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.
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
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.

<table>
<thead>
<tr>
<th>Data used</th>
<th>Liquification + Refrig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very first time</td>
<td>6/11 0:00 thru 8:00</td>
</tr>
<tr>
<td>Optimized</td>
<td>6/18 14:20 thru 14:50</td>
</tr>
<tr>
<td>For comparison:</td>
<td><em>ideal, mdot = 58 g/s</em></td>
</tr>
</tbody>
</table>

**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.

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

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.

<table>
<thead>
<tr>
<th>Line</th>
<th>Measured</th>
<th>Comparison, expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLPC 'east'</td>
<td>21.4 watts</td>
<td>20 watts</td>
</tr>
<tr>
<td>Solenoid</td>
<td>39 watts</td>
<td>18 watts</td>
</tr>
</tbody>
</table>

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.

<table>
<thead>
<tr>
<th>Component</th>
<th>Consumption rate</th>
<th>Expected, from EN-421</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobile purifier</td>
<td>20 gph LN2</td>
<td>35 gph</td>
</tr>
<tr>
<td>STAR, liquification mode</td>
<td>20 to 64 gph LN2</td>
<td>10 gph refriger. mode</td>
</tr>
<tr>
<td>Subcooler</td>
<td>small</td>
<td>1 to 3 gph LN2</td>
</tr>
</tbody>
</table>

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.
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,
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, D0FX1HP. 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 liquefaction 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 purifier with CDF, and beamlines. The documentation for either purifier (flow schematic, procedures) needs to be gathered and kept at D-Zero.
STAR PERFORMANCE

R. Rucinski 6/16/97
Rev. 0/18/85

Refrigeration & Liquidification Tests:

1st Dewar Fill: 6/10 ⇒ 6/11 0:00 300 liters 0/11/97 08:00 1200 liters

\[ P_{Dew} = 6.2 \text{ psig} = 0.144 \text{ MPa} \]

\[ \Delta V_{\text{Liquid}} = 112.50 \text{ liters/HR} \]

\[ P_{\text{Nitrogen}} = 116.8 \text{ kPa/m}^3 \]

\[ P_{\text{Gas}} = 24.09 \text{ kPa/m}^3 \]

\[ \dot{m}_{\text{Vapor Returned to HX}} = 24.09 \text{ kPa/m}^3 \left( 112.5 \frac{\text{liters}}{\text{HR}} \right) \left( \frac{1 \text{ m}^3}{1000 \text{ liters}} \right) \left( \frac{1000 \text{ g}}{1 \text{ kg}} \right) \left( \frac{1 \text{ HR}}{3600 \text{ s}} \right) \]

\[ = 0.75281 \frac{\text{g}}{\text{s}} + \dot{m}_{\text{Net Vapor}} \]

\[ M_1 = \left[ (300 \text{ liters}) \left( 116.8 \frac{\text{kg}}{\text{m}^3} \right) + (3600 \text{ liters}) \left( 24.09 \frac{\text{kg}}{\text{m}^3} \right) \right] \left( \frac{1 \text{ m}^3}{1000 \text{ liters}} \right) = 107.310 \text{ kg} \]

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

\[ \frac{\Delta M_{\text{Total}}}{\text{Total}} = \frac{190.749 \text{ kg} - 107.310 \text{ kg}}{(190.749 \text{ kg})} \times 1000 \text{ g} = 2.89719 \frac{\text{g}}{\text{s}} \text{ INCREASING RATE OF MASS DECREASE IN DEWAR} \]

\[ \dot{m}_{\text{Liquid Net}} = \left( 112.5 \frac{\text{liters}}{\text{HR}} \right) \left( 116.8 \frac{\text{kg}}{\text{m}^3} \right) \left( \frac{1 \text{ m}^3}{1000 \text{ liters}} \right) \left( \frac{1000 \text{ g}}{1 \text{ kg}} \right) \left( \frac{1 \text{ HR}}{3600 \text{ s}} \right) = 3.65 \frac{\text{g}}{\text{s}} \]

\[ \dot{m}_{\text{In}} = 0.96 \text{ FROM CONTROL} \Rightarrow \dot{m}_{\text{In}} = 26 \frac{\text{g}}{\text{s}} \text{ Penrose} \]

Refrigeration:

\[ Q = \frac{\dot{m}_{\text{Vapor Returned}}}{\Delta h_{\text{v}}} \]

\[ Q = (0.75281 \frac{\text{g}}{\text{s}}) (30.28 - 12.2 \frac{\text{kJ}}{\text{g}}) \]

\[ Q = 13.61 \text{ WATTS} \]

True Liquefaction:

\[ R = \left( 2.89719 \frac{\text{g}}{\text{s}} \right) \left( \frac{1}{116.8 \frac{\text{kg}}{\text{m}^3}} \right) \left( \frac{1 \text{ kg}}{1000 \text{ g}} \right) \left( \frac{1000 \text{ liters}}{1 \text{ m}^3} \right) \left( \frac{3600 \text{ s}}{1 \text{ HR}} \right) \]

\[ R = 89.30 \frac{\text{L}}{\text{HR}} \]

DATA PT. = 89.30 \frac{\text{L}}{\text{HR}} + 13.6 \text{ WATTS}.

\[ X_{\text{Net}} = \frac{m_3}{m_{\text{Total}}} = 0.75281 \frac{\text{g}}{\text{s}} - 0.1402 \frac{\text{g}}{\text{s}} \text{ FROM DEWAR, AT LEAST} \]

\[ \text{TOTAL} = \frac{3.650 \frac{\text{g}}{\text{s}}}{0.16782} \text{ } \]
STAR PERFORMANCE

LHe MAKE RATE = 2

0/18/97 14:20:00

LHe DEWAR LEVEL = 2148.7
* WET ENGINE INLET TEMP = 9.1 K, 550 RPM
* DRY ENGINE INLET = 35 K, 1400 RPM
* DRY OUT = 23 K
* 2218 LIQUID LITERS
* LHe DEWAR PRESSURE = 5.5 PSIG
* DISCHARGE PRESSURE = 265 EXIT 3 HP.

* CONSTANT:

\[ \frac{\Delta V}{t} = \frac{69.3 \text{ L}}{29 \text{ min}} \times \frac{60 \text{ min}}{1 \text{ HR}} = 143.38 \text{ L/HR} \]

\[ P = 0.14 \text{ MPa}, \quad T_{\text{SAT}} = 4.584 \text{ K} \]

\[ S_1 = 116.8 \text{ Kg/m}^3, \quad \rho_1 = 24.09 \text{ Kgs/m}^3 \]

\[ M_1 = \left( 2148.7 \text{ LITERS} \right) \left( 116.8 \text{ Kgs/m}^3 \right) + \left( 1151.3 \text{ LITERS} \right) \left( 24.09 \text{ Kgs/m}^3 \right) \left( \frac{1\text{ m}^3}{1000 \text{ L}} \right) \]

\[ M_1 = 278.703 \text{ Kg} \]

\[ M_2 = \left( 2218 \text{ LITERS} \right) \left( 116.8 \text{ Kgs/m}^3 \right) + \left( 1082 \times 24.09 \text{ Kgs/m}^3 \right) \]

\[ \left( \frac{1}{1000} \right) = 285.128 \text{ Kg} \]

\[ \Delta M_{\text{TOTAL}} = \frac{285.128 \text{ Kg} \cdot 788.703 \text{ Kg}}{(29 \text{ min}) \left( \frac{60 \text{ min}}{1 \text{ HR}} \right) \left( \frac{1000 \text{ g}}{1 \text{ Kg}} \right)} = 3.6924 \frac{\text{ g}}{\text{ g}} \]

LIQUIFICATION:

\[ R = 3.6924 \frac{\text{ g}}{\text{ g}} \left( \frac{1}{116.8 \text{ Kgs/m}^3} \right) \left( \frac{1000 \text{ L}}{1 \text{ m}^3} \right) \left( \frac{360.05}{1 \text{ HR}} \right) \]

\[ R = 113.8 \text{ L/HR} \]

REFRIGERATION:

\[ \dot{m}_{\text{RETURNED}} = 24.09 \text{ Kgs/m}^3 \left( 143.38 \frac{\text{ L}}{\text{ HR}} \right) \left( \frac{1 \text{ m}^3}{1000 \text{ L}} \right) \left( \frac{1000 \text{ g}}{1 \text{ Kg}} \right) \frac{7 \text{ HR}}{3600 \text{ s}} \]

\[ \dot{m}_{\text{RETURNED}} = 0.95945 \frac{\text{ g}}{\text{ HR}} + \dot{m}_{\text{VAPOR \ WET OUT}} \]

\[ Q = \dot{m}_{\text{RETURNED}} \Delta h = 0.95945 \frac{\text{ g}}{\text{ HR}} \left( 30.28 \frac{\text{ g}}{\text{ HR}} \right) \]

\[ Q = 17.35 \text{ WATTS} \]
MAXIMUM LIQUIFICATION TEST 6/18/97

\[ \frac{\Delta V}{dt} = 143.4 \text{ L/HR} \]

TRUE LIQUIFICATION = 113.8 L/HR

R. Rucinski
6/19/97
Figure 7.3: Capacity of star refrigerator and (1) identified steady state heat load, (2) max. expected charging heat load

Figure 8.1: An existing vacuum heat utility head, vacuum heat purging. It will be used.

8.1 Get

VACUUM HEAT PURGING

8.2 Int

A simplified cleanup and solenoid operations would be used. The pump speed of 500 rpm is calculated, and the lowest vacuum is obtained in the cryostat. The vacuum head is mounted between the lowest vacuum layer insulator and the cryostat. The vacuum will be recycled if necessary.
**LHe Dewar Heat Leak**

**Measured**

<table>
<thead>
<tr>
<th>DATA FROM 6/13/97</th>
<th>1047 LITERS - 1017 LITERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta V_{\text{GR}} = \frac{1047 \text{ LITERS} - 1017 \text{ LITERS}}{6.5 \text{ HRS}} )</td>
<td>( \Delta V_{\text{Liq}} = \frac{4.61538 \text{ LITERS}}{\text{HR}} )</td>
</tr>
</tbody>
</table>

\[ Q = m \Delta h_{f_0} \]

\[ V_{\text{total}} = 3300 \text{ LITERS}. \]

\[ \dot{m} = 4.61538 \frac{\text{LITERS}}{\text{HR}} \times 109.4 \frac{\text{Kg}}{\text{m}^3} \times \frac{1 \text{m}^3}{1000 \text{L}} \times \frac{1000 \text{Kg} \cdot \text{S}}{1 \text{m}^3} = 0.14026 \frac{\text{Kg}}{\text{S}} \]

\[ h_{f_0} = h_f - h_i = 29.295 \frac{1}{3} - 14.025 \frac{1}{3} = 15.27 \frac{1}{3} \]

\[ Q = (0.14026 \frac{\text{Kg}}{\text{S}})(15.27 \frac{1}{3}) = 2.14 \text{ W} \]

**Model as Normal Uniform State, Uniform Flow Process (USUF)**

**1st LAW**

\[ m_{1} (U + \frac{V^2}{2} + gZ)_{1} + \int m_{1} (U + \frac{V^2}{2} + gZ) = m_{2} (U + \frac{V^2}{2} + gZ) + \int m_{e} (U + \frac{V^2}{2} + gZ) \]

\[ m_{1} = V_{\text{GR}} \cdot \rho_{1} = (3300 \text{ LITERS} - 1047 \text{ LITERS})(31.29 \frac{\text{Kg}}{\text{m}^3}) \times \frac{1 \text{m}^3}{1000 \text{L}} = 70.4964 \text{ Kg} \]

\[ m_{1, \text{Liq}} = (1047 \text{ LITERS})(109.4 \frac{\text{Kg}}{\text{m}^3}) \times \frac{1 \text{m}^3}{1000 \text{L}} = 114.5418 \text{ Kg} \]

\[ U_{\text{gas}} = 23.845 \frac{1}{3} \]

\[ U_{\text{Liq}} = 12.47 \frac{1}{3} \]

**Assumptions:**

- Neglect \( V^2 \) Term
- \( Z \) Terms - Small
- Assume Dewar Mass Does Not Change Temperature or Energy Content

\[ W_{CV} = 0 \Rightarrow m_{i} = 0 \Rightarrow m_{e} = m_{1} - m_{2} \]

\[ m_{2, \text{gas}} = (3300 - 1017)(31.29)(\frac{1}{1000}) = 71.43507 \text{ Kg} \]

\[ m_{2, \text{Liq}} = (1017 \text{ LITERS})(109.4)(\frac{1}{1000}) = 111.2598 \text{ Kg} \]

\[ m_{e} = m_{1} - m_{2} = (70.4964 + 114.5418) - (71.43507 + 111.2598) = 2.3433 \text{ Kg} \]
Q_{cv} = m_2 u_2 + 2m_1 h_0 - m_1 u_1.

Q_{cv} = \frac{m_2 u_2 + m_2 u_2 + m_1 h_{\text{gas}} - m_1 u_1 - m_1 u_1}{\text{gas gas liq liq}}.

Note: \( U_1 = U_2 \text{ gas} \quad U_1 = U_2 \text{ liq} \).

Q_{cv} = \frac{U_{\text{gas}} (m_2 - m_1) + U_{\text{liq}} (m_2 - m_1) + m_1 h_{\text{gas}}}{\text{gas liq liq}}.

Q_{cv} = \left( 23.845 \frac{\text{J}}{\text{g}} (71.43507 \text{ kg} - 70.4964 \text{ kg}) + 12.47 \frac{\text{J}}{\text{g}} (111.2598 - 114.5418 \text{ kg}) \right) \times \frac{1000 \text{ g}}{1 \text{ kg}}

Q_{cv} = 50,103.0 \text{ J (Joules)}

\frac{Q}{6.5 \text{ J}} \times \frac{1 \text{ hr}}{3600 \text{s}} = 2.14 \text{ Watts}

---

Additional heat leak test, boil off

Data: 6/18/97 21:00 19.13 liters
6/19/97 6:00 18.53 liters
P = 5.5 P31G = 0.14 MPa

\[ \Delta V_{\text{liq}} = \frac{600 \text{ liters}}{9 \text{ hours}} = 6.67 \frac{\text{liters}}{\text{hr}}. \]

\[ \dot{m} = 6.67 \frac{\text{liters}}{\text{hr}} \times 116.8 \frac{\text{kg}}{\text{M}^3} \times \frac{1 \text{m}^3}{1000 \text{L}} \times \frac{1000 \text{g}}{1 \text{kg}} \times \frac{1 \text{hr}}{3600 \text{s}} = 0.2164 \frac{\text{g}}{\text{s}}. \]

\[ Q = \dot{m} h = (2.164 \frac{\text{g}}{\text{s}}) \left[ 30.28 \frac{\text{J}}{\text{g}} - 12.20 \frac{\text{J}}{\text{g}} \right]. \]

\[ Q = 3.913 \text{ W} \]

\% per day:

\[ \frac{0.67 \frac{\text{liters}}{\text{hr}} \times 24 \text{ hrs}}{1883 \text{ liters}} \times 100 = 8.5\%. \]

\[ \frac{4.154 \frac{\text{liters}}{\text{hr}} \times 24 \text{ hrs}}{1022 \text{ liters}} \times 100 = 10.8\%. \]
LHe HEAT LEAK DATA

1047 LITERS
9.8 PSI

1017 LITERS
9.8 PSI

1:28

DO_CCRS1: DO_BDEN.P_CV Helium Dewar Pressure Transmitter
DO_CCRS1: DO_CCRS1:DO_BDEN.P_CV Helium storage vessel pressure
DO_CCRS1: DO_CCRS1:LHS_VOL.P_CV Dewar volume based on diff. pressure 1.013
LHE Lid: Conduction Contributions

\[ 4 \times 1 \frac{3}{8}'' \times 0.035 = 4 \left( \frac{0.15119 \text{ in}^2}{\text{in}} \right) = 0.60476 \text{ in}^2 \]
\[ 2 \times 3 \frac{3}{8}'' \times 0.035 = 2 \left( \frac{0.08247 \text{ in}^2}{\text{in}} \right) = 0.16493 \text{ in}^2 \]
\[ 2 \times \frac{1}{2}'' \times 0.035 = 2 \left( \frac{0.05498 \text{ in}^2}{\text{in}} \right) = 0.10996 \text{ in}^2 \]
\[ 4 \times \frac{1}{4}'' \text{-20 threaded rod} = 4 \left( \frac{0.0318 \text{ in}^2}{\text{in}} \right) = 0.12720 \text{ in}^2 \]

\[ \text{Threaded Rods} = \frac{0.1272}{1.00685} = 0.02364 \text{ in}^2 \]

\[ \frac{4''}{0.035} \rightarrow A = 0.02364 \text{ in}^2 \]

\[ Q_{\text{conduction}} = \frac{A}{L} \int_{-\frac{L}{2}}^{\frac{L}{2}} K_{c7} dT = \frac{0.00685 \text{ in}^2}{36 \text{ in}} \left( \frac{36 \text{ in}}{1 \text{ in}} \right) \left( \frac{0.02364 \text{ in}^2}{1 \text{ in}} \right) \]

\[ Q = 2.174 \text{ watts} \]

\[ Q_{\text{neck}} = 1.8 \text{ watts} \text{ at 5 K temp. depression} \]

Threaded Rods need to support say, 100 psi's each w/o breaking.

\[ G_u = \frac{P}{A} \quad A_{\text{req'd}} = \frac{-100 \text{ psi's}}{80,000 \text{ psi}} = 0.00125 \text{ in}^2 \]

\[ \frac{\pi D^2}{4} = A_{\text{req'd}} \Rightarrow D = 0.0399 \text{ in} \]

Say 4-40NC

\[ A_{\text{stress}} = 0.0060 \text{ in}^2 \]
\[ G_{\text{yield}} = 35 \text{ ksi} \quad P_{\text{yield}} = 210 \text{ lbs} \]
\[ A_{\text{rads}} = 4 \left( 0.006 \right) = 0.024 \text{ in}^2 \rightarrow 2.7\% \checkmark \]


\[ \text{Ass}_{\text{TOTAL}} = 943.25 \text{ in}^2 \times 2^\frac{3}{4} - 20 \text{ threaded ROO.} \]

\[ Q_{\text{ss convetion}} = \frac{943.25 \text{ in}^2}{48 \text{ in.}} \times (3.060 \frac{\text{W}}{\text{in}^2})(0.0254 \text{ m}) \]

\[ = 1.527 \text{ Watts.} \]

\[ A_{\text{str}} = \frac{\pi (5.9 \text{ in.})^2}{4} - 4 \frac{\pi (1.375 \text{ in.})^2}{4} - 2(0.0318 \text{ in}^2) = 21.337 \text{ in}^2 \]

\[ Q_{\text{line cond}} = \frac{21.337 \text{ in}^2}{48 \text{ in.}} \times (23 \frac{\text{W}}{\text{in}^2})(0.0254 \text{ m}) = 0.26 \text{ W} \]

\[ Q_{\text{TOTAL}} = 1.8 \text{ Watts} \]
Solenoid X-Fer line

6/19 - 6/20 Running line & LN2
INLET TEMP. = 94 K TR 3021 H 7:17 6/20
OUTLET TEMP. = 19 K
LINE LEVEL = 737 L @ 7:17
853 L @ 0:17
Dewar Press = 5.9
Dp Evapor Closed x 1.7 hrs @ a time
then swings open, max 35.3 %

LN2 Usage
8:45 7631 gallons
3:00 7977 gallons
8:00 7855 gallons
\[ \frac{122 \text{ gallons}}{5 \text{ hrs}} = 24.4 \text{ GPH} \]

PURIFIER ON LINE USING 20 - 24 GPH.
NO CONCLUSIVE DATA FOR N2 HEAT LOAD.

HEAT LEAK CALC.
\[ Q = \dot{m} \Delta h \]
\[ \dot{m}_{\text{MAX}} = 16.57 \frac{\text{L/Hr}}{} \times 116.8 \frac{\text{kg}}{\text{m}^3} \times \frac{1000 \text{L}}{1000 \text{kg}} \times \frac{1 \text{m}^3}{1000} \times \frac{1 \text{hr}}{3600 \text{s}} = 0.5376 \text{g/s} \]

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

\[ \dot{m}_{\text{to replace}} = 16.57 \frac{\text{L/Hr}}{} \times 24.09 \frac{\text{kg}}{\text{m}^3} \times \frac{1}{3000} = 0.011088 \text{g/s} \]

\[ Q = (0.5376 - 0.011088) \left[ 113.1 \frac{1}{2} - 50.66 \frac{1}{2} \right] \]
\[ Q = 26.65 \text{ WATTS} \] MAXIMUM

QUICK ESTIMATE WAS 18 WATTS
SO REASONABLE.

CONSIDERING DEWAR HEAT LEAK @ 4.6 L/HR \[ \dot{m} = 1.2 \frac{\text{L/Hr}}{} = 0.3893 \text{g/s} \]
\[ Q_{\text{est}} = 0.3893 \text{g/s} \left[ 113.1 \frac{1}{2} - 50.66 \frac{1}{2} \right] = 24.3 \text{ WATTS} \]
REO'D HEAT LOAD IN SOLENOID LHE SUPPLY
U-TUBE HE-320-H UP TO TR3027-H?

\[ \dot{m} = 0.3893 \frac{g}{s} \]

\[ h_{\text{inlet}} = h_{f} = 12.20 \frac{J}{g} \]

\[ h_{3027-H} = 50.66 \frac{J}{g} \]

\[ T = 7.5 \text{K} \]

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

EXCESSIVE, TR3027-H MUST BE READING HIGH-

TOTAL HEAT LEAK, LHE DEWAR TO TR3007-H

\[ = 24.3 + 15 \text{W} = \boxed{39.3 \text{ WATTS}} \]

DISCREPANCY:

WHY WOULD DEUDEL OPEN IF THE RATE OF LIQUID WITHDRAWAL EXCEEDED BOIL-OFF RATE OF ISOLATED DEWAR? ... DEWAR HEAT LEAK MUST HAVE BEEN HIGHER? ...
TR3007-H on helium exit, $T = 19$ K

LHC Dewar Level Drop = 16.0 m

TR3027-H on helium inlet piping, $T = 7.5$ K

EVDew Valve Position

Solenoid Helium Transfer Line
Heat Leak Test Data

R. Rucinski
2/30/97
VLPC EAST HE LINE, HEAT LEAK.

DATA FROM 6/18/97 0:00 - m = 0.26 g/s
THRU 4:00 STATION RATE TR-4054-H = 16.0 K ± 4 K
AVERAGE TR-4054-H = 15.5 K ± 0.8 K

P_dew = 5.5 psi g. = 0.14 MPa
h_f = 12.20 J/kg

h_oar = 94.532 J/kg (T=15.5K, P=0.14 MPa)

Q = m Δh = [C - 0.26 g/s] [94.53 - 12.20]
Q = 21.4 WATTS

ESTIMATED HEAT LOAD = 20 WATTS

IN GOOD AGREEMENT!
VLPC EAST HELIUM TRANSFER LINE

HEAT LEAK TEST DATA

R. Rucinski
6/30/97
TRANSFER LINE HEAT LOAD ESTIMATES

ESTIMATE X-FER LINE LOADS W/ W/O SHIELD.

Solenoid x-fer line: 3 valves, 3 u-tubes, 150 ft. x-fer line

<table>
<thead>
<tr>
<th></th>
<th>W/ LN₂</th>
<th>W/O LN₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solenoid</td>
<td>15 W</td>
<td>33 W</td>
</tr>
<tr>
<td>VLPC</td>
<td>39 W</td>
<td>129 W</td>
</tr>
</tbody>
</table>

Insignificant heat load. Skip W/O LN₂ shield test.

How much LN₂ needed W/ LN₂:

> 57 watts

Fri, Sat, Sun, Mon.

15 hrs 24 24 8 = 72 hrs

= 5746 liters?

LHe Dewar will go empty.

VLPC ~ 28 watts

4 turns on:

\( h_{fg} = \frac{120}{10^3} \)

\( Q = m \Delta H \)

\( \text{let } T_{amb} = 10 \text{K} \)

\( h_{H} = 13.43 \frac{\text{J}}{\text{g} \text{K}} \)

\( \text{let } T_{amb} = 65.5 \text{K} \)

\( m = \frac{28.75}{65.5 - 13.43} \times 0.54 \)
**LN2 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:**
- 6/11/97 8:00 4668 gallons
- 6/10/97 20:00 5166 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 (Steady State Liquif. Mode):**
- 6/16/97 19:30 4834 gallons
- 6/17 9:30 3548 gallons

\[ \frac{1286 \text{ gallons}}{14 \text{ hrs}} = \boxed{91.86 \text{ GPH}} = 1.53 \text{ GPM} \]

**No!**
- Evx2 closed too far, HTX1 working too hard, Star not in good running mode.

**Mobile Purifier + Star + Subcooler (LN2 Temp. Holding):**
- 6/15/97 10:00 6087 gallons
- 6/16/97 10:00 5572 gallons

\[ \frac{515 \text{ gallons}}{24 \text{ hrs}} = \boxed{21.46 \text{ GPH}} = 0.3576 \text{ GPM} \]

**Average:**
- Mobile Purifier ≈ 20 GPH
- Subcooler ≈ 1 to 3 GPH
- Star 20 GPH to 64 GPH
FLOW RATE OF \( \text{GN}_2 \) & \( \Delta P \)

- \( Q = 20 \text{ GPH} \times \frac{9.311 \text{ scf}}{1 \text{ gallon liquid}} \times \frac{1 \text{ hr}}{60 \text{ min}} = 31.0 \text{ scfm \ N}_2 \)

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

@ 31 scfm, Air @ 70°F \( \Delta P = \pm 1.5 \)

LOWEST POINT ON CURVE, \( \Delta P = 1.5 \text{ psi} \) 2 GO scfm AIR

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

ESTIMATE OF SUBCOOLER FLOW:
- Sam 3 atm
- Sam subcool 30 GPH
- \( T_{sat} = 34 \text{ psig} \)
- \( T = 80 \text{ K} \)
- \( T_{sat} = 88.077 \text{ K} \)
- \( h_F = -98.938 \frac{\text{j}}{\text{g}} \)
- \( h_g = 84.167 \frac{\text{j}}{\text{g}} \)
- \( h_{sc} = -115.815 \frac{\text{j}}{\text{g}} \)

\( m = 30 \text{ gallons} \times \frac{3060 \text{ g}}{\text{gallon liquid}} \times \frac{1 \text{ hr}}{3600 \text{ s}} = 25.5 \frac{\text{g}}{\text{s}} \)

\( h_{in} = -98.938 \frac{\text{j}}{\text{g}} + 25 \frac{1}{3} \times \left( \frac{1}{25.5 \frac{\text{g}}{\text{s}}} \right) = -97.96 \frac{\text{j}}{\text{g}} \)

\( Q_{\text{subcool}} = 25.5 \frac{\text{g}}{\text{s}} \left[ -115.815 - \left( -97.96 \frac{\text{j}}{\text{g}} \right) \right] \)

\( Q_{\text{subcool}} = -455.4 \text{ watts} \)

\( \dot{m}_{ \text{ref-o}} = \frac{455.4 \frac{\text{j}}{\text{s}}}{78.415 \frac{\text{j}}{\text{g}} - (-97.96)} = 2.58 \frac{\text{g}}{\text{s}} \)

\( \approx 3 \text{ GPH} \)
LN\textsubscript{2} CONSUMPTION;

6/18/97 10:29:34 1662.1 gallons > 344.5 gallons ÷ 5.5 hours

15:59:13 1317.6 gallons

\underline{MAX. LIQUID TESTS.}

\underline{62.6 GPH}

\underline{STAR + MOBILE PURIFIER + SUBCOOLER.}

\underline{62.6 - 20 = 42.6 GPH}

\underline{42.6 ÷ 20 \approx \text{SUBCOOLER}}

\underline{40. GPH - STAR.}

6/17 14:32:25 3394.1 gallons > 1732 gallons ÷ 20 hours

6/18/97 10:29:34 1662.1 gallons

\underline{= 86.6 GPH}

\underline{86.6 - 2.6}

\underline{20}

\underline{64 GPH. STAR}
LN₂ STORAGE REQUIREMENTS

Currently 6 P.W. we have a 20,000 gal LN₂ storage dewar that full can hold 12,000 gal due to safety issues.

Existing usage: 44 gal/hr for 1 Dewar, 3 calorimeter (steady state) + boil off.

Time buffer is \( \frac{8000 \text{ gal} \times 1 \text{ day}}{44 \text{ gal/hr} \times 24 \text{ hrs}} \approx 7.6 \text{ days} \)

Solenoid use: Per Fermilab design report; 281.1 Watts

Refrigerator: Cold & running 38 liters/hr = 10 gal/hr.

Cooldown 300K to 90K 23.3 hrs, 105 liters/hr

Steady state 65 \( \frac{\text{liters/hr}}{44 \text{ gal/hr}} \approx 9.63 \text{ gal/hr} \)

*From satellite refrigerator design manual.

\[
\dot{m} = \frac{281.1 \text{ watts}}{200 \text{ V/g}} = 1.4 \text{ g/s}
\]

\[
= 1.4 \text{ g/s} \times \frac{1 \text{ kg}}{1000 \text{ g}} \times \frac{3262 \text{ gal liquid}}{1 \text{ kg}} \times \frac{3600 \text{ s}}{1 \text{ hr}} = 1.65 \text{ gal/hr}
\]

VLPC use:

Estimate heat load to LN₂ is in same ratio that it is for the solenoid, a factor of 10.

\[
\dot{q}_{\text{LN₂}} = 10 \times 200 \text{ watts} = 2000 \text{ watts}
\]

\[
\dot{m} = 11.74 \text{ g/s}.
\]

Better estimate per Ted Gasteiger phone conversation.

\[
\dot{q}_{\text{LN₂}} = 3000 \text{ watts} \times \frac{\dot{m}}{\text{VLPC LN₂}} = 17.6 \text{ g/s}.
\]
**LN₂ STORAGE REQUIREMENTS**

- **PURIFIER FOR HE STREAM:**
  - LN₂ → 100 K
  - 80 K

  Per Schmitt, heat exchanger is pretty good.
  To figure consider 100 K GHE in 80 K GHE out, \( m = 57.3 \) g/s.

  **Pressure = 20 atm = 2 MPa**

  \[
  Q = m (h_w - h_{out}) = 57.3 \left( 540.3 \frac{J}{g} - 435.7 \frac{J}{g} \right) 
  = 5962 \text{ WATTS}
  \]

  \[
  Q_{\text{gallon}} = 1 \ \frac{\text{gal}}{\text{hr}} \times \frac{1 \ \text{hr}}{3600 \ \text{s}} \times \frac{6.745 \text{ lbs}}{1 \ \text{gal}} \times \frac{200 \ \text{Joules}}{1 \ \text{gallon}} \times \frac{1000 \ \text{grams}}{2.2 \ \text{lbs}} 
  = 170.33 \text{ WATTS FROM 1 gal/hr OF LN₂}
  \]

  **For purifier = 35 gal/hr**

**TOTAL ADDED LN₂ USE:**

\[
\dot{m}_{\text{total}} = 1.7 \ \frac{\text{gal}}{\text{hr}} + 10 \ \frac{\text{g}}{\text{hr}} + 17.6 \ \frac{\text{g}}{\text{hr}} + 35 \ \frac{\text{g}}{\text{hr}} = 64.3 \ \frac{\text{g}}{\text{hr}}
\]
\[ \Delta P \text{ HX EXIT TO VENT LINE:} \]

\[ \frac{1}{2} '' \text{ sec, } 10 \times 40 \text{ ft, } \text{ FLOW } = 70 \text{ GPH max.} \]

Ref. P. 7 calls.

For 250 ft 1/2'' pipe, 30 gph, \( W = 202.35 \text{ lb/m} \)

\[ \text{Re} = \frac{6.31 \frac{W}{dM}}{C} = \frac{6.31 \left(202.35 \text{ lb/m} \right)}{ \left(0.674 \text{ in} \right) \left(0.0178 \text{ cp} \right)} = 1.064 \times 10^5 \]

\( \frac{W}{dM} \). Micro poises... = \( 178 \times 10^{-6} \) poises x \( \frac{100 \text{ cp}}{1 \text{ poise}} \)

\[ \frac{W}{dM} = 0.0178 \text{ cp} \]

\[ \Delta P = 3.36 \times 10^{-6} \frac{\text{FLW}^2}{d^5} \]

\[ = 3.36 \times 10^{-6} \left(0.026\right) \left(40 \text{ ft} \right) \left(202.35 \frac{\text{lb}}{\text{m}} \right)^2 \]

\[ \left(0.07245 \frac{\text{lb}}{\text{ft}^3} \right) \left(0.674 \text{ in} \right)^5 \]

\[ \Delta P = 14.2 \text{ psi} \]

Recalculate assuming pipe is moved so that flow must travel thru 40 feet of 1/2'' pipe.

\[ \Delta P = 3.36 \times 10^{-6} \frac{\left(202.35 \frac{\text{lb}}{\text{m}} \right)^2}{0.07245 \frac{\text{lb}}{\text{ft}^3}} \left( \frac{40 \text{ ft} \left(0.021 \right) + 10 \text{ ft} \left(0.023 \right)}{ \left(1.682 \right)^5 + \left(1.097 \right)^5} \right) \]

\[ \Delta P = 1.899 \left[ 0.04239 + ,1448 \right] \]

\[ = 0.393 \text{ psi} \]

Solution: Move HX GN2 VENT to 1'' TEE immediately upstream of 1 1/2'' VENT piping. LESS \( \Delta P \), BETTER PERFORMANCE. ON HX LN2 POT CONTROL.
LIQUIFICATION MODE:

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

CORRECT BY RAISING EVX2 LOW LIMIT TO 50%.