Fermilab
*Particle Physics Division, ETT, D-Zero*

COMMISSIONING TEST RESULTS

FOR

D-ZERO'S HELIUM REFRIGERATOR

D-ZERO ENGINEERING NOTE # 3823.115 - EN - 457

June 30, 1997

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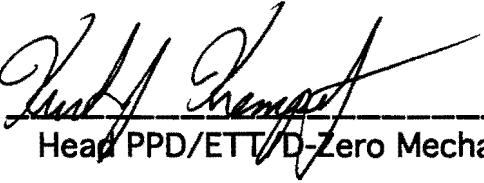
Approved: _____
Head PPD/ETT/D-Zero Mechanical group

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TEST OBJECTIVES

1. Make liquid helium and measure refrigerator capacity.
2. Measure liquid helium dewar heat leak, transfer line heat leak, and liquid nitrogen consumption rates.
3. Operate all cryogenic transfer lines.
4. Get some running time on all components.
5. Debug mechanical components, instrumentation, DMACs user interface, tune loops, and otherwise shake out any problems.
6. Get some operating time in to get familiar with system behavior.
7. Revise and/or improve operating procedures to actual practice.
8. Identify areas for future improvement.

SUMMARY OF RESULTS

D-Zero's stand alone helium refrigerator (STAR) liquified helium at a rate of 114 L/hr. This is consistent with other STAR installations. Refrigeration capacity was not measured due to lack of a calibrated heat load.

Measured heat leaks were within design values. The helium dewar loss was measured at 2 to 4 watts or 9% per day, the solenoid and VLPC helium transfer lines had a heat leak of about 20 watts each. The liquid nitrogen consumption rates of the mobile purifier, STAR, and LN2 subcooler were measured at 20 gph, 20 to 64 gph, and 3 gph respectively.

All cryogenic transfer lines including the solenoid and visible light photon counter (VLPC) transfer lines were cooled to their cryogenic operating temperatures. This included independent cooling of nitrogen shields and liquid helium components. No major problems were observed.

The system ran quite well. Many problems were identified and corrected as they came up. Areas for improvement were noted and will be implemented in the future. The instrumentation and control system operated commendably during the test. The commissioning test run was a worthwhile and successful venture.

DETAILS

Cool down
The system was cooled from room temperature to liquid helium production temperatures in 34 hours.

Cool down was initiated on Monday June 9 at 10:30. Gaseous helium (GHe) flow was heat exchanged with LN2 in HTX 1, flowed through the helium dewar, west VLPC transfer line, and was returned directly to suction. For the first four hours, a secondary cool down flow on the shell side of the heat exchanger was also used. GHe flowed through the external GHe to LN2 cooldown heat exchanger, through the east VLPC transfer line and then through the shell side of the heat exchanger back to suction. By 17:00 that evening the gas

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exiting the LHe dewar was down to 140 Kelvin (TR-4054-H, TR-4056-H). The expansion engines were started at 8:00 the next day. Liquid began to accumulate in the bottom of the LHe dewar at 20:00. That evening, liquid was added to the dewar at a rate of 113 liquid liters per hour.

STAR performance

A generic STAR performance curve exists that describes the nominal capacity in terms of liquification (L/hr) rate and refrigeration (watts). See the figure numbered 7.3 in the appendix. The maximum liquification rate at no refrigeration load is given as 125 liters/hour. The maximum refrigeration load with no liquefaction is given as about 620 watts. During the commissioning test the liquification rate was measured. The liquification rate is defined as the rate that the STAR can change warm gaseous helium into liquid. Numerically, the liquification rate is slightly less than the rate at which liquid accumulates into the liquid helium storage dewar due to the fact that cold saturated helium is returned to the STAR at the same volumetric rate as the liquid accumulation. This lessens the rate at which room temperature gas helium is withdrawn from storage and added to the system. The returned cold saturated gas is considered a refrigeration component of the capacity. At the time of the test run, the dewar heater which we could have used for a refrigeration test, was not ready.

	Data used	Liquification + Refrig.
Very first time	6/11 0:00 thru 8:00	89.3 L/hr + 13.6 watts
Optimized	6/18 14:20 thru 14:50	113.8 L/hr + 17.3 watts
For comparison:	*ideal, mdot = 58 g/s*	*122 L/hr + 20 watts*

Heat loads, consumption rates

The heat leak of the liquid helium storage dewar was calculated using the boil-off rate of the liquid in the dewar while the dewar pressure was held steady. The refrigerator did not add any inventory to the dewar during the test. The wet expansion engine was off, EVXJT was closed and valve EVXBY was open. The measured heat load was very close to what was expected. The design calculations considering the transfer lines and GHe conduction down the neck was 1.8 watts. The dewar itself was specified to be less than 0.5 %/day.

Dewar level	Time period	Boil-off rate = Watts = % per day
1047 to 1017 liters	6.5 hours, 6/13	4.62 L/hr = 2.1 w = 10.8 %/day
1913 to 1853 liters	9 hours, 618	6.67 L/hr = 3.9 watts = 8.5 %/day
For comparison:	*Conduction in neck*	*1.8 watts*

The transfer line heat leak of the VLPC and solenoid helium transfer lines was calculated. The data was collected while flowing He through the lines along with LN2 cooling the radiation shields and valve stem intercepts. The method of calculation was simply multiplying the helium mass flowrate by it's change

in enthalpy inlet to outlet. Keep in mind that there is some uncertainty in the measurements and interpretation of the measurements.

The VLPC line measured was the 'east' supply and return piping. The 'west' piping was cold but stagnant. The mass flow rate through the VLPC line was obtained from the flow venturi, FT-4052-H. The inlet state of the fluid was saturated liquid helium as it was drawn from the bottom of liquid helium storage dewar. The exit state was vapor at an average temperature of 15.5 Kelvin measured by the Cernox temperature sensor TR-4056-H. The VLPC 'east' line heat load was measured to be 21.4 watts.

The mass flow rate for the solenoid transfer line had to be calculated from the LHe dewar level drop. The inlet state was saturated liquid and the outlet state was determined from Cernox temperature sensor TR-3007-H in the solenoid valve box. By this method, the solenoid heat load was measured to be 39 watts.

Line	Measured	Comparison, expected
VLPC 'east'	21.4 watts	20 watts
Solenoid	39 watts	18 watts

The liquid nitrogen consumption rates of the mobile purifier and STAR were measured from data for the liquid level in LN2 dewar 39. The subcooler consumption was very small and was calculated from thermodynamic considerations.

Component	Consumption rate	Expected, from EN-421
Mobile purifier	20 gph LN2	35 gph
STAR, liquification mode	20 to 64 gph LN2	10 gph refrig. mode
Subcooler	small	1 to 3 gph LN2

Transfer line tests

The VLPC transfer lines were used quite a bit during the commissioning test because of their versatility. The valving allowed the helium lines to be supplied from either the GHe cooldown heat exchanger or from the liquid helium dewar. The return flow can be sent back to the shell side of the heat exchanger or bypassed to the suction header through the cooldown return line. The VLPC helium line experienced all combinations of the 'east' helium piping, 'west' helium piping and nitrogen piping, in the cold (80K or below) and warm states. The vacuum jacket pressure was checked and remained about the same before and after the commissioning run. No temperature depression was observed at the tee to the assembly hall feed can or elsewhere on the line. One problem that was discovered was a leak at the TR-4101-H electrical connector on the west end feed can. The couple inch area at the connector frosted up overnight. Cold snoop indicated a leak. The area was warmed up with a heat gun and the leak went away without even tightening the connector flange screws. A couple of times during the commissioning test, liquid helium was dumped from the dewar to suction through the VLPC line. It

took about 40 minutes for the line to get cold, after which liquid could be dumped at 400 liters/hour. The dumping rate was high enough to heavily frost the suction header all the way to the DA compressor building (50 feet) during a warm sunny day.

The solenoid transfer helium line was cooled with and without flow through the nitrogen shield. Also the nitrogen shield was cooled with the helium system warm. No problems with vacuum or cold spots on the vacuum jacket were observed.

Important things learned:

1. If you don't want the Mycom fully loaded, you should leave it in automatic and then lock the minimum and maximum valve position settings to the amount of loading. If you put it in manual at a fixed position, it will slowly drift up. The hydraulics leak causing the valve position to change. When in manual mode there is no feed back to correct for this. For instance if you put it in manual at 50%, it may drift up to 90% in 24 hours. Future operators need to know this.

2. We can conveniently take gas from the TEV header using the EVCL control loop controlled through ACNET. The loop is on ACNET page "F8", House "DA", loop 10. D-Zero obtained approval from the Beams division (Jay Theilacker) and central helium liquifier (CHL, x 4191) prior to doing this.

3. Valve EVXJT leaks through slightly when closed. It was zeroed, but still leaks enough such that if the heat exchanger is at operating pressures, 265 psig and EVXBY is closed, and the wet expansion engine is off, the gas will leak past EVXJT and into the LHe dewar. This will cause the LHe dewar to experience higher than necessary boil-off rate. The solution is to open EVXBY when in such an operating state.

4. The LN2 subcooler/ GHe heat exchanger fill valve, PV-2713-N leaks a little bit even after zeroing. This is only a problem if there is no load on the subcooler. It can cause the subcooler to overfill, which is indicated by about 13.1" on LI-2726-N. At this level, any excess liquid nitrogen will go out the vent line and soon vaporize. The top plate of the subcooler will also become cold enough to condense water and drip.

5. A large 8" butterfly valve, MV-491-H, which isolates D-Zero from the TEV suction header leaks through a little. [Actually at the start of our run the valve was discovered to be a half notch from fully closed. We lost about half a tube trailer to the TEV before finding the problem.] Even in the fully closed position is suspected that some leakage occurs if D-Zero's system pressure is much different than the TEV's. The TEV was operating around 1.4 psig, so we put our operating suction pressure just below it so we didn't lose inventory.

6. Acnet is pretty awkward to use. We learned that since our training lesson one now needs to first go to the 'Utilities' page and 'enable' the console before Acnet will allow changes. It takes some practice to get the right sequencing of entering data and clicking in the proper spots to get Acnet to do what you want.

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7. We discovered that the wet expansion engine we have is one of the few ones at the lab that does not have it's pressure transducer ports moved to a less vulnerable (to grease clogging) location. It is noted that modified engines have bolted on lids. Ours is still the welded lid variety.

8. The suction header main relief valve (2" x 3" AGCO series 93) originally leaked under vacuum. A check valve on the pilot sensing line alleviated that problem. A tee and valve was also added to allow us to remotely apply pressure to the pilot. It was then discovered that the main valve leaked when in service at inlet pressures under 1 psig. It was bench tested and confirmed to leak below 0.9 psig. The main valve seat o-ring looked fine but was replaced. The valve then leaked below 0.4 psig. The manufacturer could not offer an explanation of the leaks and suggested providing 2 to 3 psig of source gas to the pilot dome through the remote sensing line. That extra pressure in the dome would increase the sealing force on the main valve's o-ring. The final solution to the problem was to add a light spring in the dome of the main valve. Calculations were done to assure the spring did not defeat the valve. It was field tested in place and was found to relieve at 6.3 psig.

Improvements to be made

1. The most serious improvement that needs to be made is the re-routing of the heat exchanger's gaseous nitrogen exhaust line to a less restrictive vent path. The current configuration was an oversight on my part. It can be changed without much effort. The problem was discovered by observations that the LN2 supply pressure downstream of the heat exchanger's control valve got quite high. I saw it up to 30 psig at times (PT-2708-N). The exiting vent line from the heat exchanger is a non-vacuum jacketed 1 1/2" pipe size. The mistake was to reduce this into a 1/2" pipe size and combine it with the nitrogen return flow from the solenoid and VLPC transfer lines. The combined flow must pass through an equivalent of about 40 feet of 1/2" pipe before it is expanded back to 1 1/2" pipe size. At a maximum flow of 70 gph from the heat exchanger, this section of pipe is calculated to develop 14 psid. The solution is to cut and then extend the 1 1/2" non-vacuum jacketed piping about 30 feet and tee it into the existing 1" pipe size non-vacuum jacketed vent tie in. The 1" pipe size flow path is a few feet long at which point it expands to 1 1/2" inside the vacuum jacketed vent.

2. The line leading to the pressure transducer on the wet expansion engine is clogged. It is the cylinder on the east side. It needs to be blown out or in by the engine group.

3. The intake VPT on the dry expansion engine has a leak in it. The external tubing was leak checked before the commissioning test and no leaks were found. It was bled down to atmosphere before the test began.

4. The pressure transducers for the hydrogen VPT's need to be changed out to the absolute type. The VPT's give useful temperature indications at less than gage pressure. The transmitters that were originally installed were 0 to 100 psig.

5. The arc cell sampling line from the LHe storage dewar seems to have a contamination problem. The arc cell reading which should be negligible,

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reads high, on the order of 40 ppm N2. The reading drops if the flow rate through the sample line is increased using the purge line that is in parallel with the analyzer to take the excess flow.

6. Many of the threaded piping connections on the tube trailer fill station leak and need to be re-made with epoxy. On this panel only, many of the threaded connections were made up with a red colored hydraulic fitting type sealant. At the time of make up the joints that leaked (detected with snoop) were re-made and tested tight. Over time, and with pressure, snoop detectable leaks have been discovered. The quantity of sealant also appears to be less than what was originally installed.

7. It is very easy to frost up the warm helium and nitrogen exhaust piping on the heat exchanger. The drip trays under these pipes don't extend far enough to catch all the condensing/melting water. The water from these pipes can fall on several flow transmitters, DOFSTOR, FT-2040-H, DOFX1HP. These transmitters stopped working when they got wet. They probably need to be sent back to Hastings for repair.

8. I would like to add Cernox temperature sensors to u-tubes of the dry and wet expansion engines. The temperature indications from the VPT's are questionable. This addition will allow us to better understand how the engines are operating. By observing these temperatures during a long operating run, we will be able to foresee engine problems before they get obvious.

9. I would like to add a platinum temperature sensor in the nitrogen return vent line. a convenient place will be where the heat exchanger vent currently ties into the vent. This location is a low spot, trap so to speak that will accumulate liquid should the nitrogen control be poor. The information from this sensor will be useful in conjunction with the temperature control points on the solenoid and VLPC systems.

10. We have plans to put a heater in the liquid helium storage dewar. This has many benefits. It will give an easy way to keep the refrigerator in a steady state operating mode under changes in liquification and refrigeration requirements. It will also give an indication of our refrigerator's excess capacity in the form of power draw of the heater. A notable decrease in the heater power could indicate a developing problem with the refrigerator during a long operating run.

11. Ideally D-Zero would like to have a dedicated helium purifier. If this is not realized, D-Zero can share the existing RD/Cryo mobile purifer with CDF, and beamlines. The documentation for either purifier (flow schematic, procedures) needs to be gathered and kept at D-Zero.

• REFRIGERATION & LIQUIFICATION TEST:

1ST DEWAR FILL: 6/10 → 6/11   6/11/97 0:00   300 LITERS
                                    6/11/97 08:00   1200 LITERS

$$P_{DEW} = 6.2 \text{ PSIG} = 0.144 \text{ MPa}$$

$$\Delta \dot{V}_{LIQUID} = 112.50 \frac{\text{LITERS}}{\text{HR.}}$$

$$\rho_{LIQ} = 116.8 \frac{kg}{m^3} \qquad \rho_{gas} = 24.09 \frac{kg}{m^3}$$

$$\dot{m}_{\substack{VAPOR \\ RETURNED \\ TO HX}} = 24.09 \frac{kg}{m^3} \left(112.5 \frac{\text{LITERS}}{\text{HR}}\right)\left(\frac{1 m^3}{1000 L}\right)\left(\frac{1000 g}{1 kg}\right)\left(\frac{Hr}{3600 s}\right)$$

$$= 0.75281 \frac{g}{s} + \dot{m}_{\substack{WET \text{ inlet} \\ VAPOR}}$$

$$M_1 = \left[(300 \text{ LITER})(116.8 \frac{kg}{m^3}) + (3000 \text{ LITERS})(24.09 \frac{kg}{m^3})\right]\left[\frac{1 m^3}{1000 L}\right] = 107.310 \text{ kg}$$

$$M_2 = \left[(1200 L)(116.8) + (2100)(24.09 \frac{kg}{m^3})\right]\left(\frac{1}{1000}\right) = 190.749 \text{ kg}$$

$$\Delta\dot{M}_{TOTAL} = \frac{190.749 \text{ kg} - 107.310 \text{ kg}}{(8 \text{ HRS})(3600 \text{ s/HR})} \times \frac{1000 g}{1 kg} = 2.89719 \frac{g}{s} \quad \substack{AVG. \text{ OF MASS} \\ -RATE \text{ OF INCREASE IN} \\ DEWAR}$$

$$\dot{m}_{\substack{LIQUID \\ NET}} = \left(112.5 \frac{L}{hr}\right)\left(116.8 \frac{kg}{m^3}\right)\left(\frac{1 m^3}{1000 L}\right)\left(\frac{1000 g}{1 kg}\right)\left(\frac{1 hr}{3600 s}\right) = 3.65 \frac{g}{s}$$

$$\dot{m}_{IN} = ? \ (9.0k, 500 \text{ RPM}) \ X_{OUT} = .86 \text{ FROM CHART} \rightarrow \dot{m}_{IN} = 26 \frac{g}{s} \checkmark$$

REFRIGERATION:

$$Q = \dot{m}_{\substack{VAPOR \\ RETURNED}} \Delta h_{fg}$$

$$Q = (.75281 \frac{g}{s})(30.28 - 12.2 \frac{J}{g})$$

$$\underline{Q = 13.61 \text{ WATTS}}$$

TRUE LIQUIFICATION:
$$R = \left(2.89719 \frac{g}{s}\right)\left(\frac{1}{116.8 \frac{kg}{m^3}}\right)\left(\frac{1 kg}{1000 g}\right)\left(\frac{1000 L}{1 m^3}\right)\left(\frac{3600 s}{hr}\right)$$

$$R = 89.30 \ L/HR$$

$$\boxed{\text{DATA PT.} = 89.30 \ L/HR + 136 \text{ WATTS.}}$$

$$X_{\substack{WET \\ OUT}} = \frac{m_g}{m_{TOTAL}} = \frac{0.75281 \frac{g}{s} - 0.14026 \frac{g}{s}}{3.650 \frac{g}{s}} = 0.16782$$

FROM DEWAR HT. LEAK

⑧

LHe MAKE RATE #2

6/18/97   14:20:00   LHe DEWAR LEVEL = 2148.7
                           * WET ENGINE INLET TEMP = 9.1 K , 5.50 RPM
                           *DRY ENGINE INLET = 35 K , 1400 RPM
                           * DRY OUT = 23 K
            14:49:00   2218 LIQUID LITERS
                           * LHe DEWAR PRESSURE = 5.5 PSIG
                           * DISCHARGE PRESSURE = 265   EXIT 3 HP.

        * CONSTANT .

$$\frac{\Delta V}{t} = \frac{69.3 \, L}{29 \, MIN} \times \frac{60 \, MIN}{1 \, HR} = 143.38 \, ^L/_{HR}$$

$P = 0.14 \, MPa$, $T_{SAT} = 4.584 \, K$

$\rho_\ell = 116.8 \, ^{Kg}/_{M^3}$ $\rho_V = 24.09 \, ^{Kg}/_{M^3}$

$$M_1 = \left[(2148.7 \, LITERS)\left(116.8 \, \frac{Kg}{M^3}\right) + (1151.3 \, LITERS)\left(24.09 \, \frac{Kg}{M^3}\right)\right]\left[\frac{1 \, M^3}{1000 \, L}\right]$$

$M_1 = 278.703 \, Kg$

$$M_2 = \left[(2218 \, LITERS)(116.8) + (1082)(24.09)\right]\left[\frac{1}{1000}\right] = 285.128 \, Kg$$

$$\Delta \dot{M}_{TOTAL} = \frac{285.128 \, Kg - 278.703 \, Kg}{(29 \, MIN) \, 60 \, ^S/_{MIN}} \times \frac{1000 \, g}{Kg} = 3.6924 \, ^g/_S$$

LIQUIFICATION :

$$R = 3.6924 \, ^g/_S \left(\frac{1}{116.8 \frac{Kg}{M^3}}\right)\left(\frac{1 \, Kg}{1000 \, g}\right)\left(\frac{1000 \, L}{1 \, M^3}\right)\left(\frac{3600 \, S}{1 \, HR}\right)$$

$$\boxed{R = 113.8 \, ^L/_{HR}}$$

REFRIGERATION :

$$\dot{m}_{RETURNED} = 24.09 \, \frac{Kg}{M^3} \left(143.38 \frac{L}{HR}\right)\left(\frac{1 \, M^3}{1000 \, L}\right)\left(\frac{1000 \, g}{1 \, Kg}\right)\frac{1 \, HR}{3600 \, S}$$

$$\dot{m}_{RETURNED} = 0.95945 \, ^g/_S + \dot{m}_{VAPOR \, WET \, OUT}$$

$$Q = \dot{m}_{RETURN} \Delta h_{fg} = .95945 \, ^g/_S \left(30.28 \frac{J}{g} - 12.2 \frac{J}{g}\right)$$

$$\boxed{Q = 17.35 \, WATTS}$$

D-ZERO HEAT-EXCHANGER AND LHE DEWAR

2:38:28 PM
6/18/97
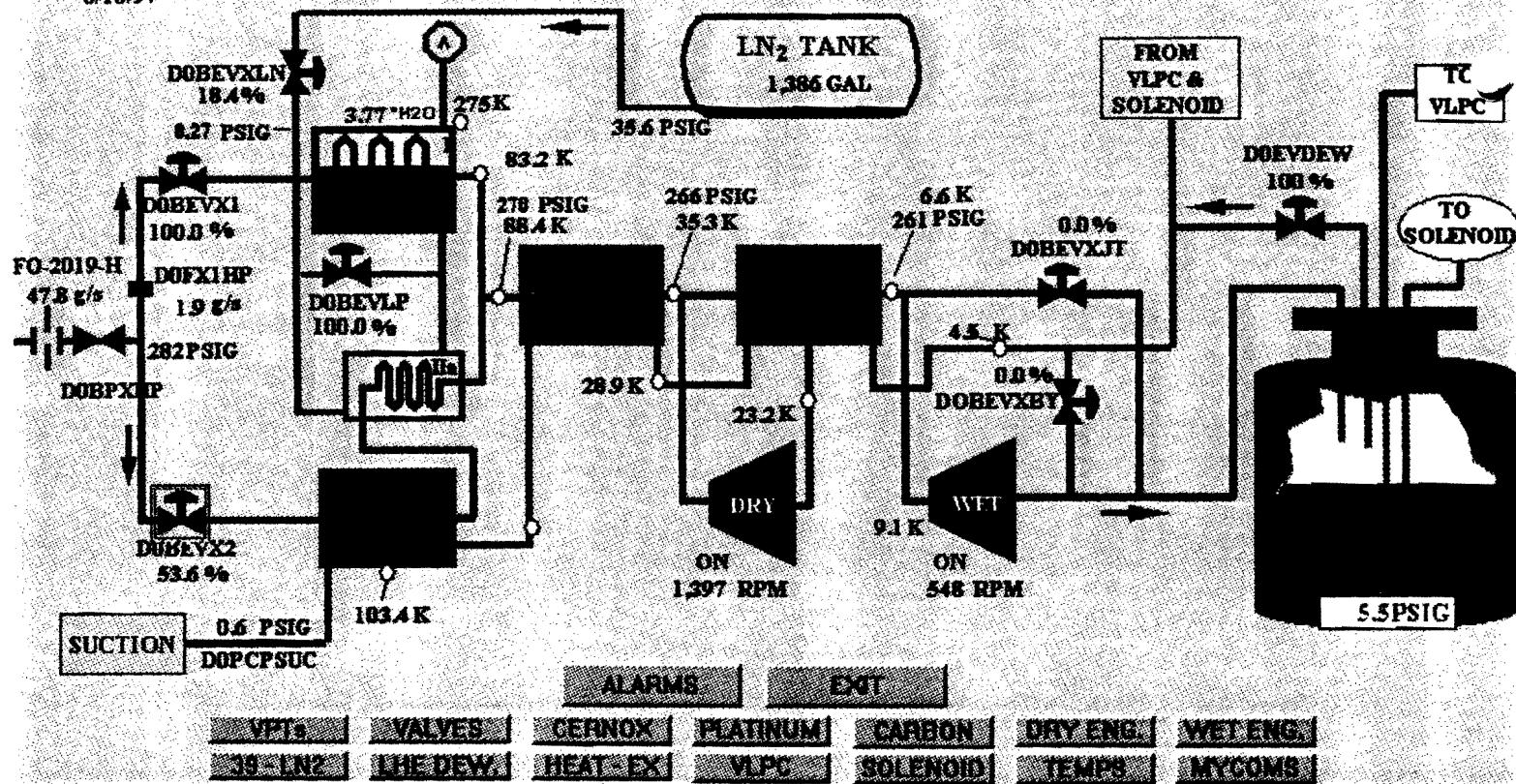
MAXIMUM LIQUIFICATION TEST   6/18/97

$$\frac{\Delta V}{dt} = 143.4 \ ^L/_{HR}$$

TRUE LIQUIFICATION = 113.8 $^L/_{HR}$

R. RUCINSKI
6/19/97

(10)

28.8 $\frac{L_{iq}L}{hr}$ = 1 $^g/_s$

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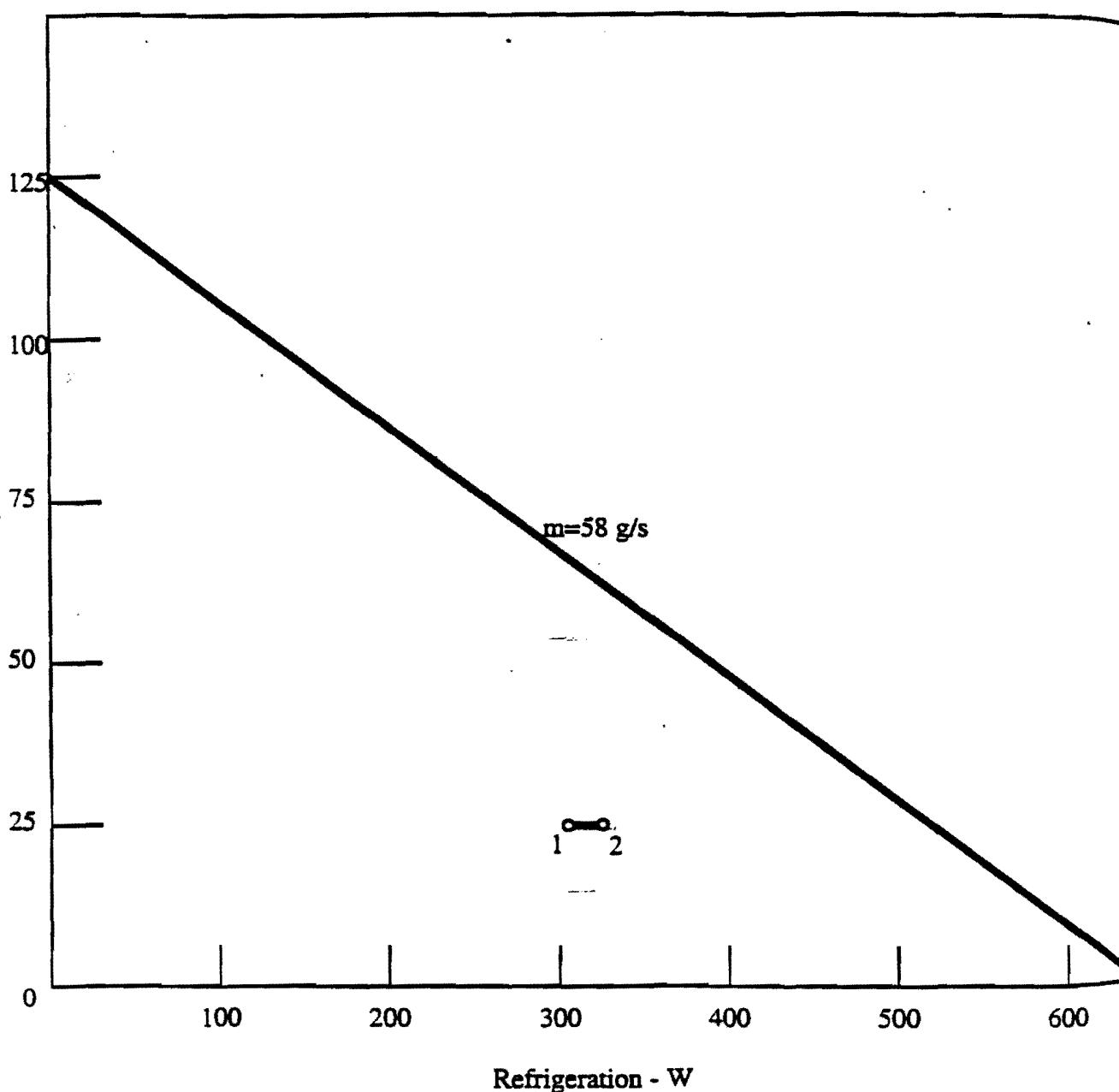
Refrigeration - W

Figure 7.3:   Capacity of star refrigerator and (1) identified steady state heat load, (2) max. expected charging heat load

(11)

DATA FROM   6/13/97

$$\Delta V_{LIQ.} = \frac{1047 \text{ LITERS} - 1017 \text{ LITERS}}{6.5 \text{ HRS}}$$

P = 9.8 PSIG
  = 0.1689 MPa
USE P = 0.17 MPa

$$\Delta V_{LIQUID.} = 4.61538 \frac{\text{LITERS}}{\text{HR}}$$

ROUGHLY:

$$Q = \dot{m} \Delta h_{fg}$$

V_{GAS}

V_L

PI
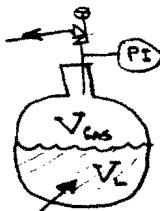
$V_{TOTAL} = 3300 \text{ LITERS}.$

Q

$$\dot{m} = 4.61538 \frac{\text{LITERS}}{\text{HR}} \times 109.4 \frac{\text{Kg}}{m^3} \times \frac{1 m^3}{1000 L} \times \frac{1000 g}{1 kg} \times \frac{1 \text{ HR}}{3600 s} = 0.14026 \text{ }^g/_s$$

$$h_{fg} = h_g - h_f = 29.295 \text{ }^J/_g - 14.025 \text{ }^J/_g = 15.27 \text{ }^J/_g$$

$$Q = (0.14026 \text{ }^g/_s)(15.27 \text{ }^J/_g) = \underline{2.14 \text{ W}}$$

MODEL AS FORMAL UNIFORM STATE, UNIFORM FLOW PROCESS (USUF)

1ˢᵗ LAW:

$$m_1 \left(u + \frac{v^2}{2} + gz\right)_1 + \Sigma m_i \left(h + \frac{v^2}{2} + gz\right)_i + Q_{cv} + W_{cv} =$$
$$= m_2 \left(u + \frac{v^2}{2} + gz\right)_2 + \Sigma m_e \left(h + \frac{v^2}{2} + gz\right)_e$$

$$m_1 \atop GAS = V_{GAS_1} \cdot \rho_g = \left(3300 \text{ LITERS} - 1047 \text{ LITERS}\right)\left(31.29 \frac{Kg}{m^3}\right) \times \frac{1 m^3}{1000 L} = 70.4964 \text{ kg}$$

$$m_1 \atop LIQ. = (1047 \text{ LITERS})\left(109.4 \frac{Kg}{m^3}\right) \times \frac{1 m^3}{1000 L} = 114.5418 \text{ kg}$$

$$U_{gas} = 23.845 \text{ }^J/_g$$

$$U_{LIQ.} = 12.47 \text{ }^J/_g$$

ASSUMPTIONS: NEGLECT V^2 TERMS, Z TERMS — SMALL (SHOULD BE)
ASSUME DEWAR MASS DOES NOT CHANGE TEMPERATURE
OR ENERGY CONTENT.

$$W_{cv} = 0 \quad, \quad m_i = 0 \quad \therefore \quad m_e = m_1 - m_2$$

$$m_2 \atop GAS = (3300 - 1017)(31.29)\left(\frac{1}{1000}\right) = 71.43507 \text{ kg}$$

$$m_2 \atop LIQ = (1017 \text{ LITER})(109.4)\left(\frac{1}{1000}\right) = 111.2598 \text{ kg}$$

$$m_e = m_1 - m_2 = \left(70.4964 + 114.5418 \text{ kg}\right) - \left(71.43507 + 111.2598\right)$$
$$= 2.3433 \text{ kg}$$

SUBST. INTO 1ST LAW.

$$Q_{CV} = m_2 U_2 + \Sigma m_e h_e - m_1 U_1.$$

$$Q_{CV} = \underset{GAS}{m_2 U_2} + \underset{LIQ.}{m_2 U_2} + \underset{GAS}{m_e h} - \underset{GAS}{m_1 U_1} - \underset{LIQ.}{m_1 U_1}$$

NOTE: $\underset{GAS}{U_1} = \underset{GAS}{U_2} \qquad \underset{LIQ}{U_1} = \underset{LIQ.}{U_2}$

$$Q_{CV} = U_{GAS}\left(\underset{GAS}{m_2} - \underset{GAS}{m_1}\right) + U_{LIQ}\left(\underset{LIQ.}{m_2} - \underset{LIQ.}{m_1}\right) + \underset{GAS}{m_e h}$$

$$Q_{CV} = \left\{ 23.845 \tfrac{J}{g} \left(71.43507 \text{kg} - 70.4964 \text{ kg}\right) + 12.47 \tfrac{J}{g} \left(111.2598 - 114.5418 \text{kg}\right) \right.$$

$$\left. + 2.3433 \text{kg}\left(29.295 \tfrac{J}{g}\right)\right\} \times \frac{1000 g}{1 kg}$$

$$Q_{CV} = 50,103.0 \quad \text{JOULES}$$

$$\dot{Q} = \frac{50,103.0 \text{ JOULES}}{6.5 \text{ HRS}} \times \frac{1 \text{ HR}}{3600 s} = \underline{2.14 \text{ WATTS}}$$

ADDITIONAL HEAT LEAK TEST, BOIL OFF

DATA: 6/18/97   21:00   1913 LITERS
        6/19/97   6:00   1853 LITERS

$$P = 5.5 \text{ PSIG} \approx 0.14 \text{ MPa}$$

$$\Delta V_{LIQ} = \frac{60 \text{ LITERS}}{9 \text{ HOURS}} = 6.67 \text{ L/HR}.$$

$$\dot{m} = 6.67 \tfrac{L}{HR} \times 116.8 \tfrac{KG}{M^3} \times \frac{1 M^3}{1000 L} \times \frac{1000 g}{1 KG} \times \frac{1 HR}{3600 s} = 0.2164 \tfrac{g}{s}$$

$$Q = \dot{m} \Delta h = \left(.2164 \tfrac{g}{s}\right)\left[30.28 \tfrac{J}{g} - 12.20 \tfrac{J}{g}\right]$$

$$Q = \underline{\underline{3.913 \text{ W}}}$$

SHOULD EXPECT MORE
HEAT LEAK @ FULLER,
HIGHER LIQUID LEVEL.

% PER DAY: $\dfrac{6.67 \text{ L/HR} \times 24 \text{ HRS}}{1883 \text{ LITERS}} \times 100 = \boxed{8.5 \%}$ ⑬

$\dfrac{4.6154 \text{ L/HR} \times 24}{1022 L} \times 100 = \boxed{10.8 \%}$

LHe HEAT LEAK DATA

1:28
1047 LITERS
9.8 PSIG

7:58
1017 LITERS
9.8 PSIG

——	D0_CCRS2::. .D0BPDEW.F_CV Helium Dewar Pressure Transmitter	9.8	
——	D0_CCRS2::D0_CCRS2:D0BPSTORH.F_CV GHe storage vessel pressure	74.3	
——	D0_CCRS2::D0_CCRS2:LHE-VOL.F_CV LHe Dewar volume based on diff. pressure 1,012		

Axis values:
12.0 / 80.0 / 1,200
11.0 / 77.5 / 1,150
10.0 / 75.0 / 1,100
9.0 / 72.5 / 1,050
8.0 / 70.0 / 1,000

X-axis:
21:00:00 6/12/97
23:24:07 6/12/97
01:48:15 6/13/97
04:12:23 6/13/97
06:36:31 6/13/97
09:00:38 6/13/97

(14)

iFFLE CALC

DESIGN
LHe DEWAR LID

<DESIGN>
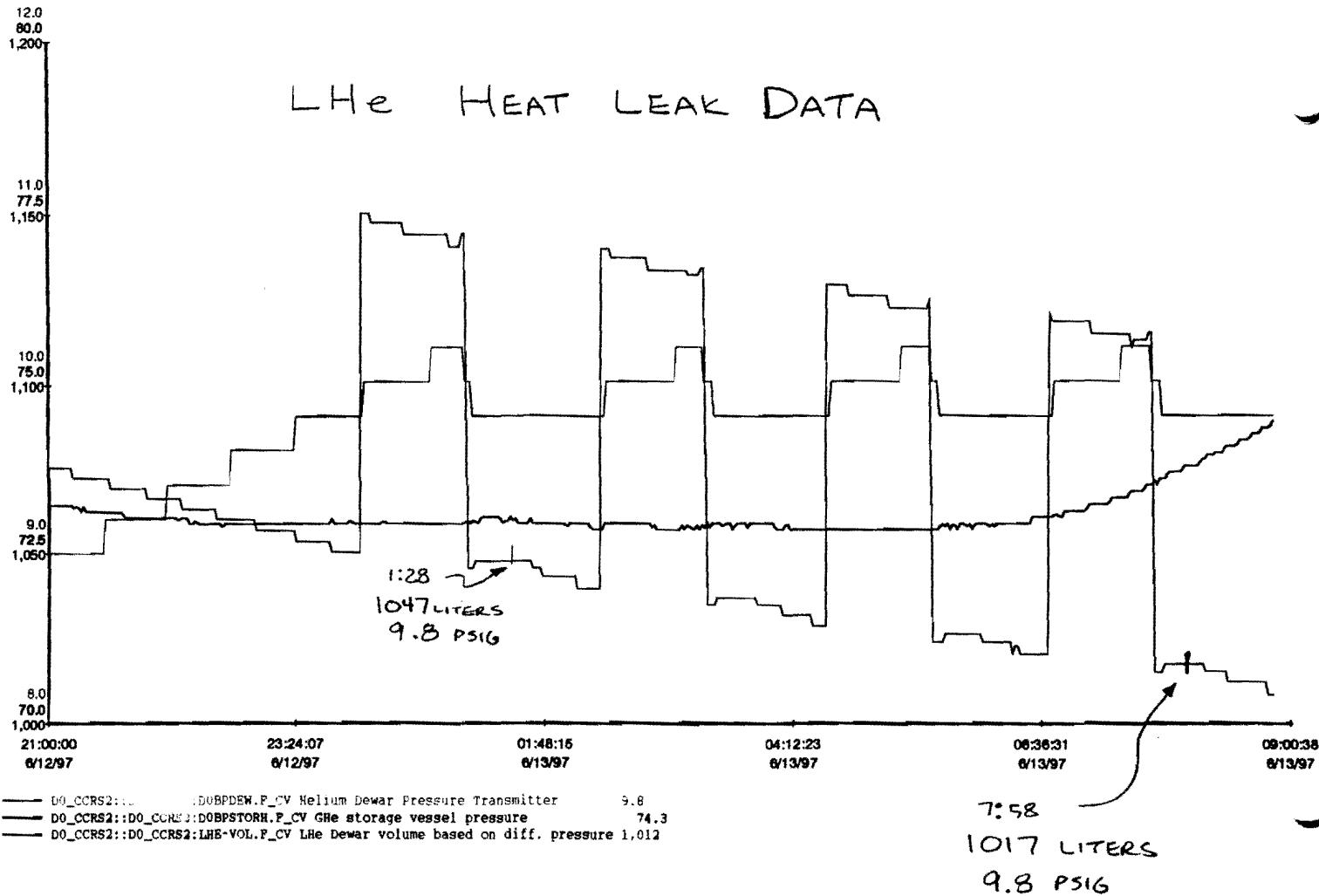
LHe DEWAR HEAT
LEAK CALCS.   R. RUCINSKI 8/28/96   ①

LHe LID : CONDUCTION CONTRIBUTIONS

$$4 \times 1\tfrac{3}{8}" \text{OD} \times .035 = 4(.15119 \text{ in}^2) = .60476 \text{ in}^2$$

$$2 \times \tfrac{3}{4}" \text{OD} \times .035 = 2(.08247 \text{ in}^2) = .16493 \text{ in}^2$$

$$2 \times \tfrac{1}{2}" \text{OD} \times .035 = 2(.05498 \text{ in}^2) = .10996 \text{ in}^2$$

$$4 \times \tfrac{1}{4}" \text{-20 THREADED ROD} = 4(.0318 \text{ in}^2) = \underline{.12720 \text{ in}^2}$$

$$1.00685 \text{ in}^2$$

$$\text{THREADED RODS} = \frac{.1272}{1.00685}(100) = \underline{12.6\%}$$

$$\tfrac{1}{4}" \text{OD} \times .035 \rightarrow A = .02364 \text{ in}^2$$

$$Q_{\text{conduction}}^{SS} = \frac{A}{L} \int_{4}^{300} K_{ss}\, dT = \frac{1.00685 \text{ in}^2}{36 \text{ in}} \left(3060 \tfrac{W}{M}\right)\left(\frac{.0254 M}{1 \text{ in.}}\right)$$

$$Q = 2.174 \text{ WATTS}$$

$$Q_{\text{NECK}} = 1.8 \text{ WATTS} @ 5K \text{ TEMP. DEPRESSION.}$$

THREADED RODS NEED TO SUPPORT SAY , 100 #'S EACH
w/o BREAKING.

$$\sigma_u = \frac{P}{A} \qquad A_{\text{REQ'D}} = \frac{100 \text{ #'S}}{80,000 \text{ psi}} = .00125 \text{ in}^2$$

$$\frac{\pi D^2}{4} = A_{\text{REQ'D}} \Rightarrow D = .0399 \text{ in}$$

$$\uparrow$$
VERY SMALL.

SAY 4-40NC

$$A_{\text{STRESS}} = .0060 \text{ in}^2$$

$$\sigma_{\text{yield}} = 35 \text{ ksi} \qquad \underline{P_{\text{YIELD}} = 210 \text{ lbs}}$$

$$A_{\text{RODS}} = 4(.006) = .024 \text{ in}^2 \rightarrow 2.7\% \checkmark$$

$A_{SS \atop TOTAL} = .94325 \text{ in}^2$ ⟵ GO WITH ONLY,, $2 \sim \frac{1}{4} - 20$ THREADED ROD.

$Q_{SS \atop CONDUCTION} = \dfrac{.94325 \text{ in}^2}{48 \text{ in.}} \left(3060 \frac{w}{m} \right) \left(\dfrac{.0254 m}{1 \text{ in}} \right)$

$$= 1.527 \text{ WATTS.}$$

$A_{GHe} = \dfrac{\pi (5.9 \text{ in})^2}{4} - 4 \dfrac{\pi (1.375 \text{ in})^2}{4} - 2(.0318 \text{ in}^2) = 21.337 \text{ in}^2$

$Q_{GHe \atop COND} = \dfrac{21.337 \text{ in}^2}{48 \text{ in}} \left(23 \frac{w}{m} \right) \left(\dfrac{.0254 m}{1 \text{ in}} \right) = \underline{.26 \, w}$

$$Q_{TOTAL} = \underline{1.8 \text{ WATTS}}$$

SOLENOID X-FER LINE,   PV-3035-N = 35%

PV-3062-H = 25%

PT 3006-H = 1.7 PSIG

6/19 - 6/20   RUNNING LINE $ LN_2

INLET TEMP. = ~~24~~ 7.5 K   TR 3027-H   7:17   6/20

OUTLET TEMP = ~~18~~ 19 K.

LHe LEVEL = 737 L @ 7:17 $\frac{116 L}{7 HRS} = 16.57$ L/HR

853 L @ 0:17

DEWAR PRESS = 5.9   DØ EVDEW CLOSED ≈ 1.7 HRS @ A TIME
THEN SWINGS OPEN, MAX. 35.5 %

LN_2 USAGE   8:45   7831 GALLONS

3:00   7977 GALLON

8:00   7855 GALLON $\frac{122 GALLONS}{5 HRS} = 24.4$ GPH

PURIFIER ON LINE USING 20 ~ 24 GPH.
NO CONCLUSIVE DATA FOR N_2 HEAT LOAD.

HEAT LEAK CALC.

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

$$\dot{m}_{MAX} = 16.57 \text{ L/HR} \times 116.8 \frac{kg}{m^3} \times \frac{1000 g}{1 kg} \times \frac{1 m^3}{1000 L} \times \frac{1 HR}{3600 s} = 0.5376 \text{ g/s}$$

* NOTE: THIS IS CONSERVATIVELY HIGH SINCE SOME OF THIS
FLOW WENT OUT EVDEW.

$$\dot{m}_{\substack{TO\ REPLACE \\ LIQUID \\ IN\ DEWAR}} = 16.57 \text{ L/HR} \times 24.09 \frac{kg}{m^3} \times \frac{1}{3600} = 0.11088 \text{ g/s}$$

$$Q = (0.5376 - .11088 \text{ g/s}) \left[113.10 \text{ J/g} - 50.66 \text{ J/g} \right]$$

$$Q = 26.65 \text{ WATTS} \quad *MAXIMUM$$

QUICK ESTIMATE WAS 18 WATTS   ⑰

SO REASONABLE.

CONSIDERING DEWAR HEAT LEAK @ 4.6 L/HR → $\dot{m}_{\substack{XFER \\ LINE}} = 12 \text{ L/HR} = 0.3893 \text{ g/s}$

$$Q_{EST} = 0.3893 \text{ g/s} \left[113.10 \text{ J/g} - 50.66 \text{ J/g} \right] = \boxed{24.3 \text{ WATTS}}$$

→ REQ'D HEAT LOAD IN SOLENOID LHe SUPPLY U-TUBE HE-320-H UP TO TR3027-H?

$$\dot{m} = 0.3893 \, g/s$$

$$h_{INLET} = h_{f_{DEWAR}} = 12.20 \, J/g$$

$$h_{\emptyset \atop 3027-H} = 50.66 \, J/g$$
$$= 7.5 K$$

$$\omega = 0.3893 \, g/s \left[50.66 \, J/g - 12.20 \, J/g \right] = 14.97 \text{ WATTS}$$

EXCESSIVE, TR3027-H MUST BE READING HIGH.

TOTAL HEAT LEAK, LHe DEWAR TO TR3007-H

$$= 24.3 + 15w = \boxed{39.3 \text{ WATTS}}$$

DISCREPANCY:
WHY WOULD DØEVDEW OPEN IF THE RATE OF LIQUID WITHDRAWAL EXCEEDED BOIL-OFF RATE OF ISOLATED DEWAR? ... DEWAR HEAT LEAK MUST HAVE BEEN HIGHER??....

TR-3007-H ON HELIUM EXIT, T = 19K

LHe DEWAR LEVEL
DROP ≈ 16.6 ℓ/hr.

TR 3027-H ON HELIUM
INLET PIPING, T ≈ 7.5K

EVDEW
VALVE POSITION

00:00:00	01:36:05	03:12:10	04:48:15	06:24:20	08:00:26
6/20/97	6/20/97	6/20/97	6/20/97	6/20/97	6/20/97
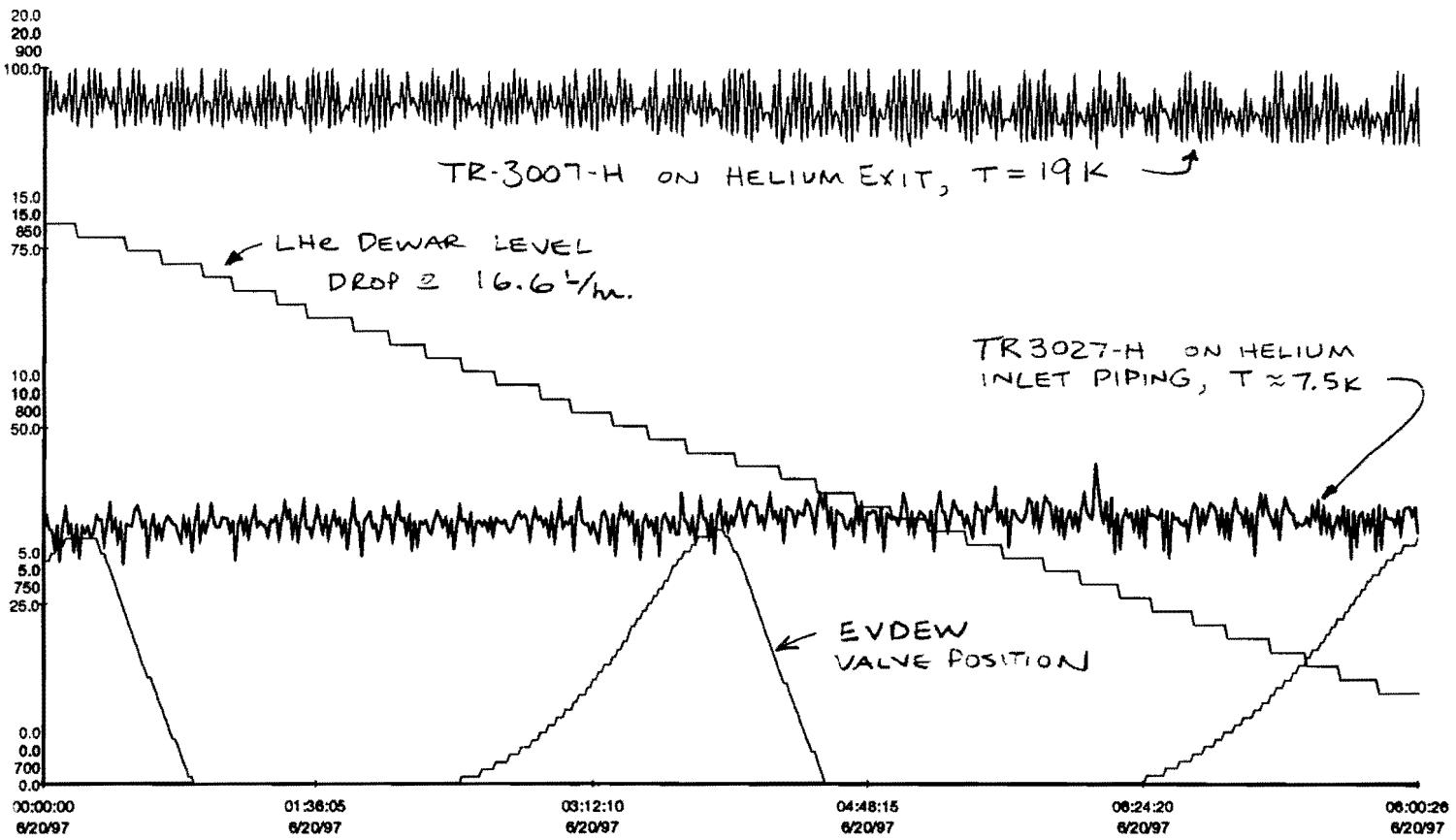
──── D0_CCRS2::D0_CCRS2:TR3007H-T.F_CV Temperature for X02953 (TR-3007-H) RTD   18.1
──── D0_CCRS2::D0_CCRS2:TR3027H-T.F_CV Temperature for X03536 (TR-3027-H) RTD   7.5
──── D0_CCRS2::D0_CCRS2:LHE-VOL.F_CV LHe Dewar volume based on diff. pressure 793
──── D0_CCRS2::D0_CCRS2:D0EVDEW.F_CV Helium Dewar Bypass Return Control Valve 33.4

SOLENOID HELIUM TRANSFER LINE
HEAT LEAK TEST DATA

R. RUCINSKI
6/30/97

⑲

VLPC EAST HE LINE, HEAT LEAK.

DATA FROM 6/18/97 0:00 $\sim$ $\dot{m} = 0.26\,g/s$
THRU 4:00
STEADY STATE   TR-4054-H $= 16.0\,K \pm 4\,K$

AVG. $= \overline{TR-4054-H} = 15.5\,K \pm 0.8\,k$

$P_{DEW} = 5.5\,PSIG. = 0.14\,MPa$

$h_f = 12.20\,J/g$

$$\begin{array}{ll} T = 16.5 & h = 99.8 \\ 14.5 & h = 89.2 \end{array}$$

$h_{out} = 94.532\,J/g$ (T = 15.5K, P = .14MPa)

$Q = \dot{m}\,\Delta h = \left[\, 0.26\,g/s \right]\left[94.53 - 12.20 \right]$

$Q = \underline{\underline{21.4\,WATTS}}$

ESTIMATED HEAT LOAD $= 20\,WATTS$

$\rightarrow$ IN GOOD AGREEMENT!

	20.0
	0.29
	17.5
	0.28
	15.0
	0.27
	12.5
	0.26
	10.0
	0.25

| 00:00:00 | 00:48:02 | 01:36:05 | 02:24:07 | 03:12:10 | 04:00:13 |
| 6/18/97 | 6/18/97 | 6/18/97 | 6/18/97 | 6/18/97 | 6/18/97 |

MASS FLOW
THRU VENTURI
$\dot{m} = 0.26\ ^{3}/_{S}$

HE EXIT GAS
TEMPERATURE
$T_{AVG.} = 15.5$ KELVIN

DO_CCRS2::DO_CCRS2:TR4054H-T.F_CV Temperature for X03537 (TR-4054-H) RTD   14.9

DO_CCRS2::DO_CCRS2:PT4052-H-G.F_CV Integer Mass flow rate   0.26
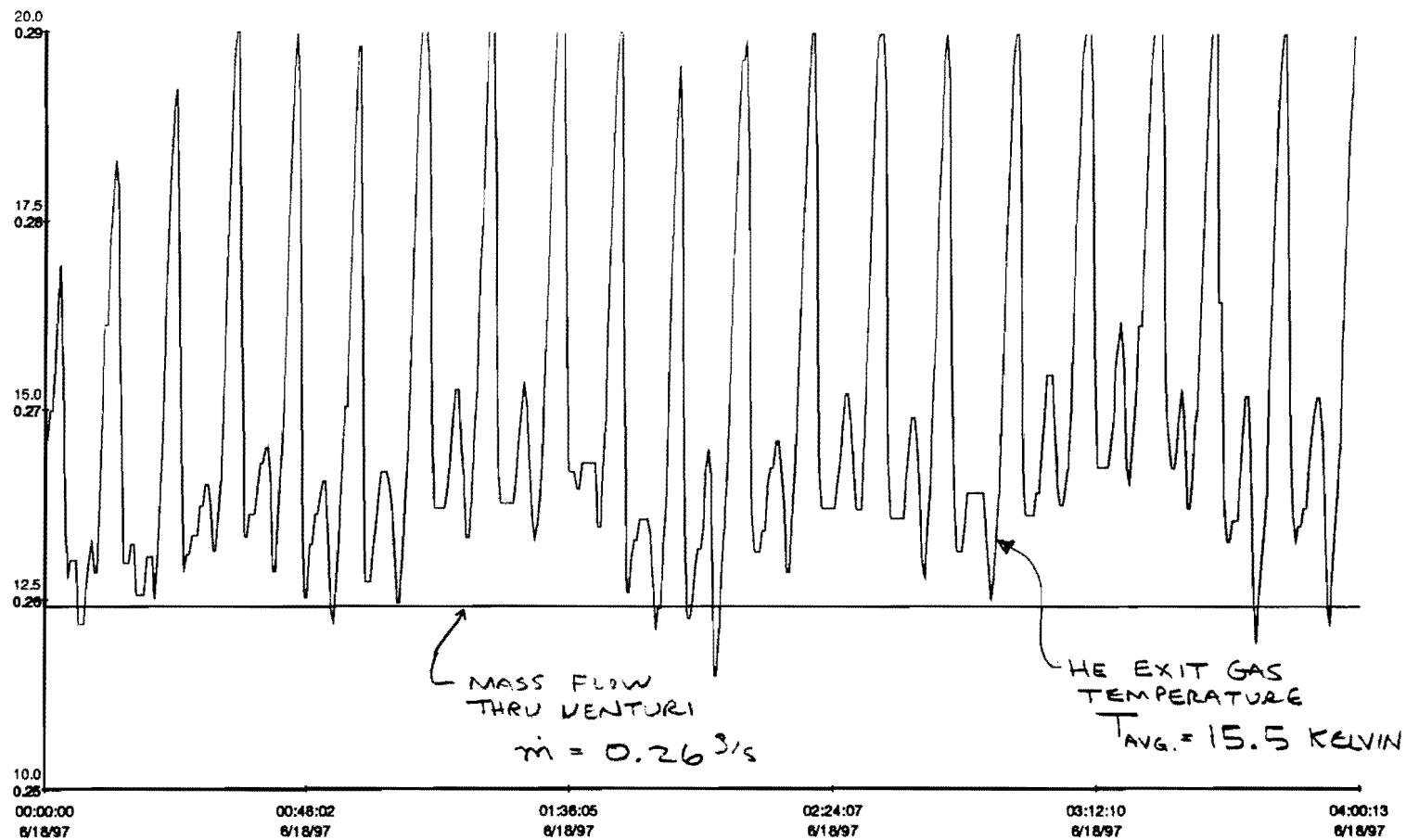
VLPC EAST HELIUM TRANSFER LINE

HEAT LEAK TEST DATA

R. RUCINSKI
6/30/97

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SUBJECT	NAME
TRANSFER LINE HEAT LOAD ESTIMATES	Russ Rucinski
	DATE 6/13/97 REVISION DATE

ESTIMATE X-FER LINE LOADS w/ w/o SHIELD.

SOLENOID X-FER LINE: 3 VALVES, 3 U-TUBES, 150 FT. X-FER LINE

$$\text{w/o } LN_2 \quad 3 \text{ WATTS}, \quad \overset{15}{\cancel{12}}\text{W}, \quad +5 \text{ WATTS}$$

$$\text{w/ } LN_2 \quad 1.5 \text{ WATTS}, \quad \overset{15}{\cancel{12}}\text{W}, \quad 1.5 \text{ WATT}$$

VLPC X-FER LINE: 3 VALVES, 3 U-TUBES, 300 FT X-FER LINE
× 2 LINES

$$\text{w/o } LN_2 \quad 6 \text{ WATTS}, \quad 30 \text{ WATTS}, \quad 60 \text{ WATTS}$$

$$\text{w/ } LN_2 \quad 3 \text{ WATTS}, \quad 30 \text{ WATTS}, \quad 6 \text{ WATTS}.$$

	w/o LN_2	w/ LN_2
SOL.	33 W	18 W
VLPC	96 WATTS	39 WATTS.
	129 WATT	57 WATTS.

INSIGNIFICANT HEAT LOAD.
SKIP w/o LN_2 SHIELD TEST.

HOW MUCH LHe NEEDED w/ LN_2 ≈ 57 WATTS

· 80 $^4/_{HR}$ ROUGHLY

FRI, SAT., SUN, MON.

15 HRS 24 24 8 → 72 HRS 5746 LITERS?

LHe DEWAR WILL GO EMPTY.

VLPC ~ 28 WATTS

4 TURNS ON

$$h_{fg} =$$
$$10 \text{ PSI}$$

(22)

$$Q = \dot{m} \Delta h \quad \text{LET } T_{out} = 10 K$$
$$h_{in} = 13.43 \, ^J/_g \quad h_{out} = 65.5 \, ^J/_g$$

$$\dot{m} = \frac{28 \, ^J/_S}{65.5 - 13.43 \, ^J/_g} = 0.54 \, ^g/_S$$

LN$_2$ CONSUMPTION RATES

MOBILE PURIFIER ALONE: 6/11/97 17:00   4363 GALLONS
                        6/12/97 9:00   3974 GALLONS

$$\frac{389 \text{ GALLONS}}{16 \text{ HRS.}} = \boxed{24.3125 \text{ GPH}} = 0.4052 \text{ GPM}$$

PURIFIER + STAR + SUBCOOLER: 6/10/97 20:00   5166 GALLONS
   ↳ S.S. LIQUIFICATION MODE   6/11/97 8:00   4668 GALLONS

$$\frac{498 \text{ GALLONS}}{12 \text{ HRS}} = \boxed{41.50 \text{ GPH}} = 0.6917 \text{ GPM}$$

MOBILE PURIFIER ALONE: 6/12/97 17:00   7770 GALLONS
                     6/13/97 5:00   7563 GALLONS

$$\frac{207 \text{ GALLONS}}{12 \text{ HRS}} = \boxed{17.25 \text{ GPH}} = 0.2875 \text{ GPM}$$

MOBILE PURIFIER + STAR + SUBCOOLER   6/16/97 19:30   4834 GALLONS
   ↳ STEADY STATE LIQUIF. MODE   6/17 9:30   3548 GALLONS

NO! EVX2 CLOSED TOO FAR, HTX1 WORKING TOO HARD. STAR NOT IN GOOD RUNNING MODE

$$\frac{1286 \text{ GALLONS}}{14 \text{ HRS}} = \boxed{91.86 \text{ GPH}} = 1.53 \text{ GPM}$$

MOBILE PURIFIER + STAR + SUBCOOLER   6/15/97 10:00   6087 GALLON
   ↳ LN$_2$ TEMP. HOLDING   6/16/97 10:00   5572 GALLONS

$$\frac{515 \text{ GALLONS}}{24 \text{ HRS}} = \boxed{21.46 \text{ GPH}} = 0.3576 \text{ GPM}$$

AVG.   MOBILE PURIFIER ≈ 20 GPH

SUBCOOLER   ≈ 1 TO 3 GPH

STAR   20 GPH TO 64 GPH

㉓

FLOW RATE OF GN$_2$ & ΔP

- $Q \approx 20$ GPH $\times \dfrac{93.11 \text{ scf}}{1 \text{ GALLON}_{\text{LIQUID}}} \times \dfrac{1 \text{ HR}}{60 \text{ MIN}} = 31.0$ scfm   N$_2$

CV-2710-N , P/N 1016 CHECK VALVE BIVCO

@ 31 scfm , AIR @ 70°F ΔP = < 1.5

LOWEST POINT ON CURVE, ΔP = 1.5 PSI @ 60 scfm AIR

SUBCOOLER PRESSURE   PI-2717-N   = 3 PSI
                        PT 2708-N = 11.3 PSI

ESTIMATE OF SUBCOOLER FLOW;
     SAM SUBCOOL   30 GPH $T_{SAT} = 34$ PSIG
     250 FT. X-FER LINE X .1 $^W/_{FT}$ $-T = 80$ K SUBCOOLED
          25 WATTS DEWAR TO SUBCOOLER.

SAM 3 ATM
        $T_{SAT} = 88.077$ K $h_F = -98.938 \, ^J/_g$
                                     $h_g = 84.167 \, ^J/_g$
        $T = 80$ K $h_{sc} = -115.815 \, ^J/_g$

$\dot{m} = 30 \dfrac{\text{GALLONS}}{\text{HR}} \times \dfrac{3060 \text{ g}}{\text{GALLON LIQ.}} \times \dfrac{1 \text{ HR}}{3600 \text{ s}} = 25.5 \, ^g/_s$

$h_{IN} = -98.938 \, ^J/_g + 25 \frac{J}{s} \times \left(\dfrac{1}{25.5 \, ^g/_s}\right) = -97.96 \, ^J/_g$

$Q_{SUBCOOL} = 25.5 \, ^g/_s \left[-115.815 - (-97.96 \, ^J/_g) \right]$

$Q_{SUBCOOL} = -455.4$ WATTS

$\dot{m}_{REQ'D} = \dfrac{455.4 \, ^J/_s}{78.415 \, ^J/_g - (-97.96)} = 2.58 \, ^g/_s$

                 $\hookrightarrow$ 1.2 ATM h_g

$$\boxed{\approx 3 \text{ gph}}$$

LN$_2$ CONSUMPTION;

6/18/97   10:29:34   1662.1 GALLONS $> \dfrac{344.5 \text{ GALLONS}}{5.5 \text{ HRS}}$
           15:59:13   1317.6 GALLONS

MAX. LIQUIF. TESTS. $\underline{62.6 \text{ GPH}}$

STAR + MOBILE PURIFIER + SUBCOOLER.

$$62.6 - \overset{\text{MOBILE PURIFIER}}{20} = \underline{42.6 \text{ GPH}}$$

$$\underline{- 2.6 \approx \text{ SUBCOOLER}}$$

$$40. \text{ GPH } - \text{ STAR.}$$

6/17   14:32:25   3394.1 GALLONS $> \dfrac{1732 \text{ GALLONS}}{20 \text{ HOURS}}$
6/18/97 10:29:34   1662.1 GALLONS

$$= \underline{86.6 \text{ GPH}}$$

$$\begin{array}{r} 86.6 \\ - \ 2.6 \\ \underline{20} \\ \boxed{64 \text{ GPH.}} \ \text{STAR} \end{array}$$

FERMILAB
ENGINEERING NOTE
RD/DØ | HE REFRIG. | SOLEN.

PROJECT
LN$_2$ STORAGE REQUIREMENTS (FROM EN-421)

NAME RUSS RUCINSKI
DATE 3-31-95 | REVISION DATE
CHECKED: Todd Leicht 4/4/95

CURRENTLY @ DØ WE HAVE A 20,000 GAL LN$_2$ STORAGE DEWAR THAT FULL CAN HOLD 12,000 GAL. DUE TO SAFETY ISSUES.

EXISTING USAGE: 44 GAL/HR FOR Ar DEWAR, 3 CALORIMETER (STEADY STATE) + BOIL OFF

TIME BUFFER IS $\approx \dfrac{8000 \text{ gal}}{44 \text{ gal/HR}} \times \dfrac{1 \text{ DAY}}{24 \text{ HRS}} \approx 7.6$ DAYS

SOLENOID USE: PER FERMI DESIGN REPORT; 281.1 WATTS

REFRIGERATOR*: COLD & RUNNING   38 LITERS/HR = 10 gal/HR

COOLDOWN 300K TO 90K   23.3 g/s , 105 LITERS/HR

STEADY STATE 65 lb/HR = 9.63 gal/HR

* FROM SATELLITE REFRIGERATOR DESIGN MANUAL.

$$\dot{m}_{\text{SOLENOID}} = \frac{281.1 \text{ WATTS}}{200 \text{ J/g}} = 1.4 \text{ g/s} \qquad \{ \text{BID SPEC MAX ALLOW} = 8 \text{ g/s} \}$$

$$= 1.4 \text{ g/s} \times \frac{1 \text{ kg}}{1000 \text{ g}} \times \frac{.3262 \text{ gal LIQUID}}{1 \text{ kg}} \times \frac{3600 \text{ S}}{1 \text{ HR}} = 1.65 \text{ gal/HR} \quad \text{FOR SOLENOID}$$

VLPC USE:

ESTIMATE HEAT LOAD TO LN$_2$ IS IN SAME RATIO THAT IT IS FOR THE SOLENOID, A FACTOR OF 10.

$$Q_{\text{LN}_2} \approx 10 \times 200 \text{ WATTS} = 2000 \text{ WATTS}$$

$$\dot{m} = \underline{11.74 \text{ gal/HR}}.$$

BETTER ESTIMATE PER TED GASTEYER. PHONE CONVERSATION

$$Q_{\text{LN}_2} = 3000 \text{ WATTS} \quad \text{or} \quad \dot{m}_{\substack{\text{VLPC} \\ \text{LN}_2}} = 17.6 \text{ gal/HR} \quad \boxed{26}$$

FERMILAB
ENGINEERING NOTE

SECTION
RD/DØ

PROJECT
He REFRIGERATIR

2

OBJECT
LN$_2$ STORAGE REQUIREMENTS (FROM EN-421)

NAME
RUSS RUCINSKI

DATE
4-3-95

REVISION DATE

CHECKED: Todd Zeicht 4/4/95

- PURIFIER FOR He STREAM:
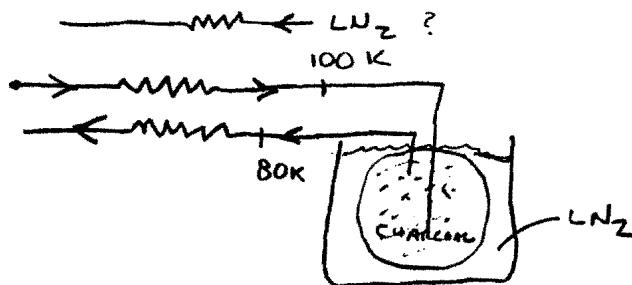
PER RICH SCHMITT, HEAT EXCHANGER IS PRETTY GOOD.
TO FIGURE CONSIDER 100 K GHe IN 80 K GHe OUT, $\dot{m} = 57\ g/s$

PRESSURE = 20 ATM = 2 MPa

$$Q = \dot{m}(h_{in} - h_{out}) = 57\ g/s\ [540.3\ \tfrac{J}{g} - 435.7\ \tfrac{J}{g}]$$

$$= 5962\ WATTS$$

$$Q_{1\ gal/hr} = 1\ \frac{gal}{hr} \times \frac{1\ HR}{3600\ s} \times \frac{6.745\ lbs}{1\ gal} \times \frac{200\ Joules}{1\ gram} \times \frac{1000\ grams}{2.2\ lbs}$$

$$= 170.33\ WATTS\ FROM\ 1\ gal/hr\ OF\ LN_2$$

FOR PURIFIER. $= 35\ gal/hr$

○ TOTAL ADDED LN$_2$ USE:

$$\dot{m}_{TOTAL} = 1.7\ \frac{gal}{hr} + 10\ \frac{gal}{hr} + 17.6\ \frac{gal}{hr} + 35\ \frac{gal}{hr} = 64.3\ \frac{gal}{hr}$$

SOLENOID   REFRIGERATOR VLPC   PURIFIER

(27)

ΔP HX EXIT TO VENT LINE:

$\frac{1}{2}$" SCH. 10 × 40 Ft., FLOW = 70 GPH MAX.

REF. PG. 7 CALCS.

FOR 250 ft 1$\frac{1}{2}$" PIPE, 30 gph, W = 202.35 $^{lb}/_{hr}$

$$Re = 6.31 \frac{W}{d\mu} = 6.31 \frac{(202.35 \; ^{lb}/_{hr})}{(.674 \text{ in})(.0178 \text{ cp})} = 1.064 \times 10^5$$

$$\mu = 178 \text{ MICRO POISES} = 178 \times 10^{-6} \text{ POISES} \times \frac{100 \text{ cp}}{1 \text{ POISE}}$$

$$\mu = .0178 \text{ cp}.$$

$$\Delta P = 3.36 \times 10^{-6} \frac{FLW^2}{\rho d^5}$$

$$= 3.36 \times 10^{-6} \frac{(.026)(40 \text{ ft})(202.35 \; ^{lb}/_{hr})^2}{(.07245 \frac{lb}{ft^3})(.674 \text{ in})^5}$$

$$\boxed{\Delta P = 14.2 \text{ PSI}}$$

RECALCULATE ASSUMING PIPE IS MOVED SO THAT
FLOW MUST TRAVEL THRU 40 FEET OF 1$\frac{1}{2}$" PIPE
& 10 ft 1" PIPE.

$$\Delta P = 3.36 \times 10^{-6} \frac{(202.35 \; ^{lb}/_{hr})^2}{.07245 \frac{lb}{ft^3}} \left[\frac{40 \text{ ft} (.021)}{(1.682)^5} + \frac{10 \text{ ft} (.023)}{(1.097)^5} \right]$$

$$\Delta P = 1.899 \left[0.06239 + .1448 \right]$$

$$= 0.393 \text{ PSI}$$

SOLUTION: MOVE HX GN$_2$ VENT TO 1" TEE
IMMEDIATELY UPSTREAM OF 1$\frac{1}{2}$" VENT
PIPING. LESS ΔP, BETTER
PERFORMANCE ON HX LN$_2$ POT
CONTROL.

(28)

DOBEVXLN
58.7%
27.69 PSIG

A

LN₂ TANK
3,617 GAL.

FR
VLP
SOLE

3.87 "H2O   237K

33.2 PSIG

88.3 K

DOBEVX1
100.0 %

163 PSIG
88.0 K

157 PSIG
33.7 K

6.4 K
154 PSIG

0.0 %
DOBEVXJT

TO-2019-H
35.3 g/s

DOFX1HP
10.0 g/s

272 PSIG

DOBPXHP

DOBEVLP
100.0 %

IIa

28.6 K

21.4 K

4.4 K

0.0 %
DOBEVXBY

DRY
ON
1,400 RPM

WET
ON
565 RPM

8.5 K

DOBEVX2
30.0 %

37.9 K

SUCTION   0.6 PSIG
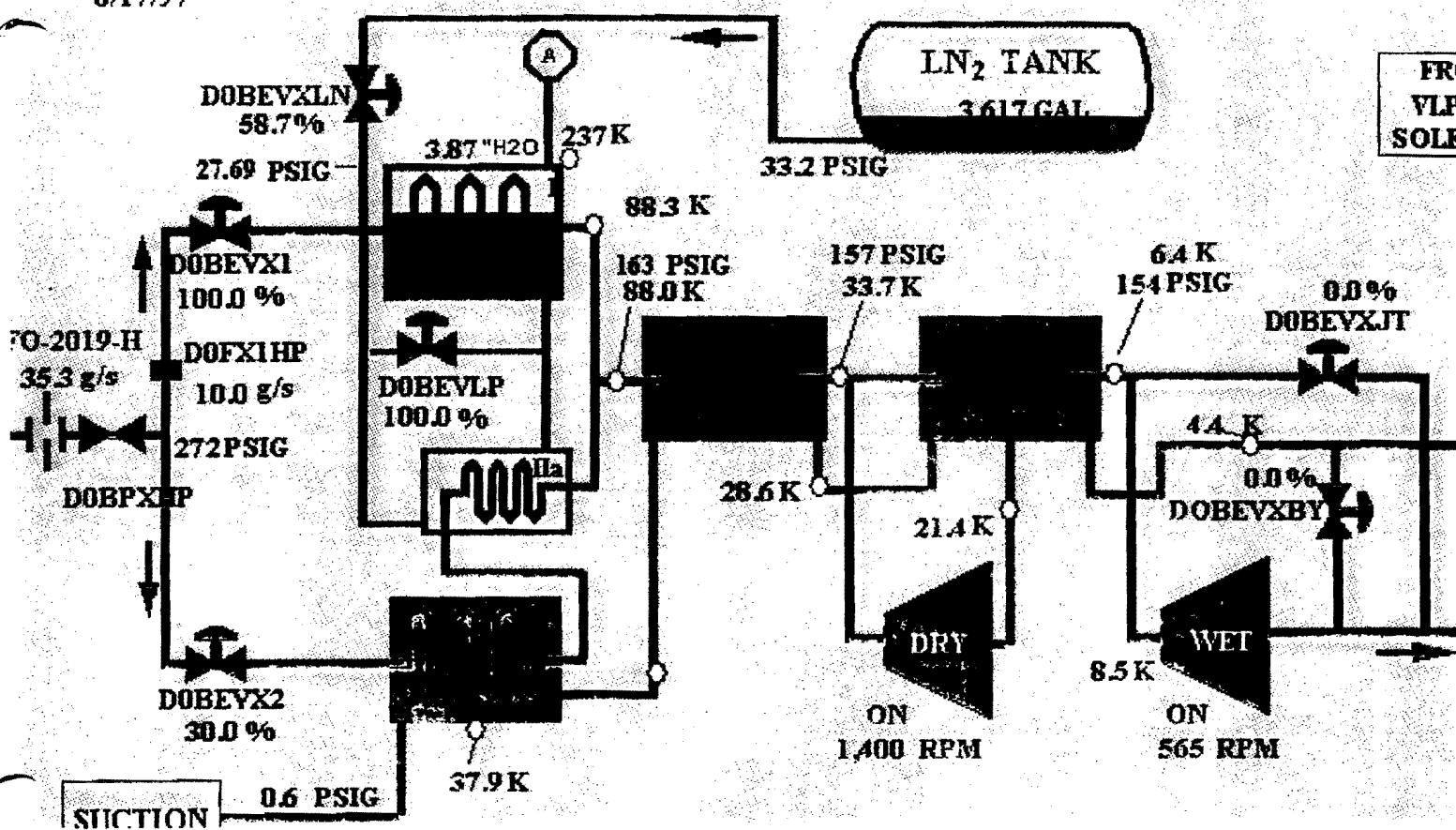
LIQUIFICATION MODE:

NOTE: HX HIGH PRESSURE
TOO LOW DUE TO EVX2
MIN. POSITION = 30%.

CORRECT BY RAISING EVX2 LOW
LIMIT TO 50%.

(29)