INTERVAL NO 7.1

SOLENOID AVERAGE TEMP = (25+15)/2 = 20 K

GAS OUTLET TEMP = 20 − 10 = 10 K

AS ASSUMED ON PAGE 20, THE COOLING POWER IN THIS TEMPERATURE INTERVAL IS PROVIDED BY LIQUID HELIUM BOILING AT 4.4 K AND THEN SUPERHEATED TO 10 K.

THE EQUATION ON PAGE 23 CAN BE USED TO CALCULATE $\dot{m}_s$ FOR THIS CASE:

$$\dot{m}_s = \frac{Q_c + Q_{HL}}{h_{g_T} - h_{f\,4.334}}$$

$Q_{HL} = 150$ W

$Q_c = 145$ W

$\Delta h = h_{g\,10} - h_{f\,4.334} = (64.93 - 10.3)$ J/g $= 54.63$ J/g

$$\dot{m}_s = \frac{145 + 150}{54.63} = 5.4 \text{ g/s}$$

THE REQUIRED FLOW RATE IS LESS THAN THE LIQUEFACTION RATE OF 15 g/s. OK

522703

INTERVAL NO 7.2

SOLENOID AVERAGE TEMP = (15 + 10)/2 = 12.5 K

GAS OUTLET TEMP = 12.5 - 10 = 2.5 K < 4.4 K

∴ IGNORE THE GAS COOLING FOR THIS AND SUBSEQUENT INTERVALS (AS ASSUMED FOR INTERVAL NO. 7 ON PAGE 20.)

USE THE EQUATION ON PAGE 21 TO CALCULATE $\dot{m}_s$.

$$\dot{m}_s = \frac{38 + 150 \text{ J/s}}{(29.98 - 10.3) \text{ J/g}} = 9.6 \text{ g/s}$$

THIS FLOW RATE IS SLIGHTLY LESS THAN THE VALUE OF 10.3 g/s CALCULATED ON PAGE 21 FOR INTERVAL NO 7.

INTERVALS NO 7.3 AND 7.4

THE STEADY STATE HEAT LOAD DOMINATES IN THESE TWO INTERVALS, JUST AS IT DID IN INTERVAL 7.1.

$\dot{m}_s$ = 26 + 150/(29.98 - 10.3)
= 9 g/s IN INTERVAL NO 7.3

$\dot{m}_s$ = 20.5 + 150/(29.98 - 10.3)
= 8.7 g/s IN INTERVAL NO 7.4

FERMILAB
ENGINEERING NOTE

SECTION	PROJECT	SERIAL-CATEGORY	PAGE
3.1	SDC		26

SUBJECT: SUMMARIZE THE MINIMUM REQUIRED FLOW RATES FOR EACH TEMPERATURE INTERVAL

NAME: AMS

DATE: 1/9/91

REVISION DATE:

TEMP INTERVAL (K)	REQUIRED FLOW RATE (g/s)	ESTIMATED AVAILABLE FLOW RATE (g/s)	INTERVAL COOLDOWN TIME (hr)
300 - 250	16	145	40
250 - 200	15.2	145	40
200 - 150	16.4	145	40
150 - 100	32.8	145	48
100 - 50	9.7	15	40
50 - 25	8.5	15	20
25 - 15	5.4	15	5
15 - 10	9.6	15	5
10 - 5	9	15	5
5 - 4	8.7	15	5

$\Sigma = 248$ hr

$= 10\frac{1}{3}$ days

522703

SUBJECT: QUENCH RECOVERY

NAME: AMS

DATE: 1/3/91 | REVISION DATE:

QUENCH RECOVERY TIME IS SPECIFIED AS 4 HOURS.

REVIEW CDF DATA TO ESTIMATE HOW MUCH OF THE STORED ENERGY IS DEPOSITED IN THE COLD MASS AFTER A QUENCH.

FROM CDF DESIGN REPORT –

COLD MASS = 5,568 kg

STORED ENERGY = 30×10^6 J

USE FIGURE III (12) TO ESTIMATE THE ENERGY DEPOSITED IN THE COLD MASS.

- FOR $R_{EXT} = 0\,\Omega$, $T_{eq} = 69$ K

$$\Delta h = \frac{30 \times 10^6 \text{ J}}{5{,}568 \text{ Kg}} = 5.39 \text{ J/g}$$

$h_{4K} = 0.000463$ J/g

$h_{final} = 0.000463 + 5.39 \doteq 5.39$ J/g $\Rightarrow T_{final} = 67$ K OK

- FOR $R_{EXT} = 0.07\,\Omega$, $T_{eq} = 63.25$ K

$h_{63.25K} = 4.46$ J/g $\doteq \Delta h$

$$\text{FRAC OF STORED ENERGY} = \frac{\left(4.46 \frac{J}{g} \times 5{,}568{,}000\,g\right)}{30 \times 10^6 J} = 0.83$$

NOTE: BOB KEPHART REPORTS THAT T_{eq} IS ACTUALLY ABOUT 45 K WITH $R_{EXT} = 0.07\,\Omega$.

522703

SDC STORED ENERGY = 190 MJ (TYPE-I)

FOR $R_{EXT} = 0$:

$$\Delta h = \frac{190 \times 10^6 \text{ J}}{24{,}000{,}000 \text{ g}} = 7.92 \text{ J/g} \Rightarrow \underline{T_{eq} \doteq 75.5 \text{ K}}$$

IGNORE THE DECREASE FOR $R_{EXT} > 0$ BECAUSE R_{EXT} IS NOT DEFINED YET.

PROCEDURE TO CALCULATE THE HELIUM FLOW RATE FOR EACH TEMPERATURE INTERVAL:

1) $Q = \dot{m}(h_2 - h_1)$

   WHERE: 2 ≡ OUTLET AND 1 ≡ INLET

2) ΔT DEFINITIONS

   SOLENOID ΔT FOR EACH INTERVAL = $T_{INITIAL} - T_{FINAL}$

   APPROACH ΔT = 3 K (GHe TO SOLENOID)

3) QUENCH RECOVERY CAPACITY IS PROVIDED BY SUPPLYING LIQUID HELIUM TO THE SYSTEM AT THE MAXIMUM LIQUEFACTION RATE. THE HELIUM IS VAPORIZED AND HEATED TO THE OUTLET GAS TEMPERATURE.

4) ASSUME THE HELIUM REFRIGERATOR CAN NOT RECOVER THE REFRIGERATION IN THE LOW PRESSURE GHe RETURN STREAM.

5) LEAD FLOW SUPPLY POINT IS DOWNSTREAM OF SOLENOID.

INTERVAL NO. 7.4 REFER TO PAGES 22 & 25

COOLDOWN FLOW = 15 g/s

SOLVE FOR THE RECOVERY TIME

$Q = \dot{m}\,\Delta h$

$Q_C + Q_{HL} = Q_{TOTAL} = \dot{m}\,\Delta h$

$= 15\,g/s\,(29.98 - 10.3)\,J/g$

$= 295.2\ W$

$Q_{HL} = 170\ W$

$\therefore\ Q_C = 295.2 - 170 = 125.2\ W$

$$\text{TIME} = \frac{(0.00084 - 0.000463)\,J/g\,(24{,}000{,}000)\,g}{125.2\,J/s}$$

$= 72\ s = \underline{0.02\ hr}$

INTERVAL NO. 7.3 REFER TO PAGES 22 & 25

$Q_C = 125.2\ W$ (SAME AS INTERVAL NO 7.4)

$$\text{TIME} = \frac{(0.0049 - 0.00084)\,J/g\,(24{,}000{,}000)\,g}{125.2\,J/s}$$

$= 778\ s = 0.22\ hr$

522703

INTERVAL NO. 7.2 REFER TO PAGES 22 AND 25

$Q_c = 125.2$ W (SAME AS INTERVALS 7.3 & 7.4)

$$\text{TIME} = \frac{(0.018 - 0.0049)\ \text{J/g}\ (24{,}000{,}000\ \text{g})}{125.2\ \text{J/s}}$$

$$= 2{,}511\ \text{s} = \underline{0.7\ \text{hr}}$$

INTERVAL NO. 7.1 REFER TO PAGES 22 & 24 (25 TO 15 K)

COOLING IN THIS INTERVAL IS PROVIDED BY LIQUID HELIUM BOILING AT 4.4 K AND THEN SUPERHEATED TO 10 K.

$$Q_c + Q_{HL} = Q_{TOTAL} = \dot{m}_s (h_{g10} - h_{f4.334})$$

$$= 15\ \text{g/s}\ (64.93 - 10.3)\ \text{J/g}$$

$$= 819.45\ \text{W}$$

$Q_{HL} = 170$ W

$\therefore Q_c = 819.45 - 170 = 649.45$ W

$$\text{TIME} = \frac{(0.112 - 0.018)\ \text{J/g}\ (24{,}000{,}000\ \text{g})}{649.45\ \text{J/s}}$$

$$= 3{,}474\ \text{s} = \underline{0.97\ \text{hr}}$$

AVERAGE SOLENOID TEMP = 20 K.

CALCULATE THE RECOVERY TIME FOR A GAS OUTLET TEMP OF 20 − 3 = 17 K. $h_{17K} = 102.2$ J/g

$Q_c = 15(102.2 - 10.3) - 170 = 1208.5$ W

$$\text{TIME} = \frac{(0.112 - 0.018)(24{,}000{,}000)}{(1208.5)(3600)} = 0.52\ \text{hr}$$

INTERVAL NO. 6 REFER TO PAGES 4 & 18

1) ASSUME THE COOLING IN THIS INTERVAL IS PROVIDED BY LIQUID HELIUM BOILING AT 4.4 K AND THEN SUPERHEATED TO 27.5 K.

$$Q_C + Q_{HL} = Q_{TOTAL} = \dot{m}_s (h_{g_{27.5}} - h_{f_{4.334}})$$
$$= 15\ g/s\ (157.2 - 10.3)\ J/g$$
$$= 2{,}203.5\ W$$

$Q_{HL} = 170\ W$

$\therefore Q_C = 2{,}203.5 - 170 = 2{,}033.5\ W$

$$TIME = \frac{(1.85 - 0.112)\ J/g\ (24{,}000{,}000)\ g}{2{,}033.5\ J/s}$$

$= 20{,}512\ s = 5.7\ hr$

2) ASSUME THE COOLING IN THIS INTERVAL IS PROVIDED BY HELIUM GAS WARMING FROM 10 K TO 27.5 K.

ESTIMATE THE COOLING THAT CAN BE PRODUCED AT A COLD END TEMPERATURE OF 10 K WITH 420 kW OF WARM COMPRESSOR POWER. REFER TO PAGE 15.

$W_{IDEAL} = T_H (s_1 - s_3) - (h_1 - h_3)$

$s_1 = 31.538\ J/g\text{-}K \quad h_1 = 1614.6\ J/g$

$s_3 = 13.64\ J/g\text{-}K \quad h_3 = 64.93\ J/g \quad (P = 1\ ATM,\ T = 10\ K)$

$W_{IDEAL} = 308\ K\ (31.538 - 13.64)\ J/g\text{-}K - (1614.6 - 64.93)\ J/g$
$= 3{,}963\ J/g$

$W_{SHAFT} = 3{,}963 / 0.25 = 15{,}852\ J/g$

$FLOW\ RATE = 420{,}000\ J/s / 15{,}852\ J/g = 26.5\ g/s$

$Q_{TOTAL} = 26.5\ g/s\ (157.2 - 64.93)\ J/g = 2{,}445\ W$ – NOT MUCH BETTER THAN #1.

522703

2) CONTINUED -

REPEAT THIS CALCULATION WITH STATE 3 AT THE ASSUMED ENGINE EXHAUST PRESSURE OF 3.5 ATM INSTEAD OF 1 ATM.

$s_1 = 28.94$ J/g-K $\quad h_1 = 1615.4$ J/g

$s_3 = 10.75$ J/g-K $\quad h_3 = 60.6$ J/g

$W_{IDEAL} = 308(28.94 - 10.75) - (1615.4 - 60.6)$

$= 4{,}048$ J/g $\doteq 3{,}963$ J/g $\rightarrow$ STOP

3) REPEAT #1 WITH SMALLER TEMPERATURE SUBDIVISIONS -

<u>50 TO 40 K</u>

SOLENOID AVERAGE TEMP $= (50+40)/2 = 45$ K

GAS OUTLET TEMP $= 45 - 10 = 35$ K

$Q_{TOTAL} = \dot{m}_s (h_{g35} - h_{f4.334})$

$= 15$ g/s $(196.3 - 10.3)$ J/g $= 2{,}790$ W

$Q_c = 2{,}790 - 170 = 2{,}620$ W

$$\text{TIME} = \frac{(1.85 - 0.755)\ \text{J/g}\ (24{,}000{,}000\ \text{g})}{2{,}620\ \text{J/s}} = 10{,}030\ \text{s}$$

$= 2.79$ hr

522703

40 TO 35 K

SOLENOID AVERAGE TEMP = (40+35)/2 = 37.5 K

GAS OUTLET TEMP = 37.5 − 10 = 27.5 K

Q_c = 2,033 W FROM #1 ON PAGE 30

$$\text{TIME} = \frac{(0.755-0.436)\,J/g\ (24{,}000{,}000\,g)}{2{,}033\ J/s} = 3{,}766\,s$$

$$= 1.05\ hr$$

35 TO 30 K

SOLENOID AVERAGE TEMP = (35+30)/2 = 32.5 K

GAS OUTLET TEMP = 32.5 − 10 = 22.5 K

$$Q_{TOTAL} = 15\,g/s\ (131.05-10.3)\,J/g = 1{,}811\ W$$

Q_c = 1,811 − 170 = 1,641 W

$$\text{TIME} = \frac{(0.436-0.232)\,J/g\ (24{,}000{,}000\,g)}{1{,}641\ J/s} = 2{,}984\,s$$

$$= 0.83\ hr$$

30 TO 25 K

SOLENOID AVERAGE TEMP = (30+25)/2 = 27.5 K

GAS OUTLET TEMP = 27.5 − 10 = 17.5 K

$$Q_{TOTAL} = 15\,g/s\ (104.8-10.3)\,J/g = 1{,}417.5\ W$$

Q_c = 1,417.5 − 170 = 1,247.5 W

$$\text{TIME} = \frac{(0.232-0.112)\,J/g\ (24{,}000{,}000\,g)}{1{,}247.5\ J/s} = 2309\,s$$

$$= 0.64\ hr$$

Σ TIMES = 5.3 hr VS 5.7 hr CALCULATED IN #1.
∴ FINER SUBDIVISION DECREASED THE TIME 7%.

522703

INTERVAL NO. 5

SOLENOID AVERAGE TEMP = (100 + 50)/2 = 75 K

GAS OUTLET TEMP = 75 − 10 = 65 K

1) CALCULATE THE RECOVERY TIME USING THE 15 g/s LIQUEFACTION RATE AND INLET TEMP OF 10 K.

$$Q_c + Q_{HL} = Q_{TOTAL} = \dot{m}_s (h_{g65K} - h_{g10K})$$

$$= 15 \frac{g}{s} (352.4 - 64.93) \, J/g$$

$$= 4{,}312 \text{ W}$$

$Q_{HL} = 170$ W

$\therefore Q_c = 4{,}312 \text{ W} - 170 \text{ W} = 4{,}142 \text{ W}$

$$\text{TIME} = \frac{(17.76 - 1.85) \frac{J}{g} (24{,}000{,}000 \, g)}{4{,}142 \, J/s}$$

$$= 92{,}187 \text{ s}$$

$$= 25.6 \text{ hr}$$ (THIS IS TOO LONG.)

RECALCULATE USING SMALLER SUBDIVISIONS. THE CALCULATIONS ARE SUMMARIZED IN THE TABLE ON PAGE 35.

SOLENOID TEMPERATURE INITIAL (K)	SOLENOID TEMPERATURE FINAL (K)	SOLENOID ENTHALPY INITIAL (J/g)	SOLENOID ENTHALPY FINAL (J/g)	AVERAGE SOLENOID TEMP (K)	GAS OUTLET TEMP (K)	GAS OUTLET ENTHALPY (J/g)	COOLING POWER (W)	RECOVERY TIME (hr)	TIME FOR #2 ON PG 35 (hr)
100	90	17.76	13.25	95	85	456.3	5,700	5.27	4.61
90	80	13.25	9.37	85	75	404.4	4,922	5.26	4.51
80	70	9.37	6.15	75	65	352.4	4,142	5.18	4.33
70	60	6.15	3.64	65	55	300.4	3,362	4.98	4
60	50	3.64	1.85	55	45	248.4	2,582	4.62	3.51
								$\Sigma = 25.31$	20.96

COOLING POWER (W) $= 15\ g/s\ (h_{GAS\ OUTLET} - 64.93)\ J/g - 170\ W$

h at 10 K. HEAT LEAK

THE TIME FOR THIS INTERVAL DECREASED 1.1% BY USING SMALL SUBDIVISIONS.

75.5	70	7.92	6.15	~73	~63	342	3,986	2.96	2.46

THE RECOVERY TIME FROM 75.5 K IS $2.96 + 4.98 + 4.62 = 12.56$ hr

OR $2.46 + 4 + 3.51 = 9.97$ hr

FERMILAB ENGINEERING NOTE

SUBJECT

SECTION 3.2

PROJECT SDC

SERIAL-CATEGORY

PAGE 35

NAME AMS

DATE 1/7/91

REVISION DATE

2) CALCULATE THE RECOVERY TIME USING THE 15 g/s LIQUEFACTION RATE AND CONSIDER THE ENTHALPY CHANGE FROM LIQUID HELIUM SATURATED AT 4.334 K TO THE GAS OUTLET TEMP.

$$Q_{TOTAL} = 15\ g/s\,(352.4 - 10.3)\ J/g = 5{,}131.5\ W$$

$$Q_c = 5{,}131.5 - 170 = 4{,}961.5\ W$$

$$TIME = \frac{(17.76 - 1.85)\ J/g\ (24{,}000{,}000\ g)}{4961.5\ J/s}$$

$$= 76{,}960\ s$$

$$= 21.4\ hr \quad \text{(THIS IS TOO LONG.)}$$

THE TIME FOR EACH 10 K INTERVAL IS NOTED IN THE LAST COLUMN IN THE TABLE ON PAGE 35.

3) USE SUBCOOLED NITROGEN TO COOL THE HELIUM GAS FLOW.

ASSUME LN_2 BATH TEMPERATURE IS 65 K.

ASSUME A 5 K APPROACH TEMP. ∴ THE HELIUM GAS STREAM IS COOLED TO 70 K.

MAX FLOW ≐ 145 g/s FROM PAGE 5.

USE THE 10 K APPROACH BETWEEN THE OUTLET GAS AND AVERAGE SOLENOID TEMP USED IN THE OTHER SECTIONS OF THIS DESIGN NOTE.

ALSO, TRY A ZERO APPROACH TEMP.
THE CALCULATION IS SUMMARIZED ON PAGE 37.
NOTE: THIS METHOD IS APPLICABLE WHEN THE COLD MASS TEMPERATURE EXCEEDS ~75 K BY A FAIRLY GOOD AMOUNT.

4) REDO #2 WITH A ZERO APPROACH TEMP AND A 3K APPROACH TEMP. THE CALCULATION IS SUMMARIZED ON PAGE 38.

5) RECALCULATE THE RECOVERY TIME FROM 50 K USING THE 3 K APPROACH ΔT. THE CALCULATION IS SUMMARIZED ON PAGE 39.

522703

SOLENOID TEMPERATURE INITIAL (K)	SOLENOID TEMPERATURE FINAL (K)	SOLENOID ENTHALPY INITIAL (J/g)	SOLENOID ENTHALPY FINAL (J/g)	AVERAGE SOLENOID TEMP (K)	GAS OUTLET TEMP (K)	GAS OUTLET ENTHALPY (J/g)	COOLING POWER (W)	RECOVERY TIME (hr)
100	90	17.76	13.25	95	85/95	456.3/508.25	11,125/18,658	2.7/1.61
90	80	13.25	9.37	85	75/85	404.4/456.3	3,600/11,125	7.2/2.33
80	70	9.37	6.15	75	-/75	-/404.4	-/3,600	-/5.96
70	60	6.15	3.64	65	-/65	-/352.4		
60	50	3.64	1.85	55	-/55	-/300.4		

$$\text{COOLING POWER (W)} = 145\ g/s\ (h_{GAS\ OUTLET} - 378.4)\ J/g - 170\ W$$

h at 70K

HEAT LEAK

SUBJECT

FERMILAB ENGINEERING NOTE

SECTION 3.2

PROJECT SDC

SERIAL-CATEGORY

PAGE 37

NAME Ams

DATE 1/8/91

REVISION DATE

522703

SOLENOID TEMPERATURE INITIAL (K)	SOLENOID TEMPERATURE FINAL (K)	SOLENOID ENTHALPY INITIAL (J/g)	SOLENOID ENTHALPY FINAL (J/g)	AVERAGE SOLENOID TEMP (K)	GAS OUTLET TEMP (K)	GAS OUTLET ENTHALPY (J/g)	COOLING POWER (W)	RECOVERY TIME (hr)
100	90	17.76	13.25	95	95/92	508.25/492.68	7299/7066	4.12/4.26
90	80	13.25	9.37	85	85/82	456.3/440.7	6520/6286	3.97/4.12
80	70	9.37	6.15	75	75/72	404.4/388.8	5742/5508	3.74/3.9
70	60	6.15	3.64	65	65/62	352.4/336.8	4962/4728	3.37/3.54
60	50	3.64	1.85	55	55/52	300.4/284.8	4182/3948	2.85/3.02
							$\Sigma =$	18.05/18.84

COOLING POWER (W) = 15 g/s ($h_{GAS\ OUTLET}$ − 10.3) J/g − 170 W

$h_{f\ 4.334\ K}$ HEAT LEAK

75.5	70	7.92	6.15	~73	73/70	394/378.4	5586/5352	2.11/2.21

THE RECOVERY TIME FROM 75.5 K IS 2.11 + 3.37 + 2.85 = 8.33 hr FOR 0 K APPROACH.

OR 2.21 + 3.54 + 3.02 = 8.77 hr FOR 3K APPROACH.

FERMILAB ENGINEERING NOTE

SUBJECT

SECTION 3.2

PROJECT SDC

SERIAL-CATEGORY

PAGE 38

NAME AMS

DATE 1/8/91

REVISION DATE

522703

SOLENOID TEMPERATURE INITIAL (K)	SOLENOID TEMPERATURE FINAL (K)	SOLENOID ENTHALPY INITIAL (J/g)	SOLENOID ENTHALPY FINAL (J/g)	AVERAGE SOLENOID TEMP (K)	GAS OUTLET TEMP (K)	GAS OUTLET ENTHALPY (J/g)	COOLING POWER (W)	RECOVERY TIME (hr)	
50	40	1.85	0.755	45	42	232.8	3,167.5	2.31	
40	35	0.755	0.436	38	35	196.3	2,620	0.81	
35	30	0.436	0.232	33	30	170.2	2,228.5	0.61	
30	25	0.232	0.112	28	25	144.1	1837	0.44	
25	20	0.112	0.048	23	20	117.9	1444	0.3	2.63
20	15	0.048	0.018	18	15	91.61	1049.65	0.19	
15	10	0.018	0.0049	13	10	64.93	649.45	0.14	
10	5	0.0049	0.00084	8	5	36.19	218.35	0.12	
5	4	0.00084	0.000463	4.5	4.5	29.81	122.65	0.02	
								4.94	

COOLING POWER = $15\ g/s\ (h_{GAS\ OUTLET} - 10.3)\ J/g = 170\ W$

$h_{f\ 4.334\ K}$ HEAT LEAK

FERMILAB ENGINEERING NOTE

SUBJECT: RECALCULATE THE RECOVERY TIME FROM 50 K USING THE 3 K APPROACH ΔT

SECTION: 3.2

PROJECT: SDC

NAME: AMS

DATE: 1/9/91

SERIAL-CATEGORY:

REVISION DATE:

PAGE: 39

SUBJECT

NAME AMS

DATE 1/9/91 | REVISION DATE

THE QUENCH RECOVERY TIME WITH 3K APPROACH TEMP AND 15 g/s HELIUM FLOW RATE IS:

TEMP INTERVAL (K)	INTERVAL TIME (hr)	TOTAL TIME (hr)
77.5 – 70	2.21	13.71
70 – 60	3.54	11.5
60 – 50	3.02	7.96
50 – 40	2.31	4.94
40 – 35	0.81	2.63
35 – 30	0.61	1.82
30 – 25	0.44	1.21
25 – 20	0.3	0.77
20 – 15	0.19	0.47
15 – 10	0.14	0.28
10 – 5	0.12	0.14
5 – 4	0.02	0.02

$\Sigma = 13.71$ hr

522703

SUBJECT: QUENCH RECOVERY WITH STORED LHe

NAME: AMS

DATE: 1/15/91

REVISION DATE:

THE GOAL IS TO ACHIEVE A QUENCH RECOVERY TIME OF 4 HOURS WITH MINIMUM COMPRESSOR HORSEPOWER.

CALCULATE THE MINIMUM FLOW RATE REQUIRED TO ACHIEVE A 4 HR QUENCH RECOVERY TIME.

THE QUENCH RECOVERY TIME FOR A 1500 W REFRIGERATOR OPERATING AT ITS MAXIMUM LIQUEFACTION RATE HAS BEEN CALCULATED AS 13.71 HR ON PAGE 40.

THE 13.71 HR MUST BE REDUCED BY A FACTOR OF 13.71/4 = 3.4.
∴ INCREASE THE HELIUM FLOW TO 4 (15 g/s) = 60 g/s.

REDO THE CALCULATIONS ON PAGES 38, 39 AND 40 WITH A HELIUM FLOW RATE OF 60 g/s.

THE CALCULATION IS SUMMARIZED ON THE NEXT PAGE.

THE QUANTITY OF STORED HELIUM IS:

$$60\ \cancel{g/s} * 3.283\ \cancel{hr} * 3{,}600\ \cancel{s/hr} = 709{,}128\ g$$

$$709{,}128\ \cancel{g} * \frac{\cancel{cc}}{0.123\ \cancel{g}} * \frac{l}{1000\ \cancel{cc}} = 5{,}765\ l = 1{,}523\ gal$$

THE GHe RETURNING FROM THE MAGNET MUST BE COMPRESSED, STORED AND THEN RELIQUEFIED.

COMPARE THIS QUANTITY OF LHe TO THE QUANTITY REQUIRED WHEN USING ONLY THE LATENT HEAT FOR QUENCH RECOVERY FROM 77.5 K (IGNORE HEAT LEAK):

$$\frac{24{,}000{,}000\ g\,(7.92 - 0.000463)\ J/g}{18.56\ J/g} = 10{,}240{,}781\ g$$

h_{fg} AT 4.5 K

$$= 83{,}258\ l$$

$$83{,}258 / 5{,}765 = \underline{14.44}$$

522703

SUBJECT

NAME: AMS

DATE: 1/14/91 | REVISION DATE

THE QUENCH RECOVERY TIME WITH 3K APPROACH TEMP AND 60 g/s HELIUM FLOW RATE IS:

TEMP INTERVAL (K)	COOLING POWER (W)	INTERVAL TIME (hr)	TOTAL TIME (hr)
77.5 - 70	21,916	0.54	3.283
70 - 60	19,420	0.86	2.743
60 - 50	16,300	0.73	1.883
50 - 40	13,180	0.55	1.153
40 - 35	10,990	0.2	0.603
35 - 30	9,424	0.14	0.403
30 - 25	7,858	0.1	0.263
25 - 20	6,286	0.07	0.163
20 - 15	4,708	0.04	0.093
15 - 10	3,107	0.03	0.053
10 - 5	1,383	0.02	0.023
5 - 4	1,000	0.003	0.003

$\Sigma = 3.283$

COOLING POWER $= 60\ g/s\,(h_{GAS\ OUTLET} - 10.3) - 170\ W$

$h_{f\,4.334}$ HEAT LEAK

522703

SUBJECT: EXAMINE CDF QUENCH RECOVERY DATA
QUENCH DATE: SEPT. 1988

NAME: AMS
DATE: 1/22/91
REVISION DATE:

NORMAL STORAGE DEWAR CAPACITY = 1500 ℓ MAX

TIME TO COOL MAGNET TO LHe TEMP AND ESTABLISH PROPER LEVEL IN SUBCOOLER = 2 hrs USING CDF COMPS.
~1.25 hrs USING TEVATRON COM
~1 hr (ONE TIME)

LHe IN STORAGE DEWAR AFTER QUENCH RECOVERY = 1,000 ℓ

STABILIZATION TIME ≐ 1 hr

SUBCOOLER LHe CAPACITY = 65 ℓ

CALCULATE THE MAGNET QUENCH TEMP ASSUMING:

1. ~3 hr RECOVERY TIME
2. 500 ℓ OF LHe IS USED TO COOL THE MAGNET BACK TO LHe TEMP.
3. 3 K APPROACH ΔT
4. 5,568 Kg COLD MASS
5. STEADY LHe FLOW RATE
6. SYSTEM HEAT LEAK = 70 W
7. COMPRESSOR CAPACITY = 58 g/s

LHe FLOW RATE = 500 ℓ / 3 hr = 167 ℓ/hr

THE CALCULATION IS SUMMARIZED ON THE NEXT PAGE.

$$167 \frac{\ell}{hr} * \frac{hr}{3600\,s} * \frac{1{,}000\,cc}{\ell} * 0.123 \frac{g}{cc} = 5.7 \; g/s < 58 \; g/s$$

OK

522703

522703

SOLENOID TEMPERATURE INITIAL (K)	SOLENOID TEMPERATURE FINAL (K)	SOLENOID ENTHALPY INITIAL (J/g)	SOLENOID ENTHALPY FINAL (J/g)	AVERAGE SOLENOID TEMP (K)	GAS OUTLET TEMP (K)	GAS OUTLET ENTHALPY (J/g)	COOLING POWER (W)	RECOVERY TIME ΔTIME (hr)	RECOVERY TIME TOTAL (hr)
5	4	0.00084	0.000463	4.5	4.5	29.81	39.16	0.015	0.015
10	5	0.0049	0.00084	8	5	36.19	75.52	0.083	0.098
15	10	0.018	0.0049	13	10	64.93	239.34	0.085	0.183
20	15	0.048	0.018	18	15	91.61	391.42	0.119	0.302
25	20	0.112	0.048	23	20	117.9	541.27	0.183	0.485
30	25	0.232	0.112	28	25	144.1	690.61	0.269	0.754
35	30	0.436	0.232	33	30	170.2	839.38	0.376	1.13
40	35	0.755	0.436	38	35	196.3	988.15	0.5	1.63
50	40	1.85	0.755	45	42	232.8	1,196.2	1.42	3.05

$\therefore T_{QUENCH} \doteq 50$ K

FOR $R_{EXT} = 0.7\ \Omega$: $T_{QUENCH} = 63.25$ K FROM CDF DESIGN REPORT (Teq ON PG 27)

$\doteq 45$ K REPORTED BY BOB KEPHART (PG 27)

$$\text{COOLING POWER} = 5.7\ g/s\ (h_{GAS\ OUTLET} - 10.66)\ J/g - 70\ W$$

$h_{f\,4.4K}$ HEAT LEAK

FERMILAB ENGINEERING NOTE

SUBJECT: CDF QUENCH RECOVERY WITH 900 ℓ

SECTION: 3.3

PROJECT: SDC

NAME: AMS

DATE: 1/22/91

SERIAL-CATEGORY:

PAGE: 44

REVISION DATE: