CALORIMETER LIQUID NITROGEN SUPPLY CALCULATIONS

D-Zero Engineering Note 3740.510-EN-382

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Approved Russell A. Rucinski Date March 16, 1994

FOREWORD

The D-Zero Detector liquid argon calorimeters must remain cold to function. For this reason, it is important that cold liquid nitrogen is available to cool the calorimeters and the argon liquid in them. A liquid nitrogen subcooler U-tube was designed to replace the liquid nitrogen supply jumper at D-Zero, but there was some doubt as to the need for the subcooler and about the ability of the subcooler to function as efficiently as claimed in the initial design calculations. Therefore, the D-Zero mechanical group performed additional calculations on the device. This engineering note is a summary of those calculations.

CONTENTS

INTRODUCTION

This note contains information on the calculations and provides a summary of the results. A simplified sketch of the nitrogen flow path shows the several reference points and their elevations used in the calculations. The property tables(tables 1 and 2) show calculated conditions of the nitrogen at the reference points. Appendix A includes the various quality calculations performed. The first group of this appendix includes the calculations for the jumper(no subcooling), the second is the U-tube with subcooler, and the third group is some of the sample calculations of liquid and gas volume fractions. Appendix B contains the subcooler heat exchanger calculations performed by Russ Rucinski referenced in the calculations of appendix A.

SIMPLIFYING ASSUMPTIONS

There were various approximations made in the analysis of the nitrogen path. The first is that the nitrogen leaving the dewar is a slightly compressed liquid at 50 psia. While the liquid removed from the dewar is probably a slightly compressed liquid, the pressure of the dewar actually tends to vary slightly depending on the amount of nitrogen in the dewar and time since filling, etc. Heat loads to the bayonets were approximations acquired from a Cryolab catalog as was the heat loading to the vacuum insulated line and the valves. Some of the bayonets and valves were Cryolab, but the lines and some of the bayonets were Fermilab constructions(Rotary bayonets). The Fermilab constructed bayonets have similar properties to those listed in the Cryolab catalog, so the catalog heat transfer values were used for simplification. Catalog C_v values for the valves were used also. Approximate elevations and line distances were taken from a number of different drawings. These drawings included: 3740.512-MC-223065 (and many of the spool drawings listed on it), 3740.510-ME-222906, 3740.220-MD-294890, and 3740.220-ME-278695 to name just a few of the many drawings of the building piping and their assemblies in and around the D-Zero Assembly building. I attempted to use the most common or seemingly most reliable information for the building piping locations when information was conflicting or vague on drawings.

INFORMATION SOURCES

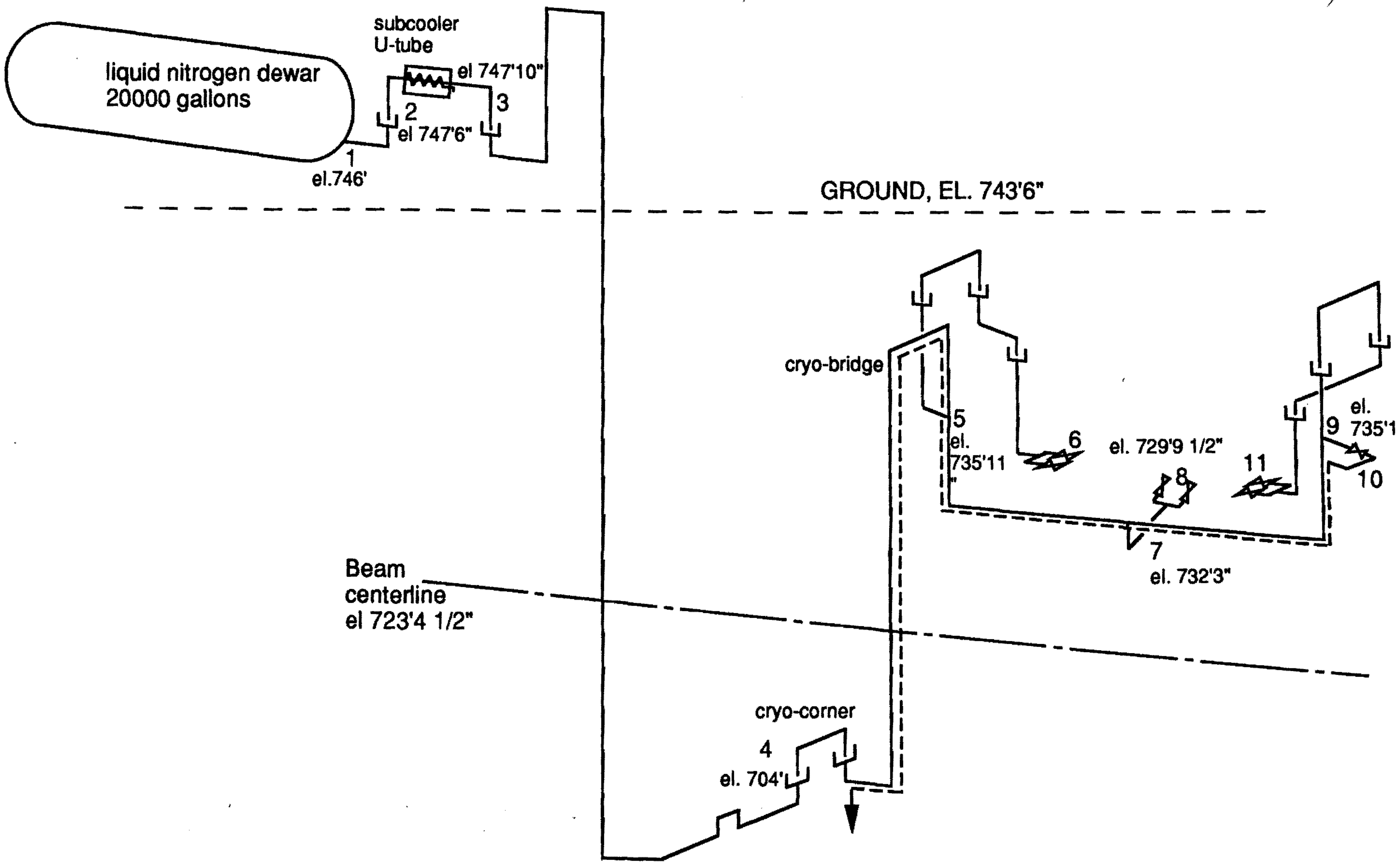
Resources of several types were used to obtain information used in these calculations. Nitrogen property values were obtained from NBS-TN-1025 *Thermodynamic Properties of Nitrogen*, and values between table values were extrapolated linearly. Flow rate for the first group of calculations (nitrogen jumper with no subcooler) was approximated from an average value of all of the nitrogen consumed during the last cooling run, approximately 34.6 grams/second. This is more of an upper bound value, since not all of that nitrogen was used for the calorimeter cooling spools. A portion of that nitrogen actually was used to cool the argon dewar. For the calculations performed with the subcooler, the actual value of about 25 grams per second was used. The Lockhart-Martinelli parameters found in chapter 7 of *Cryogenic Systems*, by Randall F. Barron were utilized in a TK Solver program to determine liquid and gas fractions. A few samples of this are included in the calculations.

CALCULATION PROCESS

The most common engineering fluids and thermodynamic simplifications were used when determining the properties of the supply nitrogen at each location. Altitude changes were always taken into consideration for pressure changes as well as potential energy changes. In the early stages, kinetic energy changes were calculated, but they can be seen to have no noticeable affect. For the later calculations, the kinetic energy effects were neglected. Pressure drops for lengths of pipes, bends and valves were calculated from either the standard k values for resistance coefficients or C_V values for friction coefficients listed in catalogs. Because of their similar constructions, all of the cryogenic valves in this line had the same approximate heat load and friction losses. As it turned out, pressure changes due to altitude differences were the dominating factor in changing pressures, with friction losses much less than the total pressure change. The properties for each section were calculated in the standard manner. A control volume is defined as the volume between each point with fluid moving in and out. Heat loads were calculated for the control volume and then a new enthalpy is calculated for the fluid as it exits. The entrance density was used to determine the outlet pressure $\Delta p = \rho g \Delta h$. Outlet pressure and enthalpy determined the new density, and the average of the original inlet and new outlet densities were used to determine a new average density. The average density is then used to recalculate the pressure change. This process is repeated until the average density calculation is the same as the input average density used to determine the change in pressure. Convergence usually required about 4 to 6 iterations. The new state of the exiting fluid in then known. The same steps are continued for each state with the new conditions of each outlet being the inlet conditions for each new control volume. For the last few stages from locations 5 to 7 to 9, it is assumed that the subcooler in the collision hall is able to take out the heat input from the lines but no more. These values are not actually known, but seem reasonable from information on that subcooler.

RESULTS

The tables show the calculated values for Temperature, pressure, mass flow rate, quality, liquid and gas volume fraction and density, and elevation at each named location on the nitrogen flow path. A definite improvement can be seen for the case with the subcooler in the U-tube since the liquid is saturated or compressed at each tee that splits off to a calorimeter. The expected result of such an improvement will be the increased efficiency in cooling the liquid argon calorimeters and keeping them cold. It is assumed that the nitrogen would most likely be at its worst condition at the entrance to the south end calorimeter since it receives the least amount of subcooling, and there is a phase separator to remove some of the nitrogen gas for the subcooler at position 9. These factors are about the only difference in conditions between locations 5 and 9. Because of this, it is likely that the nitrogen entering location 11 at the valve box for the north end calorimeter is probably slightly better than estimated. In all cases, the considerably larger liquid amounts reaching the cryostats despite smaller flow rates in the second table shows that the subcooler should be quite useful.



SIMPLIFIED NITROGEN COOLANT FLOW PATH

Table 1	LN2 Jumper	No Subcooling									
Location -->	1	2	3	4	5	6	7	8	9	10	11
Property/condition	Dewar exit	U-tube entrance	U-tube exit	Cryo corner	Tee to ECS	ECS entrance	Tee to CC	CC entrance	Tee @subcooler	SUBCOOLER	ECN entrance
mass flow rate (g/s)	34.63	34.63	34.63	34.63	34.63	10.389	24.241	10.39	13.851	IGNORED	10.39
Temperature (K)	89.5	89.4	89.4	91.4	89.55	89.5	89.7	89.78	89.5	IGNORED	89.5
Pressure (atm)	3.40 atm	3.37	3.37	4	3.42	3.475	3.456	3.48	3.417	IGNORED	3.475
quality	0	0	0.018	0	0.022	0.0325	0.0205	0.0194	0.0221	IGNORED	0.0325
Liquid volume fraction	1	1	0.491	1	0.46	0.553	0.662	0.607	0.609	IGNORED	0.55
Gas volume fraction	0	0	0.509	0	0.54	0.447	0.338	0.393	0.391	IGNORED	0.45
average density (g/cc)	0.75	0.75	0.38	0.738	0.353	0.286	0.369	0.38	0.35	IGNORED	0.286
liquid density (g/cc)	0.75	0.75	0.749	0.738	0.748	0.747	0.747	0.747	0.75	IGNORED	0.747
gas density (g/cc)	n/a	n/a	0.014	n/a	0.0144	0.0147	0.0147	0.0148	0.014	IGNORED	0.0147
elevation (feet)	746' 1/2"	747'6 3/4"	747'10"	704' 3/4"	735'11 1/4"	729'9 1/2"	732'3"	729'9 1/2"	735'11 1/4"	IGNORED	729'9 1/2"

Table 2	LN2 U-Tube	Subcooling									
Location -->	1	2	3	4	5	6	7	8	9	10	11
Property/condition	Dewar exit	U-tube entrance	U-tube exit	Cryo corner	Tee to ECS	ECS entrance	Tee to CC	CC entrance	Tee @subcooler	SUBCOOLER	ECN entrance
mass flow rate (g/s)	25	25	23.6	23.6	23.6	7.08	16.52	7.08	9.44	IGNORED	7.08
Temperature (K)	89.5	89.4	88.2	89	90	90.6	90.5	ROUGHLY	ROUGHLY	IGNORED	ROUGHLY
Pressure (atm)	3.40 atm	3.369	3.363	4.336	3.63	3.75	3.711	EQUIVALENT TO	EQUIVALENT TO	IGNORED	EQUIVALENT TO
quality	0	0.002	n/a	n/a	n/a	0.0066	n/a	POSITION 7	POSITION 5	IGNORED	POSITION 6
Liquid volume fraction	1	0.847	1	1	1	0.771	1	POSSIBLY		IGNORED	
Gas volume fraction	0	0.153	0	0	0	0.229	0	SATURATED		IGNORED	
average density (g/cc)	0.75	0.68	0.756	0.752	0.749	0.569	0.743	LIQUID		IGNORED	
liquid density (g/cc)	0.75	0.75	0.756	0.752	0.749	0.734	0.743			IGNORED	
gas density (g/cc)	n/a	0.014	n/a	n/a	n/a	0.018	n/a			IGNORED	
elevation (feet)	746' 1/2"	747'6 3/4"	747'10"	704' 3/4"	735'11 1/4"	729'9 1/2"	732'3"	729'9 1/2"	735'11 1/4"	IGNORED	729'9 1/2"

LIQUID STATE AT LOCATION 1 — DEWAR EXIT. ASSUMED TO BE SAME TEMPERATURE AND PRESSURE AS IS MEASURING PROBES

$P = 50$ psia, $= 344.7$ kPa $= 3.40$ atm
$T = 89.48$ K
ELEVATION = 746' ½" (GROUND IS 743' 6" re: 222906 ME)
$v = 1.323 + .8(1.339 - 1.323)$ 1.336 cc/g

$h = -94.338 + .8(-95.05 - 94.338) = -96.4$ J/g

$s = 3.108 - .8(3.150 - 3.104) = 3.14$

LIQUID STATE AT LOCATION 2 — ENTRANCE TO SUBCOOLER U-TUBE
LINE LENGTHS BETWEEN ① & ② 27 + 12.6 + 18.26 in
= 4' 9.76" = 4.81 ft
$\Rightarrow \Delta P_{1\to 2,f} = 4.81(.00001) = 4.81\times10^{-5}$ psi
$= 0.33$ Pa

Heat input: $0.581 \frac{Btu}{hr\,ft}(4.81\,ft) = 2.79$ Btu/hr
$= 0.819$ W

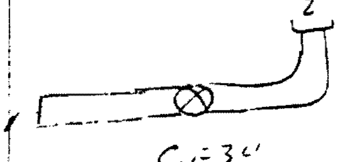
CRYOLAB BAYONET 23.6 BTU/hr (.29307 W/Btu/hr) = 6.916 W

First determine mass flow. Mass flow in = Mass flow out

Sat liq @ 3.0 atm, $v = 1.323$ cc/g $\Rightarrow$ @ 3.4 atm $v = 1.336$ cc/g
Sat liq @ 3.6 atm, $v = 1.339$ cc/g

$44\,gal/hr \cdot \frac{1\,m^3}{264.17\,gal} \cdot \frac{1\,hr}{3600\,s} \times \left(100\frac{cm}{m}\right)^3$ 46.267 cc/s

$46.267\,cc/s \cdot \frac{1\,g}{1.336\,cc} = 34.63$ g/s



CRYOLAB CV1596 APPROX. CV8 VALVE
$21.8\,BTU/hr \times \frac{1\,W}{3.4123\,BTU/hr} = 6.39$ W

$V = \dot{m}/\rho A = \frac{34.63\,g/s \cdot 1.336\,\frac{cc}{g}\left(\frac{1\,m}{100\,cm}\right)^3}{\frac{\pi}{4}(1.5^2)\left(\frac{1}{39.37}\right)^2 m^2} = 0.04$ m/s

998 kg/m³

$C_v = 34 = \frac{Q_L\sqrt{G}}{\sqrt{\Delta P}} \Rightarrow \Delta P = \left(\frac{Q_L\sqrt{G}}{34}\right)^2 \quad \frac{\left(\frac{44\,gal/min}{60}\right)\left(\sqrt{\frac{(1/1.336)\,g/cc}{.998\,g/cc}}\right)}{34}$

from CV

$\Delta P\,(psi) = \frac{44}{60}\sqrt{0.866} = 0.09$ psi $= 128$ Pa

10/18/93

LOCATION 2 $V_{out} = 0.04$ m/s

ELEVATION: 742' $6\frac{3}{4}$"

Δ ELEVATION = $18\frac{1}{4}$" = 0.46 m

ASSUMING FIRSTLY, NO DENSITY CHANGE DUE TO HYDROSTATIC PRESSURES,

$$\Delta P = \rho g h = \frac{1}{1.336}\frac{g}{cc}\left(\frac{100cc}{m^3}\right)^3\left(\frac{1\,kg}{1000g}\right)\left(9.806\frac{m}{s^2}\right)(0.46m)$$

$$= 3376\ \frac{kg}{m\,s^2} = 3376\ Pa$$

$P = 344700\ Pa - \Delta P_{valve} - \Delta P_{elevation} - \Delta P_{line}$

$= 344700 - 128 - 3376 - 0.33 = 341.2$ kPa

3.37 atm

FIRST LAW ANALYSIS, ASSUMING THAT LN2 IS STILL SATURATED BECAUSE PRESSURIZED DEWAR NITROGEN IS MOST LIKELY SLIGHTLY COMPRESSED

$$Q - \dot{W} + \dot{m}(h_{in} + pe_{in} + ke_{in}) - \dot{m}(h_{out} + pe_{out} + ke_{out}) = \frac{dE}{dt}\Big|_{system} = 0 \quad \text{(Steady State)}$$

ASSUMING VELOCITY REMAINS RELATIVELY CONSTANT

REFERENCE HEIGHT AT DEWAR ENTRANCE LEVEL

$$(\ldots)\dot{W} + .03463\frac{kg}{s}\left[-94.6\frac{kJ}{kg} + \left(9.806\frac{m}{s^2}\right)(0) + \frac{1}{2}\left(.04\frac{m}{s}\right)^2\right]$$

$$-.03463\,kg\left[h_{out} + (9.806)(0.46) + \frac{1}{2}(0.04\,m/s)^2\right] = 0$$

$$\frac{0.141\,W}{0.03463} + \frac{0.03463\frac{kg}{s}}{.03463\,kg/s}\left(-94.6\frac{kJ}{kg}\right) - \frac{0.03463}{.03463\frac{kg}{s}}\frac{kg}{s}(9.806)(.46m) = \frac{0.03463\frac{kg}{s}}{.03463\frac{kg}{s}}h$$

$$\frac{407.16\frac{J}{s}}{\frac{kg}{s}} - 94.6\frac{kJ}{kg} - 4.51\frac{m^2}{s^2}\cdot\frac{1\,kJ}{\ldots}\cdot\frac{1\,J}{\frac{kg\,m^2}{s^2}} = h$$

$$h = -94.6\frac{kJ}{kg} - 4.51 - 407.16\frac{J}{kg}\left(\frac{1\,kJ}{1000J}\right)$$

$$h = -94.19 = -94.2\ \frac{kJ}{kg}\ \text{or}\ \frac{J}{g}$$

$$T = T_{sat} @ 3.39\ ATM = 88.077 + \frac{39}{50}(89.834 - 88.077)$$

$$= 89.38K$$

SPECIFIC VOLUME $\approx 1.323 + \frac{39}{50}(1.339 - 1.323) = 1.33\frac{cc}{g}$

LOCATION 3 IS @ EXIT OF UTUBE. WE NEGLECT LOSSES DUE TO ALTITUDE CHANGE (3")

$V \approx 0.04 m/s$
ELEVATION 747' 10"

$\Delta P_{friction} = 11.9 ft (.00001 \frac{psi}{ft})(\frac{1 Pa}{1.4504 \times 10^{-4} \frac{lbs}{in^2}}) = 0.82 Pa$

$\Delta P_{head}: \frac{gh}{v} = \frac{(9.806 m/s^2)(3.28 \, ?)(\frac{?}{39.37})m}{1.33 \frac{cc}{g} \cdot (\frac{1m}{100cm})^3 \frac{1000g}{kg}} = 817 \frac{kg \, m^2}{s^2}$

NO VALVES

$P = 341200 + 817 - .82 = 342000 \; Pa = 3.37 \; atm$

HEAT LEAK INTO CRYOGEN TUBE LENGTH

$0.581 \frac{BTU}{hr \, ft}(11.9 \, ft) = 6.91 \frac{BTU}{hr} (\frac{0.29307 W}{BTU/hr}) = 2.03 W$

CRYOGEN BAYONET: 6.9 W (P. 1)

1ST LAW, NEGLECTING POTENTIAL & KINETIC ENERGY CHANGES

$Q - W + \dot{m}(h_{in}) - \dot{m}(h_{out}) = 0$

$\frac{8.93 W - 0 + 0.03463 \frac{kg}{s}(-94.4 \frac{kJ}{kg})}{0.03463 \, kg/s} = \frac{0.03463 \frac{kg}{s}(h_{out})}{0.03463 \, kg/s}$

$257.9 \frac{J}{kg} - 94.2 \frac{kJ}{kg} = h_{out} \Rightarrow h_{out} = -93.94 \frac{kJ}{kg} = (-93.9 J/g)$

CONDITIONS @ 3.0 ATM

T_{sat} = 88.077, $h_f = -98.938$, $h_g = 84.167$, v_f = 1.323, $v_g = 78.013$

@ 3.5 atm

$T_{sat} = 89.84$, $h_f = -95.?$, $h_g = 85.0?$, $v_f = 1.339$, $v_g = 67.418$

@ 3.37 atm = 89.4 K $\quad h_f = -97.27$, $h_g = 84.806$, $v_f = 1.339$, $v_g = 73.3$

$h_{fg} = 84.685 - (-96.67) = 182.1 \qquad v_{fg} = 73.3 - 1.333 = 72$

$h = -93.94 = -97.27 + x(182.1) \Rightarrow x = 0.018$

$v = 1.333 + 0.018(72) = 2.65 \frac{cc}{g}$

$V = \frac{\dot{m}v}{A} = \frac{34.63 \frac{g}{s} \cdot 2.65 \frac{cc}{g} \cdot (\frac{1m}{100cm})^3}{\;} = 0.08 \; m/s$

THIS INCREASE OF VELOCITY WOULD BE A CONSIDERABLE INCREASE OF KINETIC ENERGY, BUT IT IS STILL QUITE SMALL IN COMPARISON TO ANY OTHER CHANGES TO THIS POINT. AT COLLISION HALL ENTRANCE, I WILL DETERMINE A NEW DENSITY USING NO VELOCITY CHANGE, THEN DETERMINE VELOCITY CHANGE WITH THIS DENSITY APPROXIMATION, REPEATING UNTIL CONVERGANCE.

FROM U-TUBE EXIT TO COLLISION HALL ENTRANCE,

A 1 VALUE, MV543N, CRYOLAB SERIES, CV8, SAME TYPE AS ON PAGE 1, $C_v = 34 = \frac{Q_2\sqrt{G}}{\sqrt{\Delta P}} \Rightarrow \frac{\frac{44\,gal/hr}{60\,\frac{min}{hr}}\left(\sqrt{\frac{1/2.388\frac{g}{cc}}{.998\,g/cc}}\right)}{34} = \Delta P = 0.014\,psi$

$\Delta P = 0.014\,psi \times \frac{6.8948\times10^3\,Pa}{psi} = 96.3\,Pa$

$q = 21.8\,BTU/hr \cdot \frac{.29307\,W}{BTU/hr} = 6.38\,W$

FROM U-TUBE EXIT TO COLLISION HALL ENTRANCE, THERE ARE 14 - 90° BENDS, 1 - 45° BEND, 1 Tee

FROM FRANK M. WHITE, FLUID MECHANICS 2nd Ed. 1986 McGRAW-HILL

RESISTANCE COEFFICIENTS
90° BENDS $1\frac{1}{2}$" PIPE .44 = k 45° BEND $1\frac{1}{2}$" PIPE = 0.2 = k

BRANCH TEE, k = 0.90

LENGTH OF PIPE: 2'4" + 94 - 1" + 32'10" + 57'2$\frac{3}{4}$" + 28'11"
+ 0' 9$\frac{3}{16}$" + 3' + 2'10" × 4 + 34'5" + 2'4" = 189' 5" = 196'5$\frac{15}{16}$"

ΔP due to PIPE LOSS: 196'5 (.0001) = 0.0019 psi $\left(\frac{6.8948\times10^3\,Pa}{psi}\right)$ = 13.5 Pa

$\Delta h_{bends,etc}$ $k = 14(0.44) + 1(0.2) + 1(0.9) = 7.26$

$\Delta h\ \Sigma k \frac{V^2}{2g} = \frac{(7.26)(0.06\,m/s)^2}{2(9.806\,\frac{m}{s^2})} = 0.0013\,m$

$\Delta h = 0.0013\,m = \rho g h \Rightarrow \Delta P = (0.0013\,m)(9.806\frac{m}{s^2})\left(\frac{1}{2.036}\frac{g}{cc}\right)\left(\frac{100\,cm}{m}\right)^3\left(\frac{1\,kg}{1000\,g}\right)$

POSITION 4

746'6¾" 760'6¾" 703'4"

ELEVATION DETERMINATION from 749'10.08" − 2'4" + 14' − 57'2¾"

−0'6½" + 2'4"

ELEVATION = 704 ¾

702'9½" 705'1½

Δ ELEVATION = 747 10 − 703 ¾ = 43' 9¼" 43.9 ft

$(43.77\ ft)\left(\frac{1\ m}{3.2808\ ft}\right) = 13.38\ m$

ΔP, hydrostatic pressure ≈ $\rho g h = (13.3\ m)\left(9.806\ \frac{m}{s^2}\right)\left(\frac{1}{2.6}\ \frac{g}{cc}\right)\left(\frac{100\ cc}{m}\right)^3 \frac{1\ kg}{1000\ g}$

50 kPa

PRESSURE @ POSITION 4 = 342000 − 6.418 − 13.5 + 50000 − 96.3

↑ BEND LOSS ↑ LEVEL LOSS ↑ HYDROSTATIC GAIN ↑ VALVE

P = 392041 Pa = 3.86 atm

FROM ... LOSS TO PIPE = 0.58 $\frac{BTU}{hr\ ft}$ (196.5' ...) 114.2 $\frac{BTU}{hr}$

$114.2\ \frac{BTU}{hr}\left(.29307\ \frac{W}{BTU/hr}\right) = $ **33.5 W**

TOTAL HEAT ... = 33.5 W + 6.39 W = 39.9 W JUST PRIOR TO BAYONET

PIPE

1st LAW
$\dot{Q} - \dot{W} + \dot{m}(h_{in} + e_{p,in} + e_{k,in}) - \dot{m}_{out}(h_{out} + e_{p,out} + e_{k,out})$

Again, ASSUME VELOCITY CHANGES ARE SMALL

$\frac{39.9\ W + 0.03463\ \frac{kg}{s}\left(-93.94\ \frac{kJ}{kg} + 9.806\ \frac{m}{s^2}(0\ m)\right) - 0.03463\ \frac{kg}{s}\left(h_{out} + 9.806\ \frac{m}{s^2}(-13.3\ m)\right) = 0}{0.03463\ kg/s}$ $\frac{}{0.03463\ kg}$

$\frac{1152\ J/s}{kg/s} - 93.94\ \frac{kJ}{kg} + 130.4\ \frac{m^2}{s^2} = h_{OUT}$

$1.152\ \frac{kJ}{kg} - 93.94\ \frac{kJ}{kg} + 130.4\ \frac{m^2}{s^2} \cdot \frac{1\ kg}{kg} \cdot \frac{1\ J}{\frac{kg\ m^2}{s^2}} \cdot \frac{1\ kJ}{1000\ J} = -92.66\ \frac{kJ}{kg}$ or $\frac{J}{g}$

SO, at 3.86 atm, $T_s = 90.97$, $h_f = h_g = -92.7$ ⇒ LIQUID @ INLET TO PLATFORM JUMPER IS JUST ABOUT SAT. LIQUID FROM A FIRST APPROXIMATION STAND POINT, $v = v_{sat\,h_g} = v = 1.35$

TO APPROXIMATE ACTUAL CONDITIONS, TAKE ASSUMED DENSITY OF INLET 2.65 cc/g AND AVERAGE WITH VALUE JUST OBTAINED TO GET AVERAGE v of 2.0 g/cc

PLUGGING THIS INTO OUR HYDROSTATIC PRESSURE EQUATION,

$\Delta P_{h_{yd}} = \frac{1}{2}\frac{g}{cc}\left(\frac{100\,cm}{m}\right)^3\left(\frac{1\,kg}{1000\,g}\right)\left(9.806\frac{m}{s^2}\right)13.3\,m = 65207$ Pa

FROM THE PRESSURE EQ: 342000 - 6.[illegible] + 65000 - 96.3 - 13.5

406800 Pa = 4.016 atm

@ 4.01 atm, $h_{f,sat} = -91.761$ ⇒ OUR -92.66 WOULD BE A COMPRESSED LIQUID, $v \approx 1.355$, IMPLYING THE LAST DENSITY CALCULATION WAS QUITE CLOSE

THE VELOCITY WOULD BE $V = \frac{\dot{m} v}{A} = \frac{0.0363\frac{kg}{s}\left(1.35\frac{cc}{g}\right)\left(\frac{1000\,g}{kg}\right)\left(\frac{1\,m}{100\,cm}\right)^3}{\frac{\pi}{4}\left([illegible]\left(\frac{1\,m}{39.37\,in}\right)\right)^2}$

$= 0.04$ m/s

TO DETERMINE WHAT EFFECT, IF ANY, OUR INTERNAL ENERGY DECREASE HAS.

REDO LAST 1.3

$39.[illegible]\,W + 0.0363\frac{kg}{s}\left(-93.9[illegible] + 9.806\,m(0) + \frac{1}{2}\left(\frac{.08\,m}{s}\right)^2\right)$

$- 0.0363\frac{kg}{s}\left(h + 9.806\frac{m}{s^2}(-13.39\,m) + \frac{1}{2}\left(0.04\frac{m}{s}\right)^2\right) = 0$

$1152\,\frac{J/s}{kg/s} - 93.94\frac{kJ}{kg} + \frac{.003\,m^2}{s^2} + \frac{131\,m^2}{s^2} - \frac{.001\,m^2}{s^2} = h$

$h = 1.152 - 93.94 + \frac{131.002}{1000} = -92.66$ ⇒ NO CHANGE

STATE 4 - ELEVATION 704' 3/4", $V_4 = 0.04$ m/s

$P_4 = 392.041$ kPa $= 4.0$ atm

$h_4 = -92.66$ J/g

$v \approx 1.355$

NEXT STAGE, FROM BAYONET IN CRYO CORNER TO T @ JUNCTION OF ECS.

1 CRYOLAB BAYONET & 1 ROTARY BAYONET,

2 × 6.9 W

1 VALVE MV UAIN (CRYOLAB CV-8 SERIES) $\Delta P \approx 130$ Pa
$q = 6.39$ W

PIPE LENGTH $24\frac{3}{4}'' + 29'' + 5 = \frac{3}{4}'' + 48 + 20 + 21$
TO BOTTOM OF CRYOBRIDGE (END OF CRYO CORNER PIPING)
$195.5'' = 16'\ 3\frac{1}{2}''$

TO END OF CRYO BRIDGE, $16'\ 3\frac{1}{2}'' + 36' + 18' = 70'\ 3\frac{1}{2}$

GUESSING AFTER LOOKING @ MD 294586 THAT TEE FOR SPLITTING OFF TO ECS IS LOCATED AT

$732'\ 3\frac{1}{2}'' + 43\frac{3}{4}'' = 735'\ 11\frac{1}{4}''$

WANTED
STATE JUST BEFORE LEAVING TEE

Δ ELEVATION $= 735'\ 11\frac{1}{4}$
$- 704\ \ 3$
$31'\ 0\frac{1}{2} \times \left(\frac{1\ m}{3.2808\ ft}\right) = 9.7$ m

BECAUSE THE ELEVATION CHANGE WILL RESULT IN NEARLY AS MUCH PRESSURE CHANGE AS BEFORE, THIS POINT A REDUCTION, I WILL CHOOSE AN INTERMEDIATE DENSITY TO AVERAGE HYDROSTATIC PRESSURE DROP AND THEN LATER CHECK VALIDITY

$v_{ave} \approx 1.9$ cc/gm

$\Delta P = \rho g h = \left(\frac{1\,g}{1.9\,cc}\right)\left(\frac{1 kg}{1000 g}\right)\left(\frac{100\,cc}{m}\right)^3 \left(9.806 \frac{m}{s^2}\right)(9.7\ m) = 50$ kPa

TOTAL LENGTH FROM 4 TO 5: $70'\ 3\frac{1}{2}$ (from above) $+ 4'\ \frac{3}{4}''$
≈ 71 ft $\Delta P \approx 71(0.00001) = .0007$ psi

$.0007\ psi \times 6.8948 \times 10^3 \frac{Pa}{psi} = 4.9$ Pa

TOTAL ΔP 4→5 = −50000 (Δ ELEVATION) − 4.9 Pa (Δ Friction)
−130 Pa (Valve)

P @ 5 = 392041 - 50000 - 30-5 Pa = 341.9 kPa = 3.37 atm

From earlier, P. (3)

PROPERTIES @ 3.37 atm

$h_f = -97.27$, $h_g = 84.80$, $v_f = 1.334$ $v_g = 73.3$ $T_{sat} = 89.4$
$h_{fg} = 182.1$

AGAIN, TOTAL LINE LENGTH = 70' 3½" · .581 BTU/hr ft = 40.84 BTU/hr

(40 BTU/hr) (0.29307 W/(BTU/hr)) = 11.97 W

TOTAL HEAT IN OUT TO LINE = 11.97 W (line) + 2 × 6.0 W (BAYONETS)
+ 6.39 W (VALVE)
= 32.16

NEGLECTING VELOCITY CHANGES

$\dot{Q} - W + \dot{m}_{in}(h_{in} + ep_{in} + ek_{in}) - \dot{m}_{out}(h_{out} + ep_{out} + ek_{out}) = 0$

EB 4→5

$32.16 W - 0 + 0.03463 \frac{kg}{s}(-92.66 \frac{kJ}{kg} + g(0)) - 0.03463 \frac{kg}{s}(h_{out} + 9.806 \frac{m}{s^2}(9\ m)) = 0$

$\frac{928.7 \frac{J s}{kg/s} \cdot \frac{1 kJ}{1000 J} + 92.66 \frac{kJ}{kg}}{0.03463 \frac{kg}{s}} - 95.1 \frac{m^2}{s^2} \cdot \frac{1 kg}{1 kg} \cdot \frac{1 J}{1 kg\,m^2/s^2} \cdot \frac{1 kJ}{1000} = h_{out}$

$h_{out} = -91.8$ J/g, $h = h_f + x h_{fg}$

$-91.8 = -97.27 + x(182.1) \Rightarrow x = 0.03$

$v = 1.334 + 0.03(73.3) = 3.5$ cc/g

THE DENSITY I USE WAS TOO HIGH WHEN DETERMINING THE PRESSURE DROP

NOW I WILL GO BACK USING AVERAGE OF

$\frac{3.5 + 1.335}{2} = 2.43$

FIRST ITERATION

STATE 5
x = 0.03
P = 3.37 atm = 342 kPa
h = -91.8 kJ/kg

ELEVATION = 735 ft
v = 3.5 cc/g

$\Delta P = \frac{1}{2.4} \frac{g}{cc} \left(\frac{1\,kg}{1000\,g}\right)\left(\frac{100\,cm}{m}\right)^3 \left(9.8062 \frac{m}{s^2}\right)(9.7\,m) = 39{,}632\,Pa$

TOTAL ΔP = - 39.6 kPa - .005 kPa - .13 kPa

P@ 5 = 392041 - 39632 - 5 - 130 = 352273 Pa = 3.48 atm

@ 3.48 ATM, T_{sat} = 89.7 K — v_f = 1.338 cc/g

h_f = -95.351 J/g — v_g = 67.43 cc/g

h_g = +84.991 J/g — v_{fg} = 66.485

h_{fg} = 180.34

$h = -91.8 = -95.32 + x(180.32) \Rightarrow x = 0.020$

$v = 1.338 + .02(66.488) = 2.647$

TOO LOW A DENSITY CHOSEN

CHOOSE (1.335 - 2.7)/2 = 2.0

$\Delta P = \frac{1}{2.0} \frac{g}{cc} \left(\frac{1}{1000} \frac{kg}{g}\right)\left(\frac{100\,cm}{m}\right)^3 (9.806)(9.7) = 47559\,Pa$

P@ 5 = 392041 - 47559 - 5 - 30 = 344307 Pa = 3.40 atm

@ 3.4 Atm T_{sat} = 89.5 K

h_f = -95.93 — v_f = 1.336

h_g = 84.86 — v_g = 69.54

h_{fg} = 180.8 — v_{fg} = 68.163

$h = -91.8 = -95.93 + x(180.8) = 0.023$

v = 2.896

v_{avg} = 2.116

USING EES ADDITIONAL ITERATIONS

(1) P = 346.95 kPa = 3.424 atm

v = 2.813

v_{avg} = 2.074

(2) v = 2.842, v_{avg} = 2.080

(3) v = 2.832 v_{avg} = 2.083

(4) v = 2.836 v_{avg} = 2.085

(5) v = 2.835 v_{avg} = 2.085

WE HAVE REACHED AN AGREEMENT HERE

CONDITIONS @ 5

P = 346285 Pa = 3.418 atm — h = -91.8 kJ/kg

T = 89.55 K — x = 0.0221

ELEVATION = 735' 11 1/4"

BECAUSE I COULD LOCATE NO DRAWING SHOWING THE ACTUAL CONNECTION BETWEEN THE TEES AND THE ROTARY BAYONET STRUCTURES AND CRYOBRIDGE I ASSUMED THAT THEY FOLLOW A COMPLETELY STRAIGHT PATH IN THE SIMPLEST FASHION

EL = 150 (APPROX) 27 3/4 X → 180 Y, 27.75 X = 30" = 2.5'
180 Y 27.75 X TO 180 Y 84 X = 56.25" = 4' 8 1/4" = 4.6875'

180 Y X 84 TO 135 Y, 84 X = 45" = 3' 9" = 3.75'

135 Y 84 X TO 135 Y 60 X = 24" = 2'

135 Y 60 X TO 77 Y, 60 X = 58" = 4' 10" = 4.83
(T REF RUCINSKI SKETCH EL 729' 9 1/2")

TOTAL LENGTH = 17.78 ft

INCLUDES 5 90° ELBOWS, 1 Tee

3 ROTARY BAYONETS

HEAT WENT TO LN_2 = $3 \times 6.9\ W + 17.78\left(0.58 \frac{BTU}{ft\cdot h}\right)\left(\frac{0.29307\ W}{BTU/h}\right) =$

$20.7 + 3.026 = 23.73\ W$

FRICTION LOSS = $17.78\ ft \times .00001 \frac{psi}{ft} \cdot 6894.76 \frac{Pa}{psi} = 0.12\ Pa$

$$-\underset{\substack{\text{ELBOWS}\\ k}}{\left[5(.44)\right.} + \underset{\text{Tee}}{\left.1(.9)\right]} \frac{V^2}{2g} \rho g = 3.1 \frac{V^2}{2} \rho$$

FIRST WE NEED TO DETERMINE VELOCITY. ASSUME 10% TOTAL FLOW WILL BE USED FOR SUBCOOLER. EACH CALORIMETER WILL USE APPROX 30% OF TOTAL FLOW

$0.3(0.03463) = 0.0104 \frac{kg}{s}$

$$V = \frac{\dot{m} v}{A} = \frac{(0.0104\ kg/s)(2.835\ cc/g\ (inlet))\left(\frac{1000g}{kg}\right)\left(\frac{1m}{100cm}\right)^3}{\left(\frac{\pi}{4} 1.5^2\right)\left(\frac{1}{39.37}\right)}$$

$V = 0.026\ m/s$

ΔP DUE TO BENDS $= (3.1)\frac{(.026\ \cancel{2})^2}{2\cancel{g}} \frac{1}{\cancel{g}2.835 \frac{cc}{g} \frac{1000g}{1\ kg}\left(\frac{1m}{100cm}\right)} = 28.3$

TOTAL FRICTIONAL PRESSURE DROP = 28.4 Pa

ΔP ELEVATION = $(735' 11 3/4 - 729' 9 1/2)\left(\frac{1}{3.28084\ ft}\right) \rho$

6' 2 1/4" = 1.886 m

ΔP ELEVATION = $(1.886 m)(9.806 \frac{m}{s^2})(\frac{1}{v_{avg}})$

IF v avg IS APPROX 2.8 cc/g (I AM USING SAME DENSITY AS AT 5 HERE

ΔP ELEVATION = $+ (1.886 m)(9.806 \frac{m}{s^2})\left(\frac{1}{2.8 cc/g (\frac{1000 g}{kg})(\frac{1 m}{100 cm})^3}\right) = 6604$ Pa

FIRST ITERATION, P @ INLET TO COOLING LOOP FOR ECS = 346285 + 6604 - 24.4 = 352.86 kPa = 3.48 ATM

E8 5 → 6 NEGLECTING VELOCITY CHANGE

$$\frac{23.73\ W + 0.0104 \frac{kg}{s}(-91.8 \frac{kJ}{kg} + g(0)) - 0.0104 \frac{kg}{s}(h_{out} - 9.806 \frac{m}{s^2}\ 1.886 m)}{0.0104\ kg/s} = 0$$

$$\frac{2281\ J/s}{kg/s} - 91.8 \frac{kJ}{kg} + 18.5 \frac{m^2}{s^2} \frac{1 J}{1 \frac{kg\, m^2}{s^2}} = h_{out}$$

$h_{out} = -89.5$

USING EES

AVG VOL = 2.835

x = 0.0324	v_{avg} = 3.163	v = 3.492	ΔP = 6174
x = 0.0325	v_{avg} = 3.168	v = 3.50	ΔP = 5856.3
x = 0.0325	v_{avg} = 3.168	v = 3.50	ΔP = 5847

STATE 6 H2 ENTERING ECS

T = 89.50 K
P = 352.1 kPa = 3.475 atm
x = 0.0325
h = -89.5 J/g
v = 3.501 cc/g
EL = 729' 9½"

h_f = -95.363
h_g = 84.988
v_f = 1.330
v_g = 67.863

BECAUSE THERE IS NEARLY NO PRESSURE DROP IN THE LINES, AND EVEN LESS WITH THE REDUCED FLOW, I WILL NEGLECT IT IN THE ENSUING CALCULATIONS.

ALTITUDE CHANGE FROM 5 → 7 = $43\frac{3}{4}'' = 1.111\,m$

IF PRESSURE CHANGE IS SMALL DENSITY WILL REMAIN NEARLY CONSTANT. USE VALUE OF PRESSURE FOR STATE 5 TO DETERMINE ΔP

$$\Delta P = \frac{1}{v} g h = \left(\frac{1}{(2.835\ \frac{cc}{g})\left(\frac{1m}{100cm}\right)^3 \frac{1000g}{kg}}\right)\left(9.806\frac{m}{s^2}\right)(1.111\,m)$$

$\Delta P = 3843\ Pa$

$P_7 = 346286 + 3843 = 350.1\ kPa = 3.456\ ATM$

IF WE ASSUME AT THIS POINT THAT SUBCOOLING JUST EQUALS HEAT INPUT TO LINE

STATE 7

ITERATION 2 $v_{avg} = 2.774$ $v = 2.712$ $x = 0.0206$ $\Delta P = 3043$

" 3 $\Delta P = 3026$ $v_{avg} = 2.774$ $v = 2.712$ $x = 0.0205$

" 4 $\Delta P = 3027$ $v = 2.712$ $v_{avg} = 2.774$ $x = 0.0205$

STATE 7

$P = 350.2\ kPa = 3.456\ atm$

$T = T_{sat} = 87.686\ K$

$x = 0.0205$

$v = 2.712\ cc/g$

$v' = 7322\ in^3$

$h = -91.8$

$h_f = -95.506$

$h_g = 54.055$

$v_f = 1.238$

$v_g = 68.268$

FIND STATE 9, ASSUMING IT IS AT SAME HEIGHT AS #5

$$\Delta P = -\frac{1}{(2.712\ \frac{cc}{g})\left(\frac{1m}{100cm}\right)^3\left(\frac{1000g}{kg}\right)}(9.806)(1.111)$$ · START WITH DENSITY @ 7

$P = 350200 - \Delta P$

$h = -91.8\ J/g$

1ST ITERATION $\Delta P = 4017\ Pa$ $v = 2.838$ $v_{avg} = 2.775$

2nd $\Delta P = 3925$ $v = 2.835$ $v_{avg} =$

3rd $v = 2.836$ $\Delta P = 3927$

STATE 9 $P = 346254 = 3.417\ atm$ $T = 87.509$

$x = 0.0221$

[illegible]

NOTE, STATE 9 IS BASICALLY A REPEAT OF STATE 5

THEREFORE, AT WORST, STATE 11 WOULD BE EQUIVALENT TO STATE 6, AND STATE 8 WOULD BE SOMEWHERE BETWEEN [illegible] OF STATE 7 & STATE [illegible]. THIS IS BECAUSE IT HAS LESS HEAT LOAD (AND ROTATING BARRIERS)

I DO NOT KNOW WHERE THIS VALVE BOX ACTUALLY IS LOCATED, BUT I AM ASSUMING THAT IT IS AT THE SAME VERTICAL [illegible] AS THE OTHER TWO

TO 8 2' 6" $2.45' = de = \frac{ln}{3.2808} = 0.74 m$

FROM REFERENCE TO MY CALCULATIONS DATED 10/19/93, P. 2,

LN2 STATE 1 IS LN2 DEWAR

SAT LN2 @ 50 PSIA = 344.7 kPa = 3.40 atm

$T = 89.48\ K$

$EL = 745.5'$

$h = -96.4\ J/g$

$v = 1.336\ cc/g$

TO STATE 2 MASS FLOW = 25 g/s

$$V = \frac{\dot{m} v}{A} \qquad V = \frac{(25\ g/s)(1.336\ \frac{cc}{g})(\frac{1\ m}{100\ cm})^3}{\frac{\pi}{4}(1.6)^2(\frac{1}{39.37})^2} = 0.03\ m/s$$

$C_v = 34$

From before, ΔP VALVE IS TOO SMALL TO BE CONSIDERED SERIOUSLY ($\frac{2}{3}(128) = 85\ Pa$)

(30 gal/hr instead of 40 gal/hr)

THIS WILL BE THE VALUE [illegible] SE

TO LOCATION 2 (AFTER [illegible]) WE HAVE

$$\Delta P = \rho g h = \left(\frac{1}{1.336}\frac{g}{cc}\right)\left(\frac{100\ cm}{m}\right)^3\left(\frac{1\ kg}{1000\ g}\right)(9.806\ m/s^2)(0.46\ m) = 3376\ Pa$$

$P_2 = 344700 - \Delta P_{valve} - \Delta P_{[illegible]} - [illegible]$

? from earlier calculations 0.3 Pa

$P_2 = 344700 - 85 - 3376 - 33 \approx 341.2\ kPa = 3.37\ ATM$

HEAT INPUT

1 CV-8 SERIES CRYOLAB (APPROX)

6.39 W

1 CRYOLAB BAYONET

6.916 W

$$4.5\ ft\left(0.58\ \frac{Btu}{hr\,ft}\right) = 2.79\ Btu/hr\left(0.29307\ \frac{W}{Btu/hr}\right) = 0.819\ W$$

TOTAL HEAT INPUT = 14.1 W

EB

$$Q - W + \dot{m}(h_{in} + pe_{in} + ke_{in}) - \dot{m}(h_{out} + pe_{out} + ke_{out}) = \frac{dE}{dt}\Big|_{sys} = 0 \quad (S.S.)$$

$$\frac{14.1 - 0 + 0.025\frac{kg}{s}\left(-96.4\frac{kJ}{kg} + g(0)\right) - \frac{0.025\,kg}{s}\left(h_{out} + \left(9.806\frac{m}{s^2}\right)(0.46\,m)\right) = 0}{0.025\frac{kg}{s}}$$

$$564\frac{kJ/s}{kg/s} - 96.4\frac{kJ}{kg} - 4.5\frac{m^2}{s^2}\frac{1\,kJ}{1000\,kg\,m^2/s^2} = h_{out} = -95.8$$

POSITION 2
3.37 atm

USING EES PROGRAM DEVELOPED [illegible] FOR THIS PLANT

1ST $v_{avg} = 1.006$ $v_2 = 1.076$

2nd @ P = 3221 x = 0.002, v = 1.47 v_{avg} = 4.3

3RD ITER. v_{ol} = 1.47, x = 0.002 v_{avg} = [illegible] = 1.003
@ P = 3215
h_f = -96.148, h_g = 84.805

P = 341400 = 3.369 atm

STATE 2
P = 341.4 kPa = 3.369 atm
el = 747' 6¾"
h = -95.8 J/g
h_f = -96.148, h_g = 84.805
v = 1.47 [illegible]

T = 29.38 K

X = 0.0020

JUST SLIGHTLY 2 PHASE

TO STATE 3, SUBCOOLER.

NEGLECT Δh for mass bled off. USE IT ONLY IN COOLING WATTS.

HEAT INPUT
(11.9 ft)(0.58 BTU/hr ft) = 6.91 BTU/hr (0.293 W / BTU/hr) = 2.03 W

1 CRYOLAB BAYONET
6.916 W

ASSUME 25 g in 23.6 OUT

$\boxed{\text{SUBCOOLING} = 75\,W}$

E.B. $\dfrac{-75 + 6.916 + 2.03 + 0.0236\,kg/s\,(-95.8 + g(0)) - (0.0236\,kg/s)(h_{OUT} - 0.0889\,(9.806\,m/s^2))}{0.0236} = 0$

$-2799 + -95.4\ kJ/kg + 0.87\ m^2/s^2 = h_{OUT} \Rightarrow h_{OUT} = -98.60\ J/g$

CHOOSING A VALUE OF 1.4 AS AVERAGE v,
$P_3 = 3.363$ atm

h @ 3.363 atm 88 K $= -99.101 + 0.726(-99.075 + 99.101)$

$= -99.082$

INTERPOLATING TO FIND CONDITIONS @ 3

density $v_f = 1.335$
$v_{88} = 1.321$

$\dfrac{-99.082 + 98.60}{-99.082 + 96.205} = \dfrac{1.321 - x}{1.321 - 1.335}$

$h_f = -96.205$

$v_3 = 1.323$

CONDITIONS @ STATE 3
SUB COOLED LIQUID

ELEVATION 747' 5"
$V \approx 0.03$ m/s
flow $= 23.6$ g/s

$v = 1.323$ cc/g
$P = 340777$ Pa $= 3.363$ atm
$h = -98.6$
$h_f = -96.2$ $T = 90.3$
$h_g = 84.795$

PATH TO POSITION 4 INCLUDES:
- 1 VALVE CRYO... CV-8 SERIES
APPROX 85 Pa drop 6.39 W HEAT LOAD

- 1 CRYOLAB BAYONET $1\frac{1}{2}$" - 6.916 W HEAT LOAD

- 196.5' PIPE $\left(0.58\ \frac{BTU}{hr\text{-}ft}\right)\left(0.29307\ \frac{W}{BTU/ft}\right) = 33.5$ W

PIPE HAS 14 90° ELBOWS $K = 0.44$, 1 45° BEND, $K = 0.2$
1 BRANCH TEE $K = 0.9$

ΔP due to pipe loss ≈ 20 Pa (ref p4, calculations ... 3)

Δ ELEVATION = 43.77 ft = 13.34 M
(EL 4 = 704' $\frac{3}{4}$")

ASSUMING FOR FIRST APPROXIMATION THAT LIQUID STAYS SUB COOLED, CHOOSE 1.35 as v

ABOVE 4 atm

E.B.

$33.5 + 6.916 + 23.6 \frac{g}{s}(-98.6 \frac{kJ}{kg} + 0) = .0236 \frac{kg}{s}\left(h_{out} + (9.806 \frac{m}{s^2})(-13.34m)\right)$

$\frac{17125 J/s}{kg/s} - 98.6 \frac{kJ}{s} - 130.8 \frac{m^2}{s^2} \frac{1 kJ}{1000 \frac{kg\,m^2}{s^2}} = h_{out}$

$h_{out} = -97.018$

THIS IS SUBCOOLED STILL BETWEEN 3.5 & 4.5 atm

@ 4.0 atm $h = -97.018$ $\qquad \frac{-99.049 - 97.018}{-99.049 - 94.796} = \frac{1.321 - v}{1.321 - 1.340} = 1.330$

$v = 1.330$

@ 4.5 atm $\qquad \frac{-99.024 - 97.018}{-99.024 - 94.773} = \frac{1.321 - v}{1.32\ldots} \Rightarrow v = 1.330$

v @ 4.1 atm 1.330

THIS MEANS v @ 4.336 atm = 1.330 cc/g

SO USING A NEW AVERAGE VALUE OF 1.327 cc/g

$\Delta P = 98577.2$

$P_4 = 439.334$ kPa = 4.336 atm

P_4 $v = 1.330$
$P = 439.334$ kPa = 4.336 atm
$h = -97.0$ J/g
flow rate = 0.0236 kg/s
EL = 704' $\frac{3}{4}$"

SUB COOLED LIQUID AROUND 89 K

Path TO 5 INCLUDES:

- 1 CRYOLAB BAYONET + 1 ROTARY BAYONET
  $2 \times 6.916W = 13.832W$

- 1 VALVE MV491N CRYOLAB CV-8 SERIES $\Delta P \approx 85$ Pa, $q = 6.39$ W

- PIPE LENGTH $= 71'(.581\ BTU/hr\ ft)(0.29307\ \frac{W}{BTU/hr}) = 12.09$ W

- Δ ELEVATION 704' 3/4
  735' 1/2 $= 31'\ 10\frac{1}{2}'' = 9.7$ m

EB

$$\frac{\underbrace{(6.39+13.832+12.09)}_{32.312}W + 0.0236\frac{kg}{s}(-97.0\frac{kJ}{kg} - 0) - 0.0236\frac{kg}{s}(h_{out} + 9.806\frac{m}{s^2})(9.7m) = 0}{0.0236\ kg/s}$$

$1369.1\frac{J/s}{kg/s} - 97.0 - 95.1\frac{J}{g} = h_{out}$

$h = -95.7$ THIS IS PROBABLY SAT. LIQ OR VERY SLIGHTLY SUBCOOLED

ΔP USE AVERAGE v of 1.336 for first APPROXIMATION

THIS RESULTS IN A ΔP OF 71146 Pa

$P_5 = 366035$ Pa $= 3.632$ ATM

@ 3.5 atm $\frac{-99.\ldots - -95.7}{\ldots} = \frac{1.321 - v}{1.32\ldots - 1.339} \Rightarrow v = 1.336$

@ 4 atm $\frac{-99.00 + 95.7}{-99.00 - 9\ldots} = \frac{1.321 - v}{1.321 - 1.34\ldots} \Rightarrow v = 1.336$

$\Rightarrow v \approx 3.6$ atm $= 1.336$

USING AVERAGE VALUE OF 1.333

$\Delta P = 7135$ Pa $\quad P = 367877.5 = 3.631$ atm

STATE @ 5
EL = 735' 11 1/4"
P = 3.63 atm = 367877.5 Pa
T ≈ 90 K
h = -95.7 J/g
v = 1.336 cc/g
m = 0.0236 kg/s

LIQUID JUST BARELY SUBCOOLED

STATE 6 IS ASSUMED TO BE THE WORST CASE SCENARIO BECAUSE OF LOWEST AMOUNT OF SUBCOOLING ALONG ITS PATH, AND BECAUSE IT HAS NO PHASE SEPARATOR.

EL @6: 729'9½" ΔEL: 6'2½" = 1.886 m

FLOW ≈ 0.3(0.0236 kg/s) = 0.00708 kg/s

TOTAL LENGTH = 17.78 ft
INCLUDES: 5 90° ELBOWS, 1 BRANCH TEE
3 ROTARY BAYONETS

$\dot{q}$ TO NITROGEN = 3+6.916 + 17.78 ft (0.58 BTU/hr ft)(0.29307 W / BTU/hr) =
= 20.748 + 3.0275 = 23.775 W

EB

$$\frac{23.775\,W - 0 + 0.00708\,\tfrac{kg}{s}\left(-95.7\,\tfrac{kJ}{kg}\right) - 0.00708\,\tfrac{kg}{s}\left(h_{out} + (9.80\,\tfrac{m}{s^2})(-1.886\,m)\right) = 0}{0.00708\ kg/s}$$

$$3358\,\frac{J/s}{kg/s} - 95.7\,\frac{kJ}{kg} + 18.\ldots\,\frac{m^2}{s^2}\,\frac{1\,kJ}{1000\,kg\,\frac{m^2}{s^2}} = 0$$

$h = -92.3$ J/g

@ 4 atm THIS IS ABOUT SAT LIQ

CHOOSE VALVE 1.34 For ... ΔP = 1380'
OUR VALUE WILL BE BETWEEN 3.5 & 4 ATM
(1...)

@ 3.7... atm,

WE ARE IN THE 2 PHASE REGION

NEW PRESSURE FOR AVERAGE = 1...

3rd iteration $P_{ave} = 1.526$

... $v = v_{ave} = 1.547$ v_{ave}

CONDITION @6 $h = -92.3$, $v_i = 1.757$ cc/g
$h_f = -93.473$ J/g
$h_g = 85.380$ J/g
$v_f = 1.361$ cc/g
$v_g = 55.344$ cc/g

$x = 0.0066$

$P = 379732$ Pa $= 3.748$ atm
$T = 90.617$ K

```
vol=1.547
delP=1/vol*100**3/1000*9.806*1.886
P=(367877-100+delP)
P_atm=P/101325
d=(P_atm-3.5)*2
h_f=-95.175+d*(95.175-91.761)
h_g=85.031+d*(85.731-85.031)
h_fg=h_g-h_f
v_f=1.339+d*(1.354-1.339)
v_g=67.418+d*(59.361-67.418)
v_fg=v_g-v_f
h=-92.3
h=h_f+x*h_fg
v=v_f+v_fg*x
v_avg=(1.336+v)/2
T_sat=89.834+d*(91.414-89.834)
```

d = 0.495	delP = 11954.826	h = -92.300
h_f = -93.484	h_fg = 178.862	h_g = 85.378
P = 379731.826	P_atm = 3.748	T_sat = 90.617
v = 1.757	vol = 1.547	v_avg = 1.547
v_f = 1.346	v_fg = 62.081	v_g = 63.427
x = 0.0066		

state @ 2,

Elevation= 747' 6.5"
Flow rate =25 g/s
delP = 3215.082
h = -95.800
h_f = -96.158
h_fg = 180.963
h_g = 84.805
P = 341399.588
P_atm = 3.369
T_sat = 89.380
v = 1.471
vol = 1.403
v_avg = 1.403
v_f = 1.335
v_fg = 68.785
v_g = 70.120
x = 0.0020

Condition: 2 phase mixture

state @ 5

Elevation=735' 11.25"
Flow rate=23.6 g/s
delP = 71356.489
h = -97.000
P = 367877.511
P_atm = 3.631
T_sat = 90.302
vol = 1.333
v_f = 1.343
v_fg = 63.192
v_g = 64.536

Condition: sub-cooled liquid (nearly saturated)

state @ 6

Elevation=729" 9.5"
Flow rate = 7.08 g/s
delP = 11954.826
h = -92.300
h_f = -93.484
h_fg = 178.862
h_g = 85.378
P = 379731.826
P_atm = 3.748
T_sat = 90.617
v = 1.757
vol = 1.547
v_avg = 1.547
v_f = 1.346
v_fg = 62.081
v_g = 63.427
x =0.0066

Condition: 2 phase mixture

State @ 3

Elevation=747' 10"
Velocity=0.03 m/s
flow=23.6 g/s
h=-98.6 J/g
v=1.323 cc/g
P=340777 Pa
=3.363 Atm.
h_f=-96.2
h_g=84.795

Condition: Sub-cooled liquid

State @ 4

Elevation=704' 0.75"
P=439.334 KPa
P= 4.336 Atm
h=-97.0 J/g
flow rate=23.6 g/s
v=1.330 cc/g

Condition: sub-cooled liquid

St. Input	Name	Output	Unit	Comment
				Lockhart Martinelli correlation for two phase pressure drop through an adiabatic horizontal pipe
				Argon Calorimeter Liquid nitrogen supply pipe, rough guess at flow regime, deltaP etc. if x=0.05 Russ Rucinski 10/20/93
	valid	'invalid_		model validity
	flow	'turbulen		flow type
	f			friction factor ; Must enter a guess
.000005	epsilon		ft	pipe roughness
1.5	D		in	Pipe inside diameter
100	L		ft	Length of pipe
	A	.00114009	m^2	cross sectional area
10.39	mdot		g/s	Total mass flow rate
747	rhoL		kg/m^3	Liquid density
14.8	rhog		kg/m^3	density of the gas
99.51	muL		µPa-s	Liquid viscosity
6.26	muG		µPa-s	Gas viscosity
.00617	sigmaL		N/m	Surface tension of liquid
.0194	x			quality = mdotG/mdot
	ReL	3422		Reynold's # for liquid
	mdotL	.01018843	kg/s	Mass flow rate for liquid
	ReG	1076		Reynold's # for gas
	mdotG	.00020157	kg/s	Mass flow rate for gas
	dpdLL		Pa/m	ΔP/ΔL for the liquid
	dpdLTP		Pa/m	ΔP/ΔL for the two phase
	deltaP		psig	Total pressure drop for the pipe
	phiL	1.647664		Lockhart-Martinelli parameter
	X	5.929937		Lockhart-Martinelli parameter
1	m			L-M constant; Look up in Table 7.19
.25	n			L-M constant; Look up in Table 7.19
64	CG			L-M constant; Look up in Table 7.19
.316	CL			L-M constant; Look up in Table 7.19
10	C			L-M constant; Look up in Table 7.19
	lambda	3.0383323		Baker diagram dimensionless parameter
1.2	rhoair		kg/m^3	density of air
998	rhoH2O		kg/m^3	density of water
	sigh	6.6506878		Baker diagram dimensionless parameter
.073	sigmaH2		N/m	Surface tension of water
1000	muH2O		µPa-s	viscosity of water
	BakerXa	1020		X - axis value for Baker plot
	BakerYa	42.9	lbm/hr-ft	Y - axis value for Baker plot
	c	1		
	M	1		
	RsubL	.60691986		Volume fraction of liquid phase
	RsubG	.39308014		Volume fraction of gas phase
	GasVel	.03039028	m/s	Gas velocity
	LiqVel	.01971132	m/s	Liquid velocity

NO SUBCOOLER

St	Input	Name	Output	Unit	Comment
					Lockhart Martinelli correlation for two phase pressure drop through an adiabatic horizontal pipe
					Argon Calorimeter Liquid nitrogen supply pipe, rough guess at flow regime, deltaP etc. if x=0.05 Russ Rucinski 10/20/93
		valid	'accurate		model validity
		flow	'turbulen		flow type
		f			friction factor ; Must enter a guess
	.000005	epsilon		ft	pipe roughness
	1.5	D		in	Pipe inside diameter
	100	L		ft	Length of pipe
		A	.00114009	m^2	cross sectional area
	13.851	mdot		g/s	Total mass flow rate
	750	rhoL		kg/m^3	Liquid density
	14	rhog		kg/m^3	density of the gas
	100.192	muL		μPa-s	Liquid viscosity
	6.25	muG		μPa-s	Gas viscosity
	.00623	sigmaL		N/m	Surface tension of liquid
	.0221	x			quality = mdotG/mdot
		ReL	4518		Reynold's # for liquid
		mdotL	.01354489	kg/s	Mass flow rate for liquid
		ReG	1637		Reynold's # for gas
		mdotG	.00030611	kg/s	Mass flow rate for gas
		dpdLL		Pa/m	ΔP/ΔL for the liquid
		dpdLTP		Pa/m	ΔP/ΔL for the two phase
		deltaP		psig	Total pressure drop for the pipe
		phiL	1.6412816		Lockhart-Martinelli parameter
		X	6.002227		Lockhart-Martinelli parameter
	1	m			L-M constant; Look up in Table 7.19
	.25	n			L-M constant; Look up in Table 7.19
	64	CG			L-M constant; Look up in Table 7.19
	.316	CL			L-M constant; Look up in Table 7.19
	10	C			L-M constant; Look up in Table 7.19
		lambda	2.9610024		Baker diagram dimensionless parameter
	1.2	rhoair		kg/m^3	density of air
	998	rhoH2O		kg/m^3	density of water
		sigh	6.5840332		Baker diagram dimensionless parameter
	.073	sigmaH2		N/m	Surface tension of water
	1000	muH2O		μPa-s	viscosity of water
		BakerXa	863		X - axis value for Baker plot
		BakerYa	66.9	lbm/hr-ft	Y - axis value for Baker plot
		c	1		
		M	1		
		RsubL	.60927995		Volume fraction of liquid phase
		RsubG	.39072005		Volume fraction of gas phase
		GasVel	.04908399	m/s	Gas velocity
		LiqVel	.02599906	m/s	Liquid velocity

NO. SUB-00-E 9

St	Input	Name	Output	Unit	Comment
					Lockhart Martinelli correlation for two phase pressure drop through an adiabatic horizontal pipe
					Argon Calorimeter Liquid nitrogen supply pipe, rough guess at flow regime, deltaP etc. if x=0.05 Russ Rucinski 10/20/93
		valid	'accurate		model validity
		flow	'turbulen		flow type
		f			friction factor ; Must enter a guess
	.000005	epsilon		ft	pipe roughness
	1.5	D		in	Pipe inside diameter
	100	L		ft	Length of pipe
		A	.00114009	m^2	cross sectional area
	25	mdot		g/s	Total mass flow rate
	750	rhoL		kg/m^3	Liquid density
	14	rhog		kg/m^3	density of the gas
	100.75	muL		μPa-s	Liquid viscosity
	6.23	muG		μPa-s	Gas viscosity
	.00623	sigmaL		N/m	Surface tension of liquid
	.002	x			quality = mdotG/mdot
		ReL	8276		Reynold's # for liquid
		mdotL	.02495	kg/s	Mass flow rate for liquid
		ReG	268.2		Reynold's # for gas
		mdotG	.00005	kg/s	Mass flow rate for gas
		dpdLL		Pa/m	ΔP/ΔL for the liquid
		dpdLTP		Pa/m	ΔP/ΔL for the two phase
		deltaP		psig	Total pressure drop for the pipe
		phiL	1.1811838		Lockhart-Martinelli parameter
		X	25.403567		Lockhart-Martinelli parameter
	1	m			L-M constant; Look up in Table 7.19
	.25	n			L-M constant; Look up in Table 7.19
	64	CG			L-M constant; Look up in Table 7.19
	.316	CL			L-M constant; Look up in Table 7.19
	10	C			L-M constant; Look up in Table 7.19
		lambda	2.9610024		Baker diagram dimensionless parameter
	1.2	rhoair		kg/m^3	density of air
	998	rhoH2O		kg/m^3	density of water
		sigh	6.5962334		Baker diagram dimensionless parameter
	.073	sigmaH2		N/m	Surface tension of water
	1000	muH2O		μPa-s	viscosity of water
		BakerXa	9750		X - axis value for Baker plot
		BakerYa	10.9	lbm/hr-ft	Y - axis value for Baker plot
		c	1		
		M	1		
		RsubL	.84660832		Volume fraction of liquid phase
		RsubG	.15339168		Volume fraction of gas phase
		GasVel	.0204221	m/s	Gas velocity
		LiqVel	.03446569	m/s	Liquid velocity

SUBCOOLER
C 2

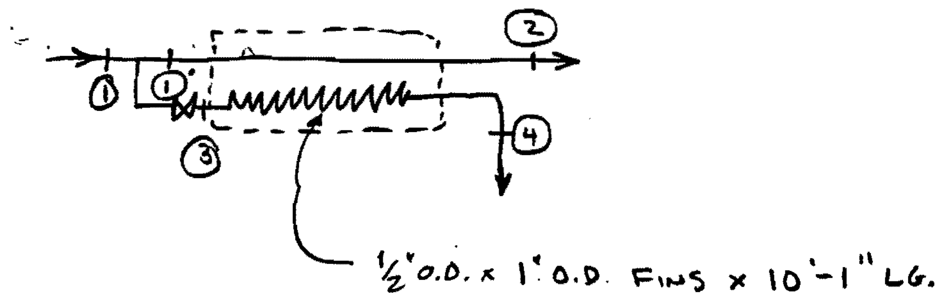
APPENDIX

FERMILAB ENGINEERING NOTE	SECTION: RD/DØ	PROJECT:	SERIAL-CATEGORY:	PAGE: 1
SUBJECT: LN_2 SUBCOOLER ON U-TUBE CALORIMETER SUPPLY	NAME: RUSS RUCINSKI	DATE: 10/21/93	REVISION DATE:	

THESE CALCS ARE TO EXPAND UPON KELLY DIXON'S CALCULATIONS. HIS CALCULATIONS CLAIM 300 W CAPACITY, BUT NO SIZING CALCS. WERE FOUND.

I WILL TRY TO ESTIMATE THE SUBCOOLER CAPACITY.

THE ORIGIN IS A SAVER CRYOGENICS SYSTEM GROUP BAYONET CAN, DRG. 1650-ME-145420 REV. F



STATE 1

$\dot{m}_1 = 25.6\ g/s$ (APPROX 30 gal/hr)

$P_1 = 50$ PSIA, SATURATED LIQUID

$h_1 = h_f = 54.5\ J/g$

$T_1 = 89.5\ K$

STATE 3

$P_3 = 1.1$ ATM

$h_3 = h_1 = 54.5\ J/g$

$h_f = 31.0\ J/g$

$h_g = 229.2\ J/g$

$T_3 = 78.$

$\dot{m}_3 = 2\ g/s$ (ESTIMATE)

HOPE STATE 2 {FROM K. DIXON CALCS}

$T = 79K$

SUBCOOLED LIQUID

$P = 50$ PSIA

$h_2 = 26.7\ J/g$

P = 29.4 PSIA

T = 80K, h = 34.89

T = 75K, h = 24.60

P = 73.5 PSIA

T = 80K, h = 35.09

T = 75K, h = 24.[illegible]

P = 50 PSIA

T = 79K

h = 26.7 J/g

$$Q_{REQ'D} = \dot{m}\Delta h = 23.6\ g/s\,(54.5\ J/g - 26.7\ J/g) = \underline{656.1\ W}$$

THAT'S ALOT OF COOLING!

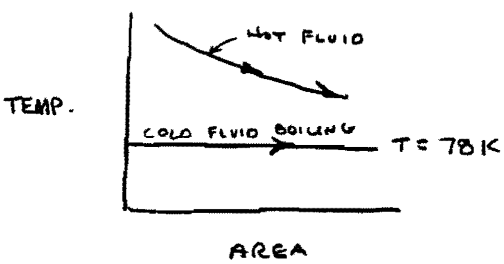
BETTER LET STATE 2 FLOAT & SEE WHAT WE COME UP WITH.

AREA:
$$A_i = \pi d \ell = \pi\,(0.50\ \text{in.})(121\ \text{in.})\left(\frac{.0254\ m}{\text{in.}}\right)^2 = 0.123\ m^2$$

$$A_o = \pi d \ell + A_{FINS}\cdot\eta_f$$
$$= 0.123\ m^2 + \left[\frac{\pi}{4}(1\ \text{in}^2 - 0.5\ \text{in}^2)\left(\frac{.0254\ m}{\text{in.}}\right)^2 \times \frac{31\ \text{FINS}}{6\ \text{in. LENGTH}} \times 121\ \text{in. LENGTH}\right)$$
$$= 0.123\ m^2 + 0.238\ m^2\ \eta_F$$

SAY $\eta_F = 0.80$ {SAME EFFICIENCY FOR HELIUM SUBCOOLER, SUBCOOLING PART. REF EN-351 CONTROL DEWAR HX.

$$A_o = 0.313\ m^2$$



$$C_h = \dot{m}_h C_{p_h} = 23.6\ g/s\left(.492\ \frac{Btu}{lb\,°F}\right)\frac{4.187}{\frac{Btu}{lb}}$$
$$= 48.6\ \frac{J}{s\ °C}$$

$$C_c = C_{MIN} = 2\ g/s \times \frac{48.6}{23.6} = 4.1\ \frac{J}{s\cdot °C}$$

$$C_R = \frac{C_{MIN}}{C_{MAX}} = \frac{2}{23.6} = \underline{0.08}$$

HEAT FLUX:

ON THE INSIDE SURFACE CONSIDER POOL BOILING,

ESTIMATE $T_{WALL} = \dfrac{T_{HOT} + T_{COLD}}{2} \approx \dfrac{89 + 78}{2} = 83\ K$ AT BEGINNING

78.5 K AT END.

$$t_w - t_{SAT} = 5\ K \text{ TO } 0.5\ K = \underline{9\ °F \text{ TO } .9\ °F}$$

$$q/A_i = 7000\ \frac{Btu}{hr\text{-}ft^2} \text{ TO } < 1000\ \frac{Btu}{hr\text{-}ft}.$$

$$= 7000\ \frac{Btu}{hr\text{-}ft^2} \times \frac{1054.9\ J}{Btu} \times \frac{1\ hr}{3600\ s} \times \frac{ft^2}{0.0929\ m^2} = 22{,}080\ \frac{W}{m^2}$$

FERMILAB
ENGINEERING NOTE

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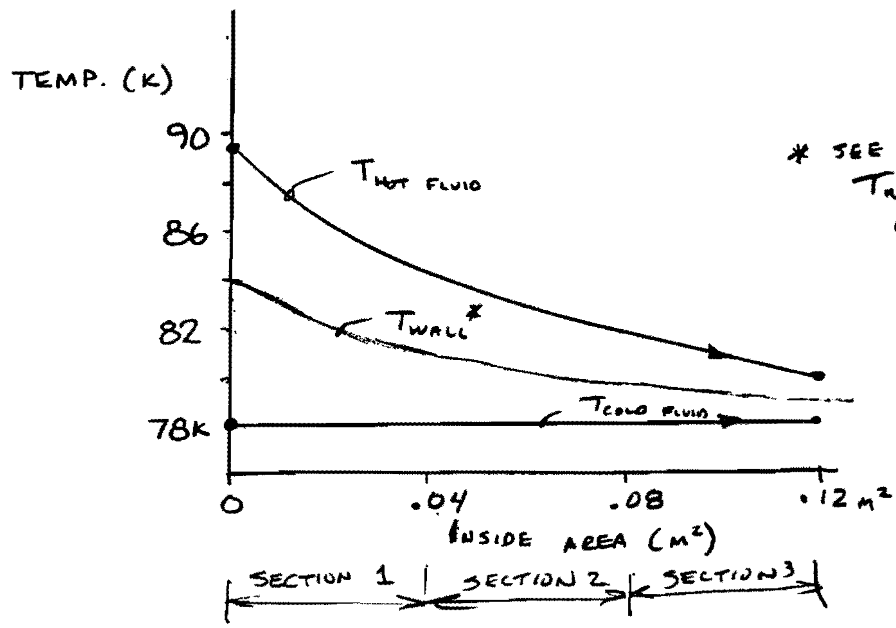
LN_2 U-TUBE SUBCOOLER	RUSS RUCINSKI	10/21/93	

I WOULD GUESS $h_o \ll h_i$ BUT SINCE $A_o > A_i$ PERHAPS

$A_o h_o \approx A_i h_i$ WHICH {WAS THE CASE FOR THE LHe SUBCOOLER}

IF ASSUME A TEMP. DISTRIBUTION SUCH LIKE:



* SEE PAGE 5, ACTUALLY $T_{WALL} \approx T_{COLD}$ BECAUSE OF MAGNITUDE OF CONVECTION COEFF.

LOOK AT FIRST $0.04\,m^2$ (INSIDE AREA)

AVERAGE WALL TEMP., $T_{WALL} = 82K$

$$Q = U_o A_o (T_i - T_o) \qquad U_o = \frac{1}{\frac{A_o}{h_i A_i} + \frac{1}{h_o}} \qquad A_o = \frac{.313\,m^2}{3} = .104\,m^2$$

CALC. h_i & h_o

$\rightarrow h_o$; NEED Re $\quad Re_o = \frac{D\dot{m}}{\mu A} = \frac{D_h \dot{m}}{\mu \frac{\pi (D_o^2 - D_i^2)}{4}} \quad D_h = D_o - D_i = 2\,\text{in.}$

$$Re_o = \frac{(2\,\text{in.})(23.6\,\text{g/s})}{(141\,\mu Pa\text{-}s)(\frac{\pi}{4})[(5.25\,\text{in})^2 - (3.25\,\text{in})^2]} \times \frac{1\,\mu Pa}{10^{-6}\,N/m^2} \times \frac{1\,\text{in}}{.0254\,m} \times \frac{1\,kg}{1000\,g} \times \frac{1\,N}{1\,\frac{kg\,m}{s^2}}$$

$Re = 987$ VERY LAMINAR. (HARDLY MOVING!)

$Pr = 2.14$

SUBJECT: LN$_2$ U-TUBE SUBCOOLER

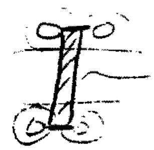
NAME: RUSS RUCINSKI

DATE: 10/21/93 | REVISION DATE:

MODEL AS FLOW NORMAL TO A BANK OF TUBES. A NEW REYNOLDS NUMBER DEFINITION APPLIES:

$$Re = \frac{D_o G_{MAX}}{\mu} \quad \text{WHERE} \quad G_{MAX} = \frac{\dot{m}}{A_{ff}} \text{ – MIN FREE FLOW A BETWEEN TUBES}$$

$$A_{ff} = 1''(4.25\,\text{in.})\,\pi \cdot \left(\frac{.0254\,m}{in}\right)^2$$
$$= .00861\ m^2$$



$$Re = \frac{(0.5\,in.)(23.6\,g/s / .00861\,m^2)}{141 \times 10^{-6}\ N\text{-}s/m^2} \times \frac{1\,kg}{1000\,g} \times \frac{1\,N}{\frac{kg\,m}{s^2}} = 9715$$

$$j_H = 0.26\,Re^{-0.4} = .26\,(9715)^{-0.4} = .0066 \quad \{\text{EQ. 3.65 BARRON}\}$$

WHERE

$$j_H = \left(\frac{h_c}{G\,C_p}\right) P_r^{2/3} \qquad h_c \text{ – FILM COEFF.} = h_o$$

$$G = 23.6\,g/s / .00861\,m^2 \times \frac{1\,kg}{1000\,g} = 2.74\ \frac{kg}{s\text{-}m^2}$$

$$C_p = 2.06\ \frac{J}{g\text{-}°C} = 2060\ \frac{J}{kg\text{-}°C}$$

$$h_c = j_H \cdot G\,C_p\,P_r^{-2/3} = (.0066)\left(2.74\,\frac{kg}{m^2\text{-}s}\right)\left(2060\,\frac{J}{kg\text{-}°C}\right)(2.14)^{-2/3}$$

$$h_c = 22.4\ W/m^2\text{-}K = h_o$$

$\rightarrow h_i$ USE POOL BOILING CHART. $T_{WALL} - T_{FLUID} = 82K - 78K$
$= 4K = 7.2\,°F$

$$q/A = 4500\ \frac{Btu}{hr\text{-}ft^2} = 14{,}194\ W/m^2$$

$$h_i = q''/\Delta T = \frac{14{,}194\ W/m^2}{4\ K} = 3549\ \frac{W}{m^2 K}$$

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SUBJECT: LN_2 U-TUBE SUBCOOLER

NAME: RUSS RUCINSKI

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$$U_o = \frac{1}{\frac{A_o}{h_i A_i} + \frac{1}{h_o}} = \frac{1}{\frac{.104 m^2}{3549 \frac{W}{m^2 K} \cdot .04 m^2} + \frac{1}{22.4 \ W/m^2 K}} = \underline{22 \ W/K\text{-}m^2}$$

ITS CLEAR THAT SINCE $h_i >> h_o$ $T_{WALL} \approx T_i = 78K$

$$Q = U_o A_o (T_i - T_o) = 22 \ \frac{W}{K\text{-}m^2} (.104 m^2)(78K - 86K)$$

$$= \underline{-18 \text{ WATTS}}$$ ← PRETTY SMALL AMOUNT OF HEAT TRANSFER.

BASED ON FIRST PASS OF FIRST 1/3 OF SUBCOOLER, CAN NEGLECT INSIDE HEAT TRANSFER AND ASSUME T_{WALL} = CONSTANT = 78K

CHECK FLUID TEMP AT EXIT OF FIRST SECTION

$$h_{liq} = h_i + Q/\dot{m} = 54.5 \ J/g + \frac{-18 \ J/s}{23.6 \ g/s} = 53.7 \ J/g$$ BARELY ANY TEMP. DROP.

REFIGURE Q,

$$Q = U_o A_o (T_i - T_o) = 22 \frac{W}{K\text{-}m^2} (.104 m^2)(78K - 89.5K)$$
$$= -26.3 \text{ WATTS.}$$

IF THIS IS TRUE THEN I WOULD GUESS THE SUBCOOLER ISNT VERY EFFECTIVE. $\underline{Q_{TOTAL} = 75 \text{ WATTS}}$ PERHAPS.

TRY A DIFFERENT MODEL. MODEL AS A COLLINS HEAT EXCHANGER SURFACE.

$$j_H = 0.118 Re^{-0.3} \quad \{\text{EQ. 3.69 BARRON}\}$$

WHERE $D_e = 4 \text{ (FREE VOLUME)} / \text{WETTED AREA.}$

FREE VOLUME $= \frac{\pi}{4}(D_o^2 - D_i^2) \times L$ — VOLUME OF FINNED TUBES

$$= \frac{\pi}{4}\left((5.25 in)^2 - (3.25 in)^2\right) \times (10 in) - \frac{\pi}{4}(.5 in)^2 (121 in)$$
$$- 625 \text{ FINS} \times (.027 in)\left(\frac{\pi}{4}\left\{(1 in)^2 - (.5 in)^2\right\}\right)$$
$$= 133.5 \ in^3 - 23.76 \ in^3 - 9.94 \ in^3$$
$$= 99.8 \ in^3 = 1.635 \times 10^{-3} \ m^3$$

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WETTED AREA = A_o + AREA OF ANNULUS. , IN MY JUDGEMENT I SHOULD ONLY USE A_o.

$$= .123 + .238(1.0) = \underline{0.361\,m^2}$$ ASSUMING $\eta_{FIN} = 1.0$ SEE PG. 2

$$De = \frac{4(1.635\times10^{-3}m^3)}{0.361\,m^2} = \underline{1.81\times10^{-2}\,m}$$

$$Re = \frac{De\,\dot{m}}{\mu A} = \frac{(1.81\times10^{-2}m)(23.6\,g/s)}{(141\times10^{-6}\frac{N\text{-}s}{m^2})\frac{\pi}{4}(1.81\times10^{-2}m)^2} \times \frac{1\,kg}{1000\,g} \times \frac{1\,N}{1\,\frac{kg\,m}{s^2}}$$

$$= 11{,}774$$

$$j_H = 0.118\,Re^{-0.3} = 0.007$$ ← NOT DIFFERENT FROM FIRST TUBE BANK MODEL. WHERE $j_H = .0066$

THEREFORE $h_o \approx 22$ OR $\underline{23}\ W/m^2K$

AND THE SAME CONCLUSION APPLIES,

$$\boxed{Q_{TOTAL} \approx \underline{75\text{ WATTS}}}$$