DESIGN OF A HELIUM RECOVERY
AND REPURIFICATION SYSTEM

by

JAMES H. WALKER

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Signature of Author________________________
Department of Mechanical Engineering
May 1, 1983

Certified by________________________
Joseph L. Smith, Jr.
Thesis Supervisor

Accepted by________________________
Warren M. Rohsenow
Chairman, Department Committee

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Abstract

A system is designed to recover and repurify helium containing 20% water saturated air at a rate of 50 scfm and a pressure of 2000 psi to a contaminant level below 50 ppm. Low pressure gas is recovered through a pipeline from the Francis Bitter National Magnet Laboratory. It is compressed, then repurified by two parallel 165 in^3 molecular sieve adsorber beds, a 10 ft LN_2 cooled freezeout heat exchanger and separator unit and a 1.3 ft^3 LN_2 cooled activated charcoal adsorber bed. Total LN_2 consumption per 5000 scf run is 137 liters. Purity monitoring, regeneration and storage capability is provided.

Thesis Supervisor: Dr. Joseph L. Smith, Jr.

Title: Professor of Mechanical Engineering

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I. INTRODUCTION

Since 1952 the MIT Cryogenic Engineering Laboratory (CEL) has operated a helium liquefaction facility. This facility has provided liquid helium for the many varied low-temperature research activities at MIT.

The present MIT central liquefier is a CTI model 2000 which provides 80 liters per hour of liquid helium. The facility provides approximately 40 users of liquid helium with a total of 8000 liters per month. About 60% of this is used by the Francis Bitter National Magnet Laboratory (FBNML) for various experiments.

The helium distribution system is run essentially open cycle. Bulk helium gas is purchased liquefied and distributed to users with no recovery of the used gas. The system has no repurification capability so all gas from the liquid helium distributed to users along with purge gas required for liquefier operation and storage dewar filling is vented.

Three closed-cycle liquid helium systems have recently been installed for the FBNML and the Superconducting Generator Test Facility (SGTF). However these systems have recovery capability only while the liquefiers are in operation.

A helium recovery and repurification system is needed at MIT to conserve helium resources, to reduce the cost of liquid helium to users and to ensure an adequate supply of liquid helium for important research when helium becomes a scarce commodity.

Approximately 2.2 X 10^6 scf of helium are purchased for liquefaction each year at a cost of $100,000. To recover this helium new equipment is needed. This equipment must meet certain criteria. It must not use valuable research space which is in short supply at MIT. It must not add any significant risk to user experiments and it must be integrated into the existing central liquefaction facility.

The purpose of this thesis is to design a helium recovery and repurification system which is integrated into the existing central liquefaction system. The system will include helium recovery pipelines from the FBNML to the CEL, pure and impure high pressure storage systems, and high pressure drying and repurifying equipment. The system should have purging capabilities and helium purity monitoring instrumentation.

II. HELIUM RECOVERY AND REPURIFICATION SYSTEM

A. Objectives

The objectives of the helium recovery and repurification system are as follows:

1. To recover helium gas used in experiments at the FBNML and to meter the amount of gas recovered.
2. To repurify recovered helium gas at a rate of 50 scfm and to monitor gas purity.
3. To provide adequate pure and impure storage for the helium gas.
4. To regenerate system adsorbers.
5. To purify continuously for a run of at least 5000 scf before regeneration is needed.
6. To minimize consumption of LN_2 used for cooling.
7. To integrate into the existing liquefaction system.

B. Design Implementation

1. Adsorption

In the chosen design helium purification is achieved mainly through contaminant removal by physical adsorption. Therefore before going on to the mechanics of the design, the adsorption process will be briefly discussed.

The adsorption process is a physical phenomenon, which occurs whenever gas or liquid molecules are brought into contact with a solid surface. Physical adsorption is due mainly to Van der Waal forces. These forces provide a weak interaction between the solid surface and any molecules which may condense on it, causing these molecules to adhere to the surface.

If a gas is allowed to come to equilibrium with a surface, it will always be found that the concentration of gas molecules is greater near the surface than it is in the free gas. This is due to unbalanced forces. In any solid or liquid the atoms at the surface are subject to unbalanced normal attractive forces; by adsorbing molecules the balance of forces can be partially restored.

The number of molecules adsorbed on a surface is determined by adsorbent properties, adsorbate properties, and system temperature and pressure.

Adsorbent properties such as chemical composition and surface configuration affect the kinds of molecules which will be adsorbed. Also, although the adsorption process is instantaneous, in finely powdered or highly porous adsorbents, gas diffusion through the adsorbent may often be slow, slowing the entire process.

Adsorbate properties such as boiling point, molecular weight, degree of polarity, concentration and, if a carbon compound, the degree of unsaturation will determine if a molecule will adsorb on a surface.

Adsorption will always occur provided that the system temperature and pressure are suitable. Since adsorption is related to liquefaction, the suitable system properties are the same as those for liquefaction. Under these conditions the adsorbate can form layers on the surface several molecular diameters thick.

Some fundamental aspects of the adsorption process and its use as a purification process are 1.) adsorption forces 2.) adsorbent capacity 3.) kinetics 4.) heat of adsorption and 5.) regeneration of adsorbent.

1. The adsorption forces are electromagnetic in origin. They are called physical or Van der Waal forces. These forces can be split into two categories.

If the adsorbate molecule is non-polar the attractive forces of interest are due to dispersion forces (see reference 5). These forces arise from instantaneous dipole or multipole moments which exist in the molecule. These moments induce resonant moments in neighboring molecules, which are in phase with those of the first molecule, causing a force of attraction.

If the adsorbate molecule is polar, in addition to dispersion forces, more common electromagnetic forces, due to differing electric charge, induce the attractive force.

2. Adsorbent capacity is most commonly plotted in the form of adsorption isotherms. These are plots of amount adsorbed versus adsorbate partial pressure at some constant temperature (see reference 6). Adsorption isotherms can take on many shapes. However in this project the isotherms are of the langmuir type shown in figure (1). This type of isotherm is associated with monomolecular adsorption layers. As adsorbate pressure is increased the amount adsorbed increases until a saturation point is reached. Any further increase in pressure doesn't affect the amount adsorbed.

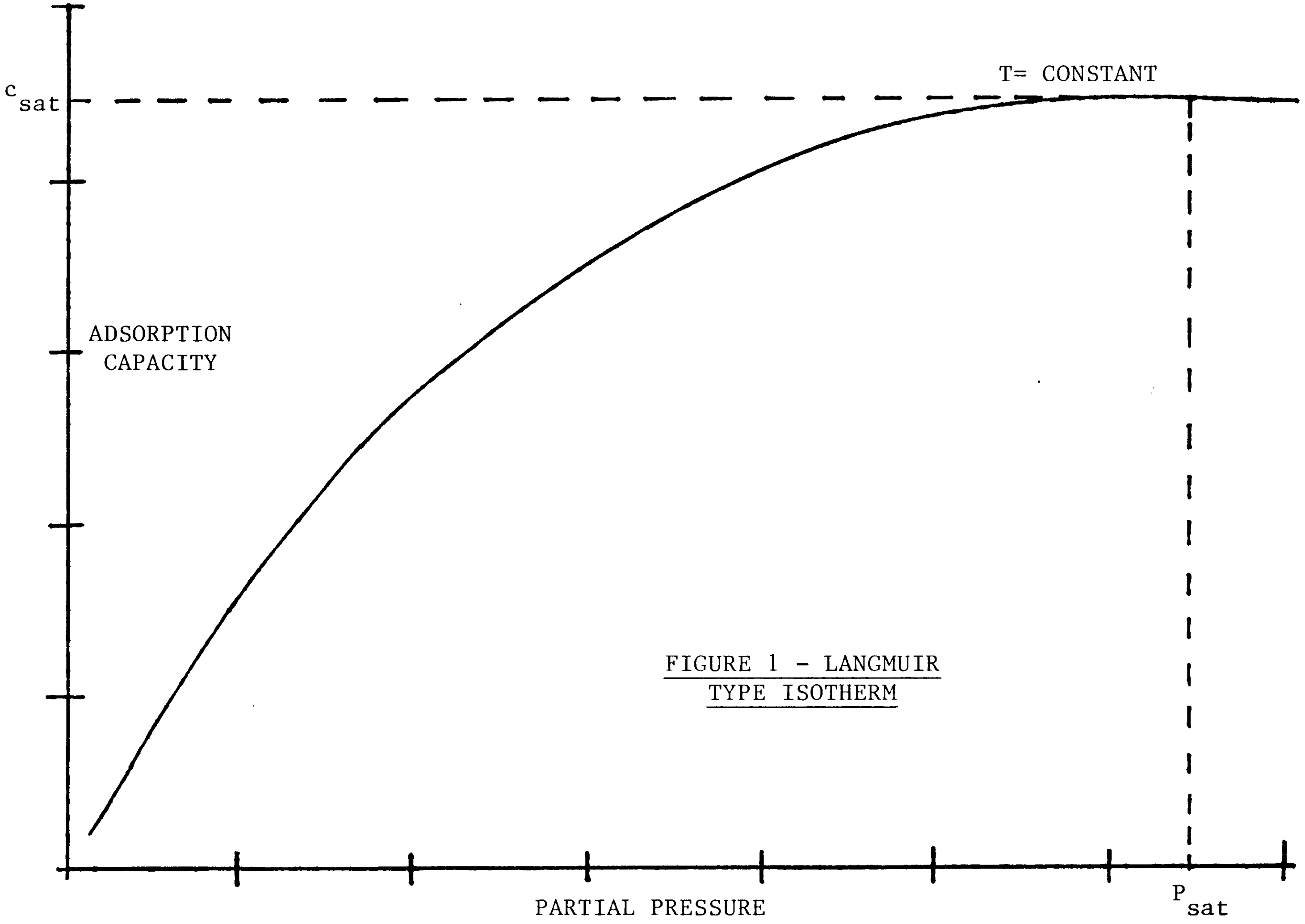

FIGURE 1 - LANGMUIR TYPE ISOTHERM

The adsorbent capacity is also affected by the type of service it is involved in and by what kinds of contaminants are present in the system.

3. The adsorption process itself is almost instantaneous, however, due to diffusive effects the adsorption rate of different adsorbates at different conditions may be very different. This diffusion affect may also be seen as a difference in adsorbent specificity before and after equilibrium occurs, these affects show the importance of considering the kinetics of the adsorption process aside from equilibrium data. However the problem is, in general, that there is no analytical way to look at adsorption kinetics, data must be collected experimentally. This means each system must be tested separately to see how it performs before reaching equilibrium. Fortunately, in the absence of experimental data, approximations can be made to determine appropriate design criteria.

4. Adsorption is a spontaneous process which reduces the free energy of the system. The process also involves a loss in degrees of freedom, due to the adsorbate passing from a free gas to an adsorbed layer, which reduces the system entropy. Therefore from the equation,

$$\Delta F = \Delta H - T\Delta S \qquad (1)$$

we see that the adsorption process must always be exothermic (see reference 5). The heat released is called the heat of adsorption.

The heat of adsorption is of the same order of magnitude as the heat of liquefaction. This heat can reduce an adsorbent's capacity and therefore must be accounted for in any design.

5. Since adsorption is an exothermic, physical process it can be reversed by supplying an amount of heat equal to the heat of adsorption. It is also possible to induce desorption by reducing system pressure at a constant temperature. This reduces adsorbate pressure and causes desorption. The reduction in adsorbate pressure can be brought about by evacuation or by means of a pure unadsorbable purge gas.

The above are all means of regenerating a saturated adsorbent so that it can be reused. This is a necessary part of any design since it would be inconvenient and costly to discard the adsorbent after a single use.

In this project both a thermal cycle and a pressure cycle are used to regenerate the adsorbent.

The above is a brief description of the adsorption process which is used to purify incoming helium gas. The selected system components are described below.

2. Design

The system selected to meet the design objectives is as shown in Figure 2. Operating conditions chosen for the system are a working pressure of 2000 psi, with drier temperature at ambient and repurifier temperature at that of LN_2.

Repurifier conditions were chosen as optimal based on data reported by A.D. Little Inc. (See Ref. 9)

Drier temperature, at the overall system pressure of 2000 psi, was chosen to be at ambient because decreasing this temperature does not increase adsorption capacity significantly. This is based on isotherms provided by Union Carbide.

The major components of the helium recovery and repurification system are:

a. The repurifier, which is a unit that accepts high pressure, dry, impure helium gas, purifies it and pipes the gas to pure storage.

b. The drier, which is a unit that accepts high pressure, water saturated helium gas, removes the water and pipes the gas to impure storage or to the repurifier.

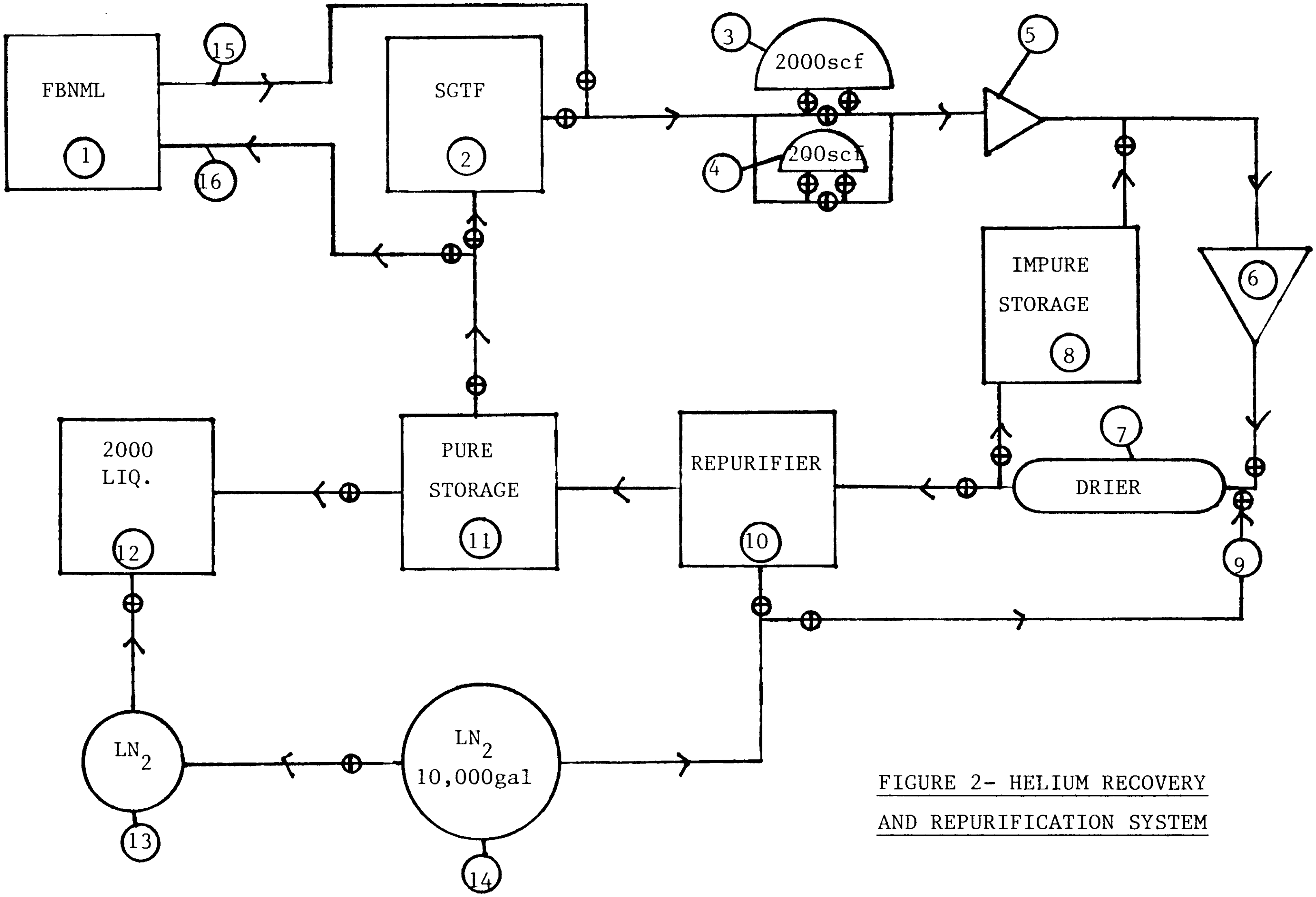

FIGURE 2- HELIUM RECOVERY AND REPURIFICATION SYSTEM

1. Francis Bitter National Magnet Laboratory (NW14)
2. Superconducting Generator Test Facility (N9)
3. Gas Bag, 2000 scf, low pressure impure storage
4. Gas Bag, 200 scf, low pressure impure storage
5. Slave compressor, 30 scfm, 1.0 atm
6. Master compressor, 30 scfm, 2000 psi
7. Drier
8. Impure storage, 20,000-40,000 scf
9. Heater
10. Repurifier
11. Pure storage, 111,000 scf
12. CTI 2000 liquefier, 80 L/hr
13. LN_2 dewar
14. 10,000 gal LN_2 tank
15. 1.0 in., low pressure, copper, impure helium recovery line
16. ½ in., high pressure, S.S., pure helium return line

FIGURE 2 (CON'T)

c. Recovery pipelines, which are the lines used to transfer helium gas between the FBNML and the CEL.

d. Pure and impure storage capability including a large gas bag.

Each of the system components will be discussed in detail in following sections. Therefore only a brief discussion is now given.

The repurifier is a high pressure unit capable of accepting dry impure helium gas at a rate of 50 scfm and at a pressure of 2000 psi. System flow rates were chosen based on predicted recovery rates. The repurifier cleans the helium gas using heat exchangers, a separator and an activated charcoal bed all at LN_2 temperature. The repurifier is cooled using LN_2 from an existing 10,000 gallon liquid nitrogen system, and it has regeneration and gas purity monitoring capability.

The drier is also a high pressure unit, capable of accepting water saturated helium gas at a rate of 50 scfm and a pressure of 2000 psi. The drier removes the water from the helium using a bed of molecular sieve, which is the most effective adsorbent at system conditions. It does so to prevent water contaminant from entering the storage tanks or the repurifier, where it could freeze up and plug the system. It also has oil filtering and regeneration capabilities. The drier can be run continuously using two adsorber columns run in parallel. While one column is in operation, the other can be regenerated.
The recovery pipelines run between FBNML and SGTF.

The low pressure line delivers impure helium from FBNML to existing lines at SGTF, from here it goes on to CEL.

The high pressure line delivers pure helium from storage at CEL to FBNML where it is used for experimentation.

The pure and impure helium gas storage consists of existing high pressure gas storage tanks at CEL, approximately 111,000 scf capacity, along with nine new "Jumbo tubes" with a capacity of about 64,000 scf at 1800 psi.

The gas bag stores up to 2000 scf of impure helium at low pressure, which is used as a supplemental feed gas.

C. Operation

A flow diagram of the complete helium recovery and repurification system is shown in Figure 2. Here an overall description of system operation is given. Detailed operation of each of the system components will be given in following sections. The internal recovery system at FBNML is not part of this thesis, however it is shown in Figure 3 for completeness.

Expended helium gas is recovered from experiments at FBNML (1) and piped through new recovery pipelines (15) to SGTF (2). Here it is sent to CEL via existing piping. The gas can then either be stored in one or both gas bags, an existing 200 scfm bag (4) or the new 2000 scfm bag (3), or it can be sent on to the existing 30 scfm recovery compressors (5,6) or a combination of both. After compression to approximately 2000 psi the gas goes to the drier (7). Here water is removed using beds of molecular sieve at ambient temperature. After drying, the gas will be sent to impure storage (8). Here it will be stored until enough has accumulated for a repurification run. This will be about 5000 scf, the predicted recovery amount per FBNML run. At this point, the gas will go again through the compressor and drier and into the repurifier (10). Here it is cooled to LN_2 temperature by heat exchangers and an LN_2 bath and purified by an activated charcoal bed. The pure gas is sent to pure storage (11) and is ready for reliquefaction or piping to either SGTF or FBNML.

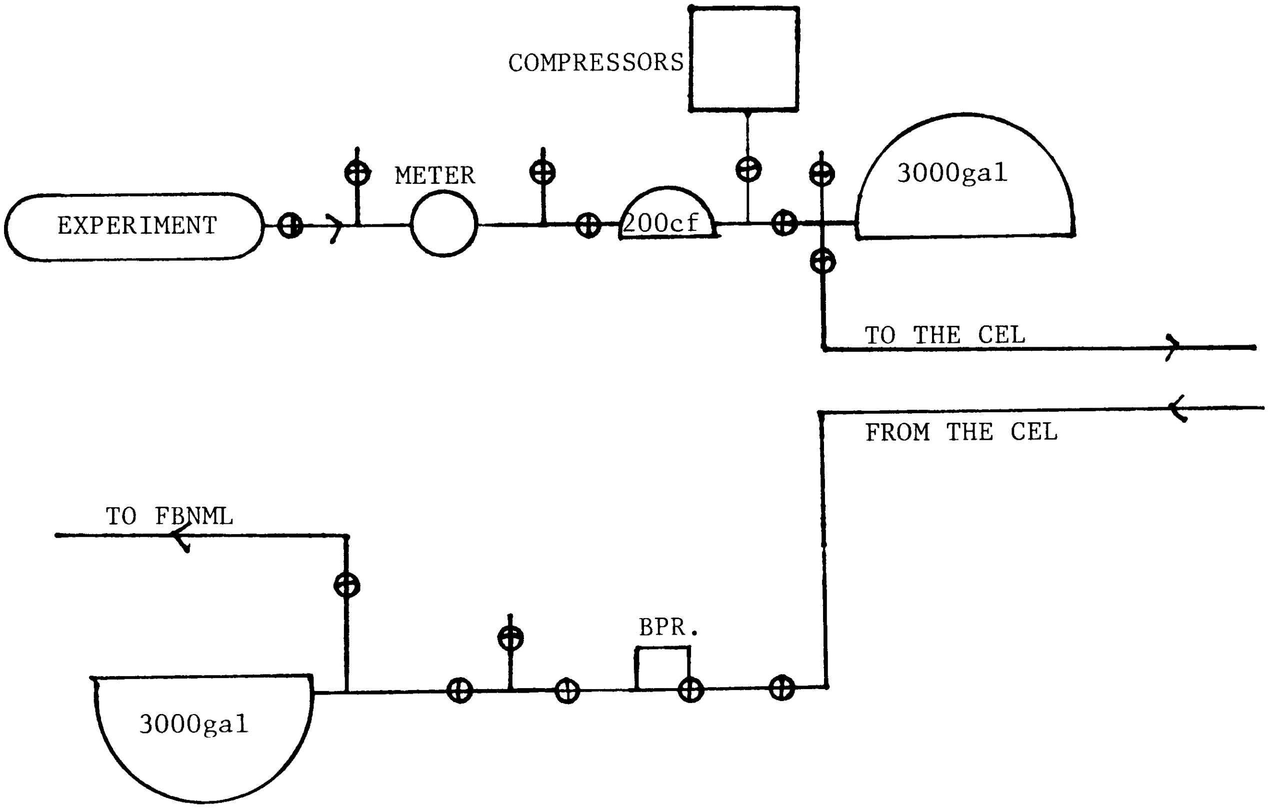

FIGURE 3- FBNML RECOVERY SYSTEM

The recovered gas is metered using temperature and pressure changes of the storage tanks. Purity is monitored by taking gas samples at various points in the repurifier and comparing them to reference samples in a thermal conductivity gas analyzer.

III. SYSTEM COMPONENTS

A. Repurifier

1. Design objectives.

The design goals for the repurifier are:

1. To repurify recovered helium gas with a maximum of 20% water saturated air contaminant, at a rate of 50 scfm and a pressure of 2000 psi, to a contaminant level below 50 ppm by volume.
2. To repurify continuously for a run of 5000 scf before regeneration is needed.
3. To minimize LN_2 consumption.
4. To regenerate adsorbers.
5. To monitor purity.

The above design goals place constraints on repurifier components. The components must be of large enough size and strength to accept the volume and pressure of gas specified. Purification must take place under conditions suitable for at least a 50 ppm contaminant level. Heat leaks and cooled mass must be minimized. And secondary regeneration and purity monitoring systems must be provided.

2. Components

A schematic and detailed flow diagram of the repurifier and its components are shown in Figures 4 and 5. Each component will now be discussed.

a. Activated Charcoal Adsorber.

This is the final step in the repurification process. It will remove any remaining air, particulate matter or other contaminants that have not already been condensed out in the cooling steps.

Charcoal adsorbent was chosen because from the data of A.D. Little Inc. it appears to have a higher capacity for air than other adsorbents at system conditions. Actually there is little experimental data on the adsorption of air from helium on charcoal. However the data available can be used as a rough estimate of the adsorption performance of charcoal.

The adsorption of air on charcoal is believed to be essentially complete at temperatures near that of LN_2. This is the method generally used for the removal of oxygen and nitrogen from helium and it is the method used by the Bureau of Mines as the final step in helium purification. The helium produced at the Bureau of Mines contains from 3 to 10 ppm of air.

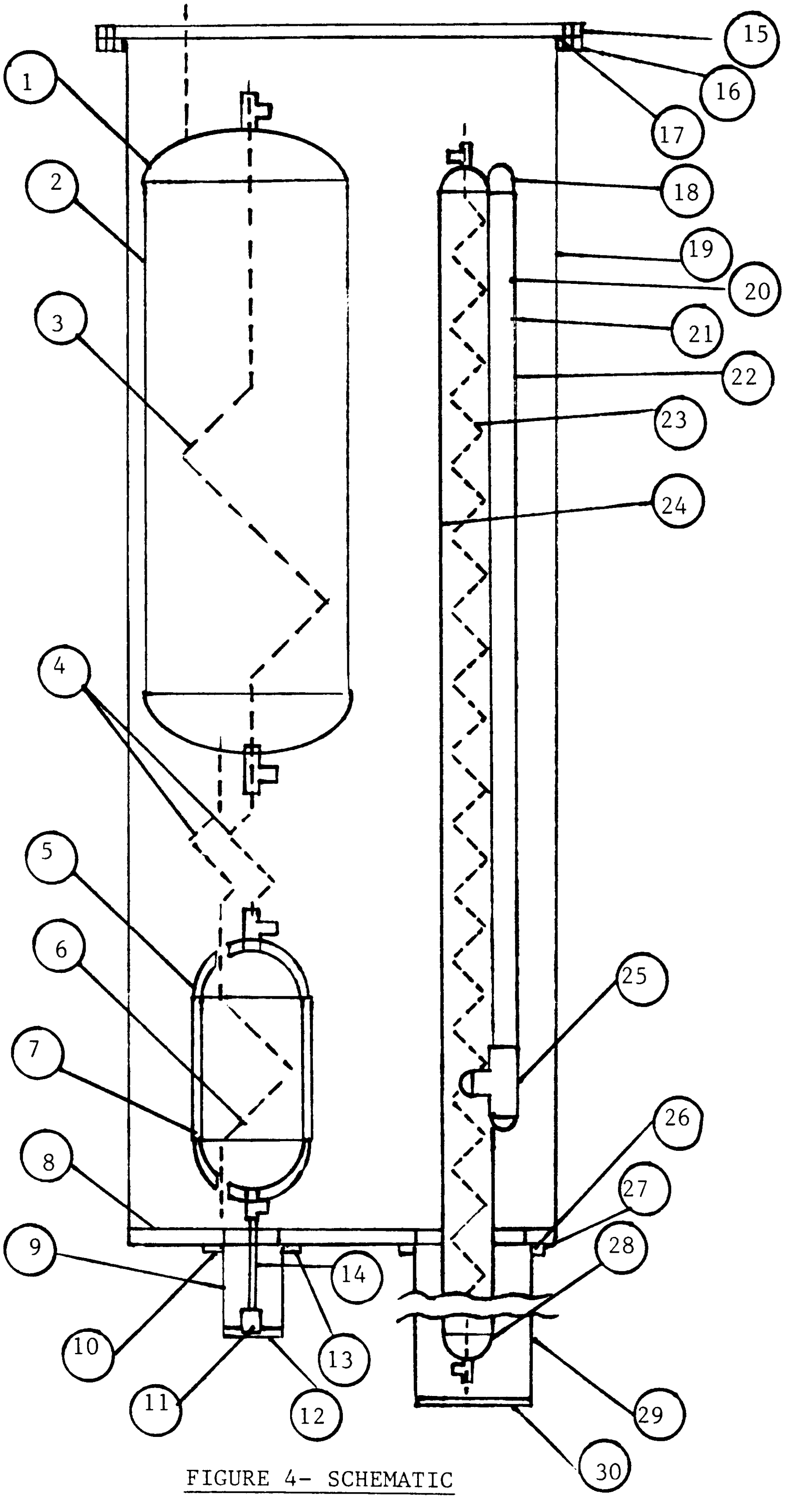

FIGURE 4- SCHEMATIC OF REPURIFIER

1. 14 in. O.D., 12 gage, 304 S.S., dished head
2. 14 in. O.D., 12 gage, 304 S.S., rolled cylinder, 3 ft.
3. Nitrogen pot coil
4. Coil springs
5. 8 IPS, SCH.80, 304 S.S. pipe cap
6. Seperator coil
7. 8 IPS, SCH.80, 304 S.S. pipe, 10 in.
8. Upper vacuum jacket lower plate, see figure 19
9. 4 IPS, SCH.40, 304 S.S.pipe, 5½in.
10. O-ring
11. SC 200 load cell
12. Transducer housing lower plate, see figure 23
13. Transducer housing flange, see figure 22
14. 5/8in. threaded rod, 7 in.
15. Top vacuum plate, see figure 16
16. Top vacuum flange, see figure 15
17. O-ring
18. Joy Tube heat exchanger top, see figure 9
19. 30 in. O.D., 10 gage, 304 S.S.rolled cylinder, 7 ft
20. Joy Tube heat exchanger, 2 x 5ft

FIGURE 4 (CON'T)

21. 1 3/4 in., 0.12 in. wall, seamless 304 S.S. tube
22. 2.0 in., 0.049 in. wall, seamless 304 S.S. tube
23. Charcoal adsorber coil
24. 4 IPS, SCH.40, 304 S.S. pipe, 15 ft
25. Joy Tube heat exchanger, bottom, see figure 10
26. O-ring
27. Lower vacuum flange, see figure 20
28. 4 IPS, SCH.40, 304 S.S. pipe cap
29. 8 in. O.D., 0.12in. wall, 304 S.S. tube, 9.5 ft
30. Lower vacuum lower plate, see figure 21

FIGURE 4 (CON'T)

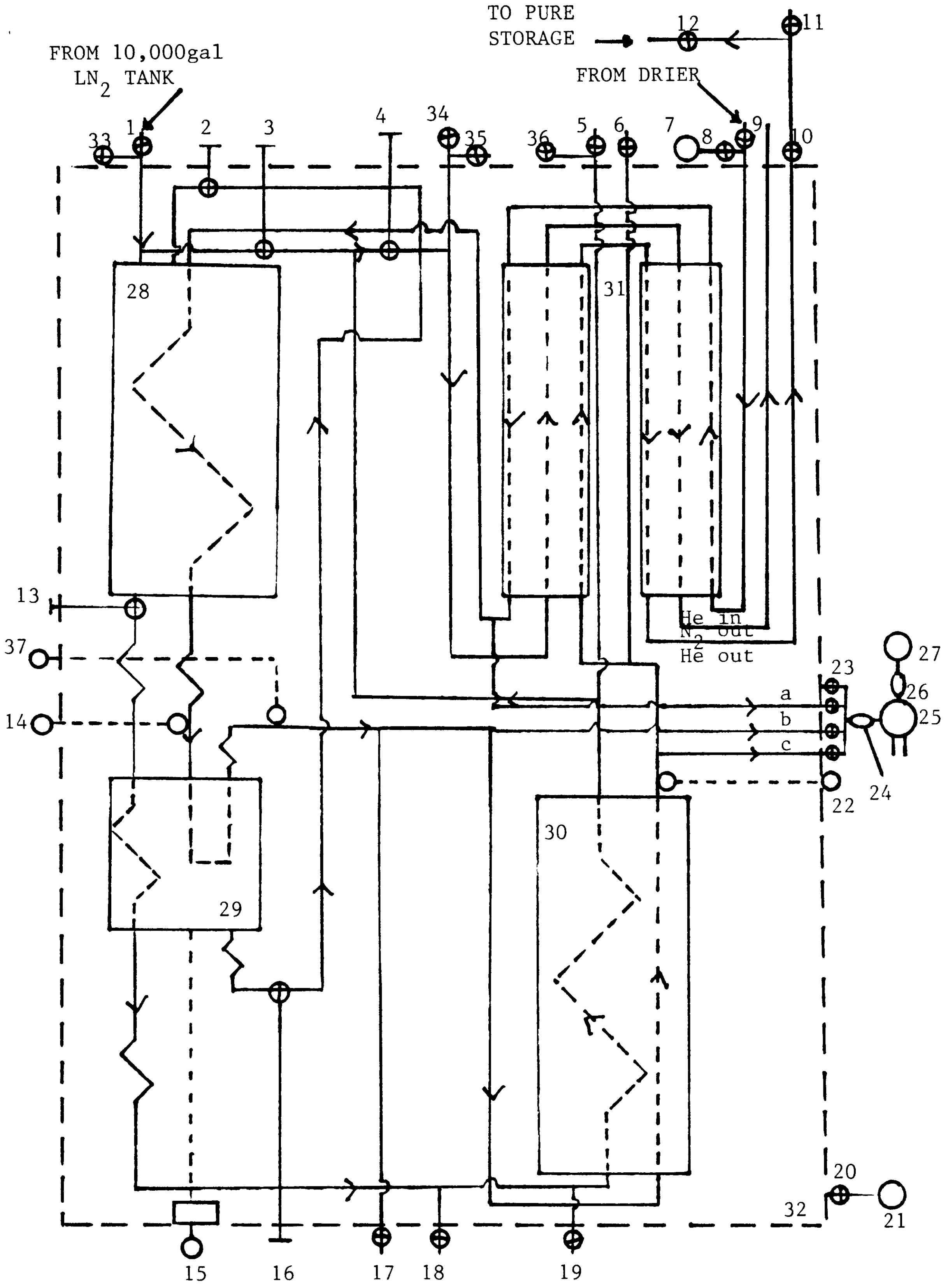

FIGURE 5- REPURIFIER FLOW DIAGRAM

1.	LN$_2$ Fill valve, Whitey 12NBSW8T, 1/2 in.
2,3,4.	N$_2$ extended control valve, Whitey 12NBSW8T, 1/2 in.
5.	Purge Fill valve, Whitey 12NBSW8T, 1/2 in.
6,17.	Relief valve, 2000 psi, Circle Seal
7.	Line vacuum pump
8.	Pump down valve, Whitey B45S8 ball valve, 1/2 in.
9.	Helium inlet, Whitey B45S8 ball valve, 1/2 in.
10,11,12.	Helium outlet, Whitey B45S8 ball valve, 1/2 in.
13.	LN$_2$ extended control valve, Whitey 12NBSW8T, 1/2 in.
14.	Vapor pressure thermometer
15.	Data instruments SC200 load cell, Acopian 24 vdc, 0.5 amp power supply
16.	Air condensate extended control valve, Whitey 3NTRS4, 1/4 in.
18.	Purge vent valve, Whitey 12NBSW8T, 1/2 in.
19,33,35,36.	Relief valve, 25 psi, Circle Seal
20.	Vacuum Valve
21.	Tank vacuum pump
22.	Vapor pressure thermometer
23.	Gas analyzer manifold, 4 Whitey B42S4 ball valves, 1/4 in.
24,26.	Matheson low pressure brass regulator
25.	Gas analyzer, Gow Mac 50-150
27.	Reference gas tank
29.	Separator
30.	Activated charcoal adsorber bed

FIGURE 5 (CON'T)

31.	Joy tube heat exchanger
32.	Vacuum Jacket
34.	N_2 Vent, Whitey 12NBSW8T, 1/2 in.
37.	Vapor Pressure Thermometer

FIGURE 5 (CON'T)

An appropriate value of the adsorption capacity of charcoal supplied by A.D. Little Inc. is 154 ft^3 of air adsorbed per ft^3 of charcoal at temperatures near LN_2, 1800 psig and 1% air contaminant. (See Ref. 9)

The above value represents the total adsorption capacity, or static equilibrium capacity, of the charcoal, we are interested in the breakthrough capacity, or the dynamic capacity. The difference between the two values is this. As shown in Figure 6 the concentration of air in the charcoal bed does not change abruptly along it length, it decreases smoothly from saturated at the entrance to pure at the exit. The breakthrough capacity of the charcoal is the amount of air adsorbed at the point where air just begins to appear at the exit of the bed. The adsorption capacity is the total amount of air adsorbed when the exit of the bed becomes saturated with air and cannot hold anymore, air has already been exiting the bed for some time. Since it is required that there be no air in the exit stream of the bed we must use the breakthrough capacity of the charcoal. An estimate of this capacity from E.I. DuPont de Nemours is 70 to 80% of the adsorbtion capacity or about 100 ft^3 of air per ft^3 of charcoal. This value of course changes with bed dimensions and contaminant level, however it appears to be a conservative estimate. (See Ref. 9)

The adsorber was sized, using an adsorption capacity value of 100 ft^3/ft^3, to handle 5000 scf He per run with 20% air contaminant and

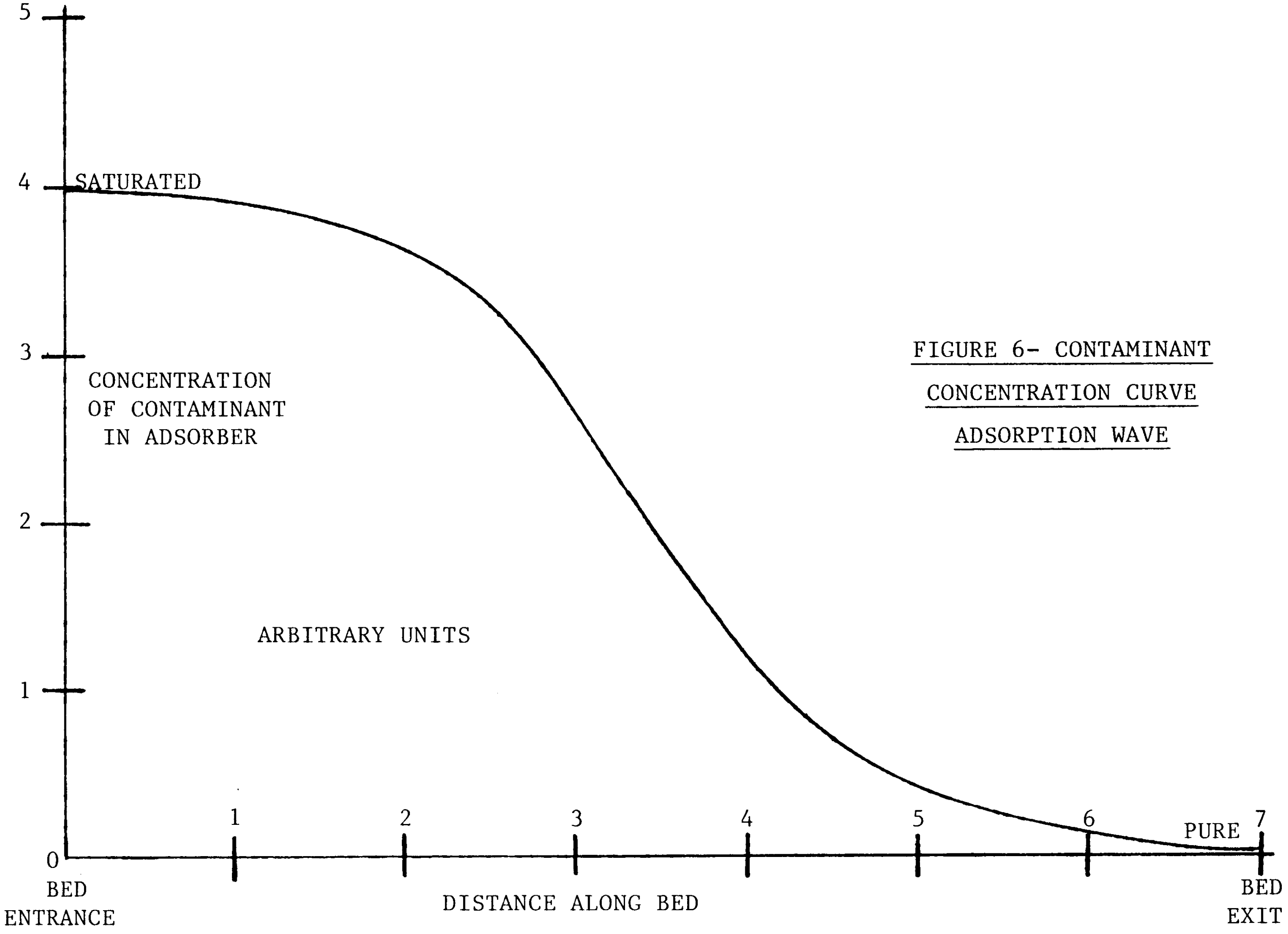

FIGURE 6- CONTAMINANT CONCENTRATION CURVE ADSORPTION WAVE

contains about 1.3 ft^3 of 6-14x mesh charcoal, see appendix A for a brief discussion on this.

This unit consists of a 15 ft length of 4 IPS, schedule 40, seamless 304 stainless steel pipe. One 15 ft section is used to facilitate piping. The ends are 4 IPS schedule 40, 304 stainless steel pipe caps drilled through the center to accommodate 3/4 in.ss. tees. These tees are used approximately like heat exchanger tees in order to reduce the number of fittings needed. This can be seen in Figure 7. The branches of the tees inlet and outlet helium while the runs inlet and outlet the N_2 cooling coil. This coil is needed to provide enough surface area for cooling of the charcoal. The coil is of 1/2 in.stainless steel tubing with an O.D. of 3.5 in.and a pitch of 2.5 in.and about 69 turns. The O.D. was chosen in order to have equal amounts of charcoal in the interior and exterior of the coil turns to ensure constant temperature throughout the charcoal. A pitch of 2.5 in. was thought reasonable, and it was calculated that at this pitch 69 turns were needed to provide enough coil surface area to completely cool the charcoal and pipe while the unit was operating.

It was also calculated that about 68 liters of LN_2 would be needed to initially cool the adsorber. All charcoal adsorber calculations can be found in Appendix A.

Pressure drop through the bed was calculated and found to be

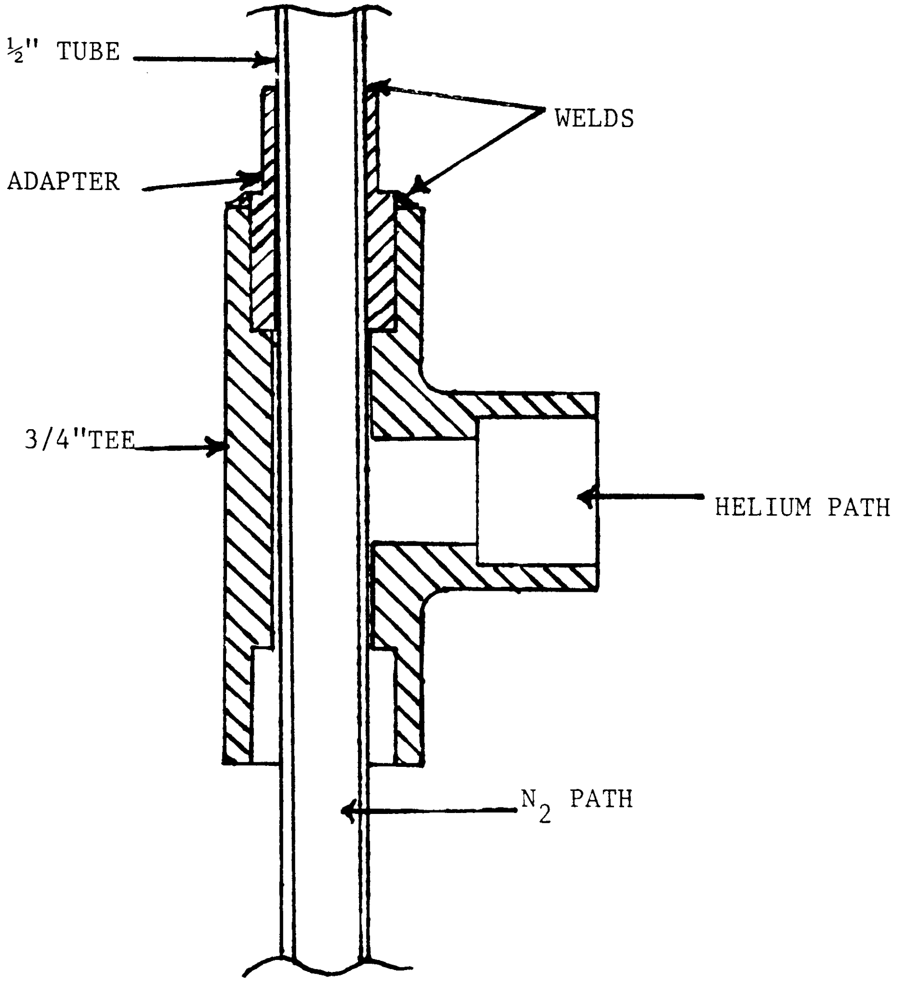

FIGURE 7- USE
OF LARGE TEES
A.C.

negligible.

Since it would be impractical to replace the charcoal adsorbent upon saturation, some means of regeneration must be provided. Regeneration of the charcoal adsorber is done in two steps. First a flow of nitrogen, about 1 scfm, at ambient temperature or heated is passed through the adsorber cooling coil. This warming of the charcoal lowers its adsorbtive capacity so air is desorbed. Heat up time at 1 scfm is approximately 23 hours. The nitrogen enters and exits through valves (5) and (18), as shown in Figure 5. By closing valves (3), (4), and (13) the warming flow goes only through the charcoal bed (30), minimizing heated mass and therefore minimizing the mass needed to be cooled during the next run. Second, the valves (5) and (18) are closed and the adsorber along with the helium flow lines are evacuated using a separate branch of the helium inlet line which was previously valved off (8). Lowering of the adsorber pressure causes desorption due to the decreased partial pressure of the air, which is a major factor in adsorption capacity. After these two steps regeneration should be essentially complete.

b. Joy Tube Heat Exchanger

This is the first step in the repurification process. It will cool the incoming stream to about LN_2 temperature so that air or other contaminants can easily be condensed out in the next two steps, the LN_2 pot and the separator.

A picture of a Joy Tube is shown in Figure 8. It consists of four concentric copper tubes. Inside the three annuli formed by the tubes are helical winds of copper ribbon soldered to the tube walls. These winds form fins which increase the heat transfer area of the Joy Tube.

The incoming helium must be cooled from ambient to about LN_2 temperature, by N_2 vapor and cold outgoing helium. To do this it was found that approximately a 10 ft length of joy tube would be needed. Calculations can be found in Appendix B. However due to height constraints it was necessary to use two five foot lengths of tube.

With a total 10 ft length, the steady state temperature difference, throughout the heat exchanger between the warm and cold counter-current flows was found to be about $10.17^{\circ}F$. This means the incoming stream is $10.17^{\circ}F$ warmer than LN_2 temperature when it exits the heat exchanger. Therefore the stream will vaporize enough LN_2 in the LN_2 pot to lower its temperature by $10.17^{\circ}F$. The amount of LN_2 consumed is approximately 3.5 lb/hr. The N_2 vapor produced is then used for cooling.

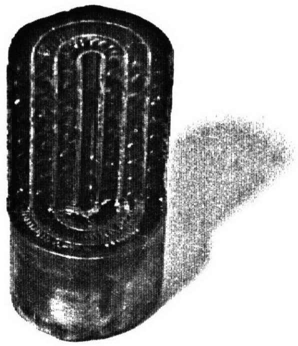

FIGURE 8 - JOY TUBE

The pressure drop through the joy tube and pressure jacket gap was found to be negligible compared with the total pressure of 2000 psi.

The construction of the heat exchanger shown at its top and bottom ends can be seen in Figures 9 and 10. The incoming warm helium flows through the outermost tube annulus (1) while the cold outgoing helium flows through the two innermost annuli (2). This scheme was chosen in order to surround the warm helium with cold flow, the cold helium on the inside (2) and on the outside cooling LN_2 vapor from the LN_2 pot, which flows through a thin walled 2.0 in. X 0.049 in. wall stainless steel tube (3) which jackets the outside of the heat exchanger.

Since the joy tube is made of copper and is run at high pressure the heat exchanger must be designed in a way that relieves the copper of the load. To do this a 1 3/4 in. X 0.12 in. wall stainless steel jacket (4) is put on the outside of the tube. This jacket carries the load of the high pressure inside.

In order to minimize the heat flow resistance of the inevitable gaps that would be found between the joy tube and the pressure jacket, a larger gap, 10 mils wide (5), capable of passing a flow is designed in. The 10 mils was chosen since it would allow easy assembly and pass a reasonable amount of gas without losing the effectiveness of the joy tube. The flow in this gap, approximately 6.7% of the total flow, increases the heat transfer

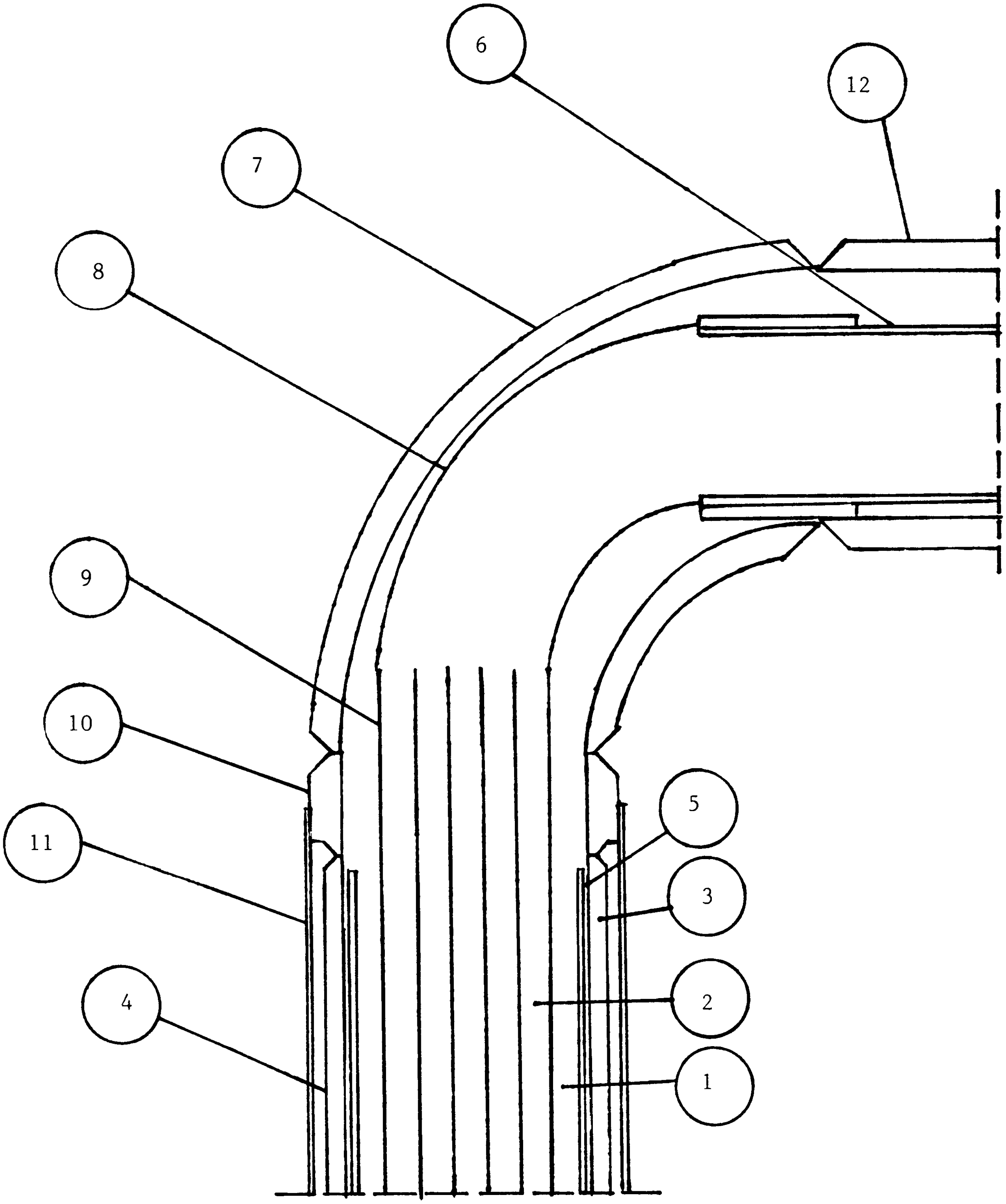

FIGURE 9- HEAT EXCHANGER, TOP

1.	Warm helium channel
2.	Cold helium channels
3.	N_2 channel
4.	1 3/4 in. O.D., 0.12 in. wall seamless S.S. tube
5.	10 mil gap
6.	1 1/8 in. O.D. type K copper tube, 6 in.
7.	1 1/2 IPS, SCH 80, long radius, S.S. elbow
8.	1 in. copper to fitting, long radius, copper street elbow
9.	Joy tube heat exchanger 5 ft, see Figure 7
10.	Adapter, S.S.
11.	2 in. O.D., 0.049 wall seamless S.S. tube
12.	1 1/2 IPS, SCH 80, S.S. pipe 4.5 in.

FIGURE 9 (CON'T)

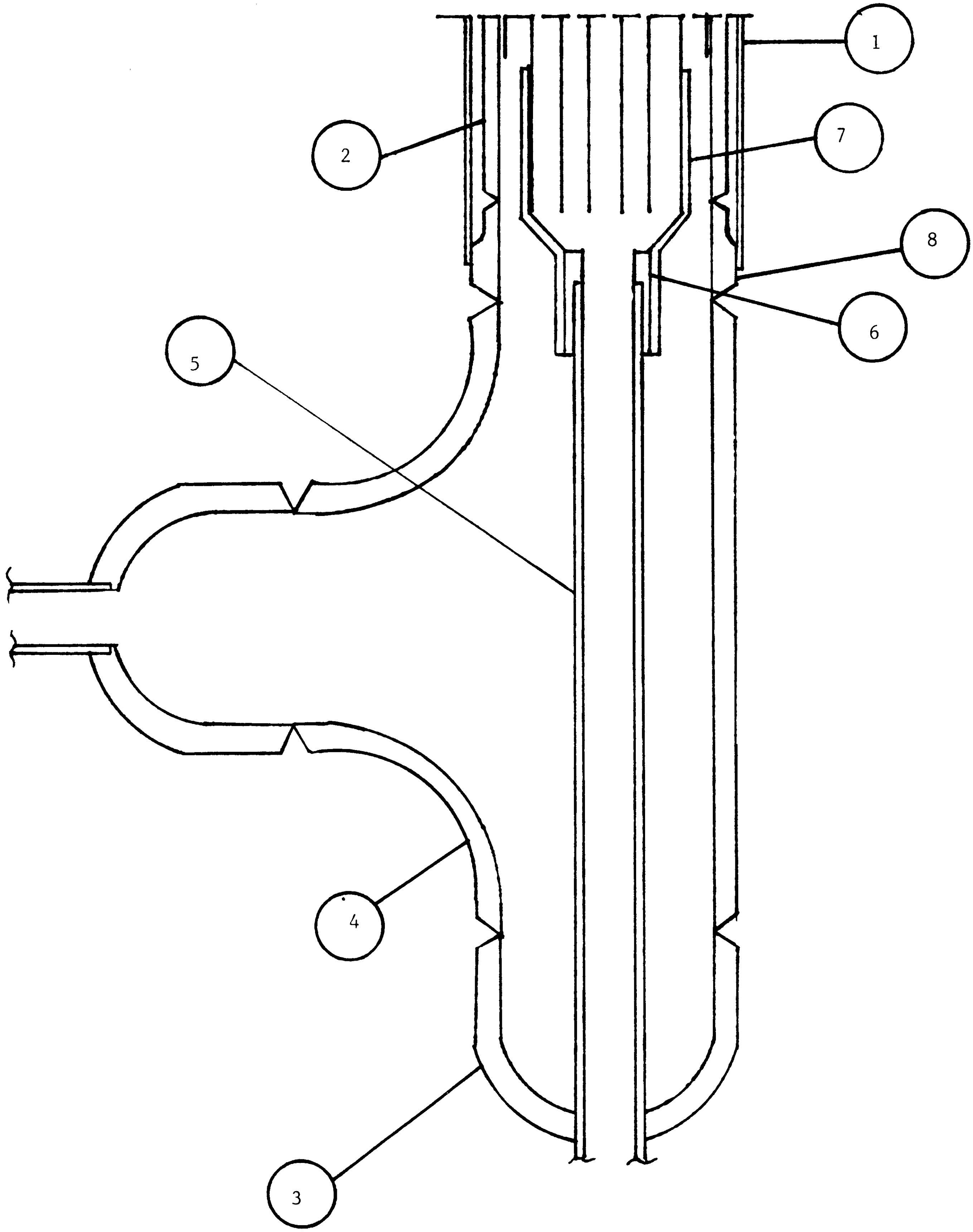

FIGURE 10- HEAT EXCHANGER, BOTTOM

1.	2 in. O.D. X 0.049 in. tube
2.	1.75 in. O.D. X 0.12 in. tube
3.	1 1/2 IPS SCH 80 pipe cap
4.	1 1/2 IPS SCH 80 tee
5.	1/2 in. tube
6.	Brass bushing
7.	1 in. to 1/2 in. extended bushing
8.	Adapter

FIGURE 10 (CON'T)

between the warm helium (1) and the N_2 vapor (3).

The ends of the heat exchanger had to be designed to keep all flows physically separate but in thermal contact. The top end of the heat exchanger, shown in Figure 9, can be seen to be simply a copper elbow (8) inside a stainless steel elbow (7) and a cold flow copper tube (6) inside a warm flow stainless steel tube (12). The stainless parts are welded with adapters used to connect the various tubes, while the copper parts are soldered. There are no stainless steel to copper joints necessary.

The lower end shown in Figure 10 consists of a stainless steel tee (4). The cold helium flow is carried out of the tee using a piece of 1/2 in. stainless steel tube (5) which is adapted to the joy tube. The warm helium flow fills the tee through the branch and flows into the outside annulus of the joy tube. The tee is capped with stainless steel pipe caps (3) drilled through the center to accommodate the 1/2 in. tube. There is one stainless to copper joint necessary. It is made using a brass bushing (6) as an intermediate adapter.

c. Liquid Nitrogen Pot.

This is the second step of the repurification process, it will liquify any remaining air or other contaminants. This process of partial condensation is a simple efficient means of removing the bulk of the contaminants, so that they do not have to be adsorbed. This dramatically reduces the size of the adsorber bed needed.

This unit contains the LN_2 used for cooling the repurifier. It is 3 ft tall with a 2 ft O.D. and dished, hemispherical heads at either end. It is made of 12 gage, 304 stainless steel, rolled and welded. The heads are drilled through the center to accommodate 3/4 in. tees. These tees are used as in the charcoal adsorber. As shown in Figure 11, the runs of the tees inlet and outlet the helium line. The branch of the top tee allows the flow of N_2 vapor in or out of the pot while the lower tee branch allows LN_2 to flow out of the pot. Both flows are controlled by extended valves.

The helium line is coiled inside the pot to increase its heat transfer area, allowing the stream to cool to LN_2 temperature causing the air contaminant to condense. The coil is near the bottom of the LN_2 pot to ensure its immersion in the LN_2, since the pot will not be completely full. The coil has 16 turns a 10 in. O.D. and a 1 in. pitch. These dimensions allow the heat transfer needed to cool the helium to LN_2 temperature.

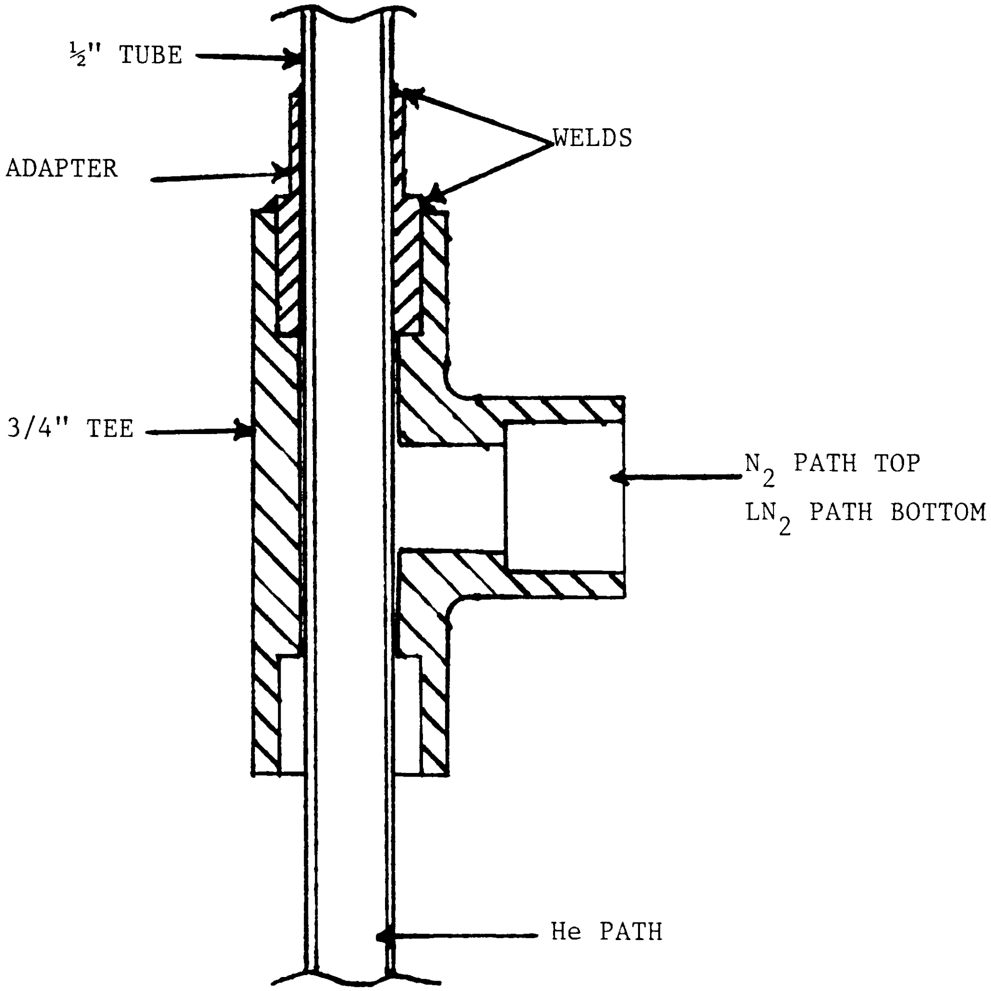

FIGURE 11- USE OF LARGE TEES LN_2

The pot is filled through lines from a 10,000 gallon LN_2 tank. The LN_2 inlet consists of a 1/2 in. tube and a weld adapter used to decrease thermal stressing of the pot head when LN_2 is flowing. The adapter is shown in Figure 12. The 1/2 in. inlet tubing is welded at the top of the adapter and enters the head through a drilled hole without touching it.

The pot holds about 9.4 ft^3 of LN_2. The amount needed to cool the 5000 scf of helium containing 20% air contaminant plus the repurifier mass is about 5.0 ft^3, which means the pot will initially be about half full. More LN_2 will probably be needed to account for losses. Calculations can be found in Appendix C.

d. Separator

This unit is the third step in the purification process. Helium and condensed liquid air enter the unit and are separated by gravity. The gaseous helium escapes through the top of the unit while the condensate falls to the bottom.

The liquid air that condenses out in the separator is used to aid in cooling, as opposed to draining it from the system. This increases the system efficiency by reducing LN_2 consumption. The condensate is channeled into the N_2 vapor line to help cool the heat exchanger. It is controlled by a throttle valve with an extended stem.

The unit consists of a 10 in. length of 8 IPS schedule 80, 304 stainless steel pipe. The ends are 8 IPS schedule 80 pipe caps drilled through the center for tees, and off center for a LN_2 cooling coil line. This coil has dimensions, 5 1/2 turns, 6.5 in. O.D., and 2 in. pitch, and is used to cool the separator mass. The top tee is 3/4 in. It allows the helium to enter through its run and to escape through its branch. The bottom tee is 1/2 in. It allows liquid air to leave through its branch while its run is used for a connection to a load cell. This will be discussed a little later.

The cooling coil enters and exits through weld adapters as in the LN_2 pot shown in Figure 12.

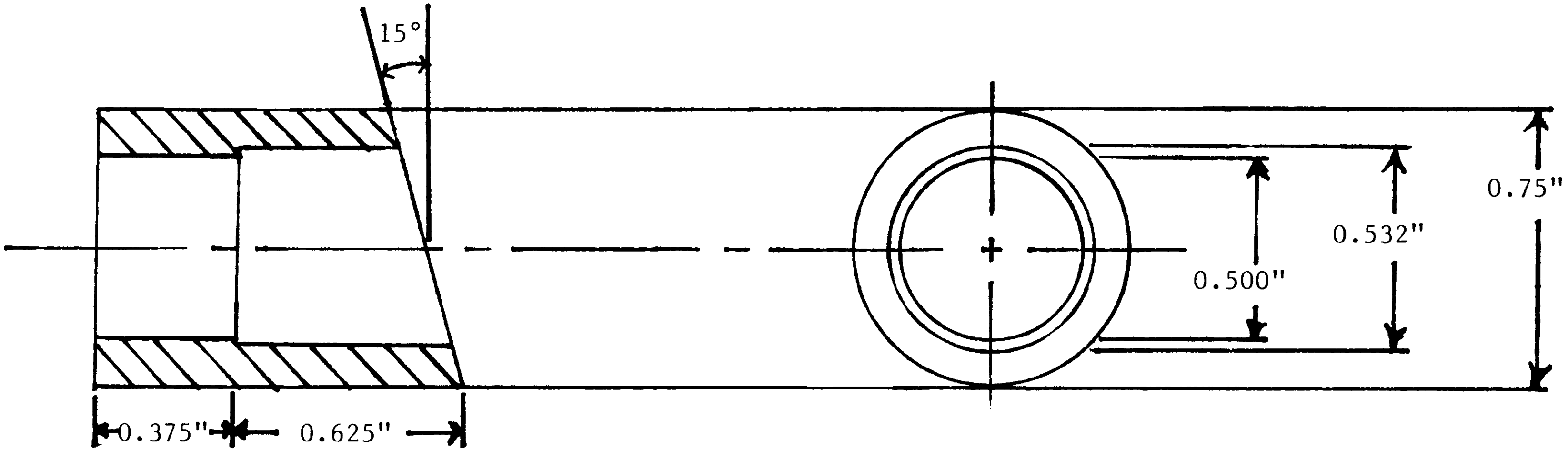

FIGURE 12- LN$_2$ POT
SEPARATOR THRU ADAPTER

In order to know how much liquid air is contained in the separator at any time a load cell is used to weigh the unit. The load cell is a Data Instruments model SC 200, maximum force 200 lb. The range of weights expected is from 61 lbs empty to 89 lbs full with the liquid air being released when the unit is approximately 1/4 to 1/2 full. The unit will not be allowed to completely fill or empty, so that condensate cannot backup the system causing a pressure increase and so that helium will not become entrained in the throttling system.

The load cell sits in a small housing at the bottom of the upper vacuum tank. Its leads are fed through the bottom plate. The load cell is connected to the separator by a threaded rod which goes from the run of the separator's bottom tee to the top of the load cell. The leads go to a 24 vdc power supply.

In order to weigh the separator it must be allowed to move freely. To do this all lines which constrain the unit have in them coils of tube which act as springs. These springs allow the weight of the separator to be carried by the load cell and not the tubing.

At 20% air contaminant it is estimated that the air will be throttled into the N_2 vapor line about every 20 minutes. All separator calculations can be found in Appendix D.

e. Gas Analyzer

It is necessary to know how the repurification process is going and at what point the charcoal adsorber reaches breakthrough. To do this a gas analyzer is used. This unit is a Gow Mac model 50-150 dual pass continuous gas analyzer. It is a thermal conductivity analyzer meaning it measures the difference in thermal conductivities between a flowing sample and flowing reference gas, and provides an output. This unit is equipped with a 0-1 mv high sensitivity meter and a high alarm which sounds when the contaminant level goes above a set point. It is sensitive to 100 ppm air in helium full scale. A dual pass analyzer is necessary to provide a flowing reference gas, to avoid possible contamination of a static reference.

The analyzer is operated (refer to Figure 5) using a reference gas from a tank (27). This gas is regulated (26) to about 6 psig and 0.01 scfm. The sample can be taken from any one of three points, after the heat exchanger (a), after the separator (b) or after the charcoal bed (c). This stepwise sampling will show how the purification is progressing. After a sample is chosen using a valved manifold (23) it too is regulated (24), then sent to the analyzer (25) and vented.

The manifold consists of 4 ball valves, three for samples and one spare. The sample and reference flows are regulated by

Matheson low pressure brass regulators and the analyzer's own flow regulators. The analyzer is equipped for all necessary calibration.

f. Valving and Piping

There are a total of 25 valves on the repurifier. (Refer to Figure 5).

Five of these are extended stem cold valves. There are four Whitey stainless steel 12 NBSW8T 1/2 in. socket weld valves used, three to control N_2 vapor flow (2,3,4) and one for LN_2 flow control (13), and one Whitey stainless steel 3NTRS4 1/4 in. swagelok valve (16) used to throttle liquid air from the separator. Schematics of the two types of extended valves can be seen in Figures 13 and 14.

There are four more 1/2 in. socket weld valves used as fill valves. One to inlet LN_2 to the LN_2 pot (1), two to inlet and outlet the purge stream (5, 18), and one N_2 vent (34).

There are six Circle Seal relief valves. Two of these valves are high pressure (2000 psi) used to relieve the helium stream before (17) and after (6) the charcoal bed in case of a pressure buildup. The other four valves are low pressure (25 psi) used on the N_2 cooling lines. They are placed before the charcoal bed (19), at the N_2 exit of the LN_2 pot (35), at the N_2 exit of the charcoal bed (36), and on the LN_2 fill line (33).

There are nine Whitey ball valves used. Four B42S4 , 1/4 in. swagelok valves are used for the gas analyzer manifold (23).

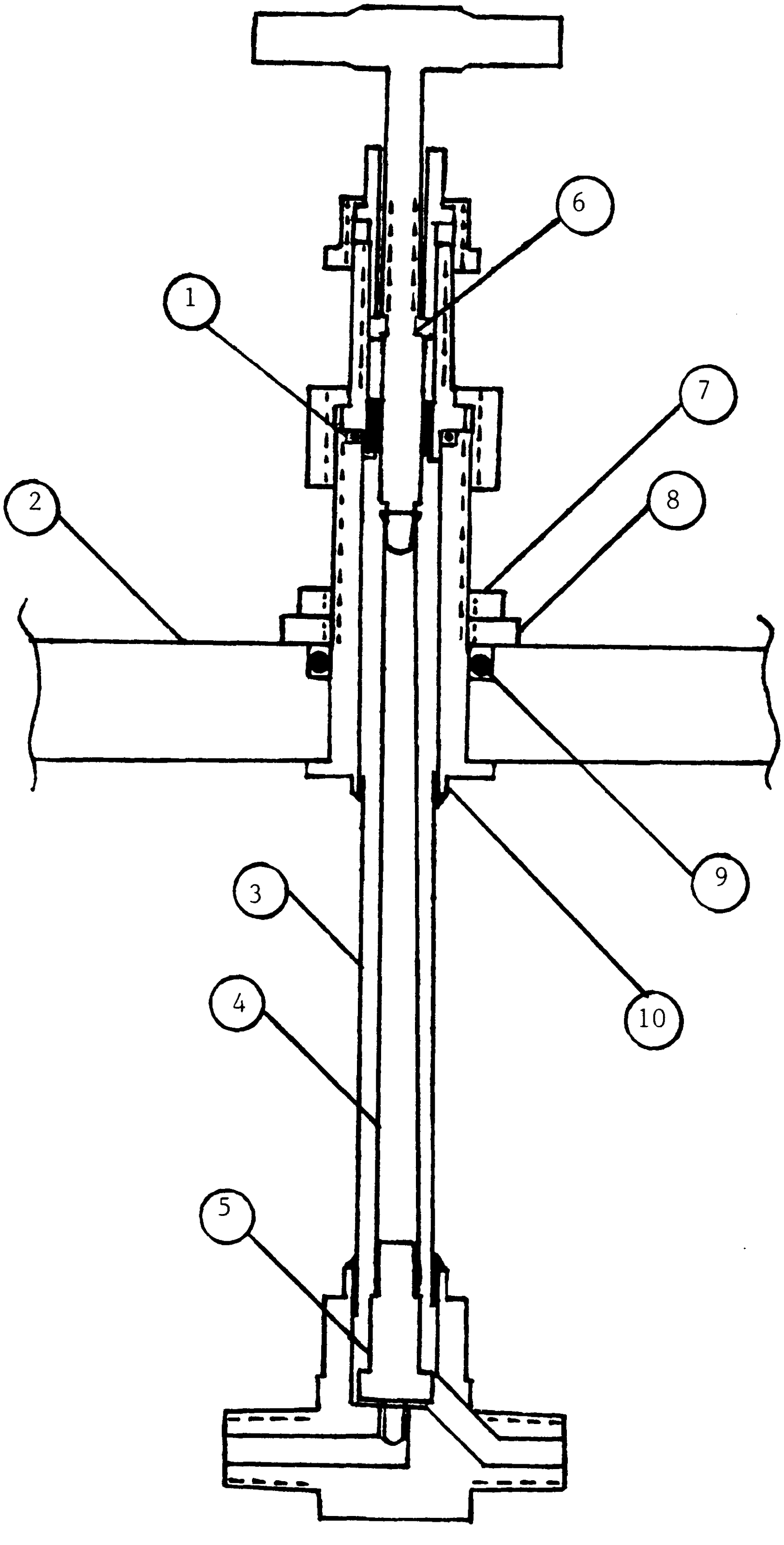

FIGURE 13- EXTENDED

VALVE- 3NTRS4

1.	O-ring
2.	Top plate
3.	1/2 in. X .028 in. 304 S.S. tube
4.	1/4 in. X .028 in. 304 S.S. tube
5.	Cut valve stem
6.	Valve stem w/o back seat
7.	Tightening nut
8.	Spacer
9.	O-ring
10.	Adapter

FIGURE 13 (CON'T)

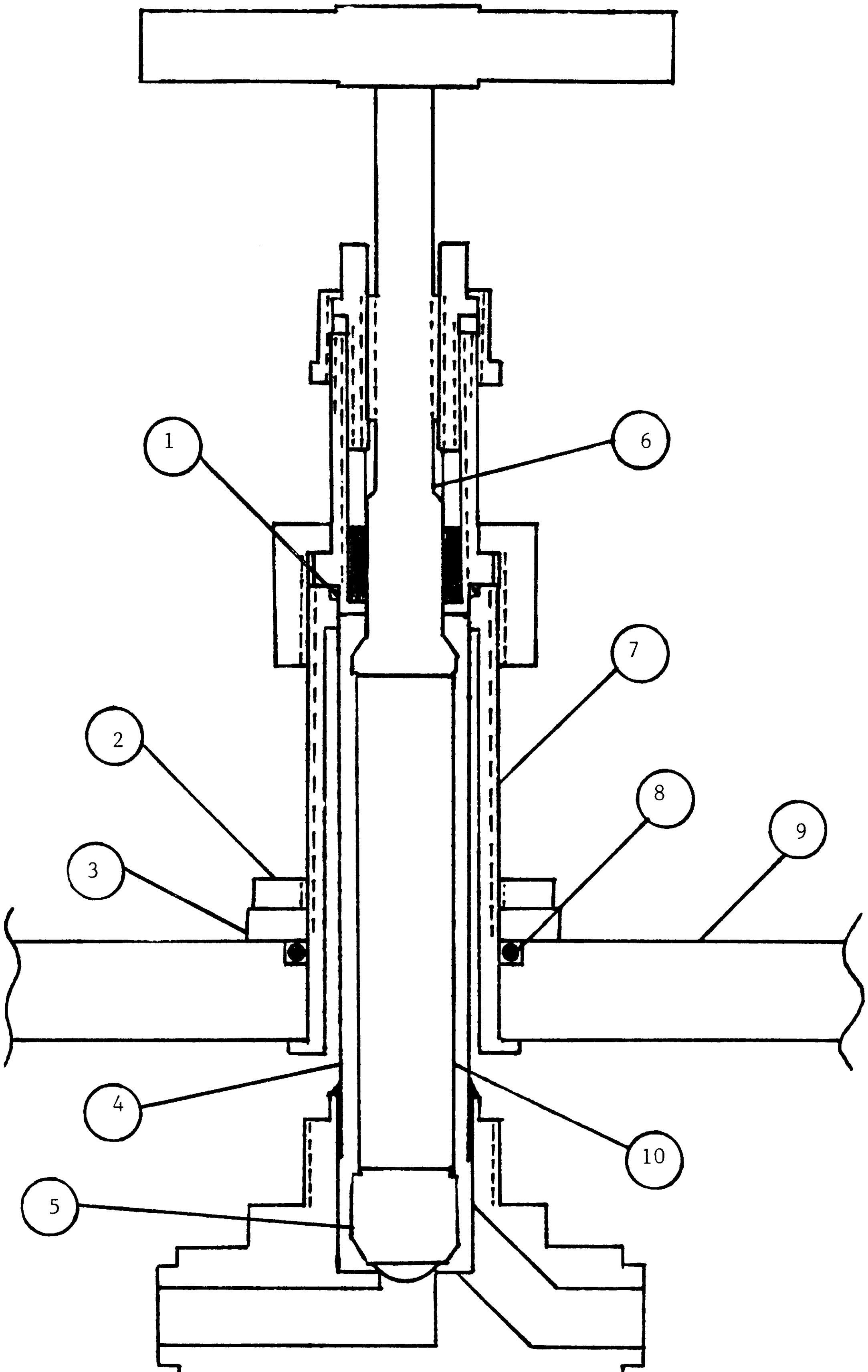

FIGURE 14- EXTENDED

VALVE 12NBSW8T

1.	O-ring
2.	Tightening nut
3.	Spacer
4.	7/8 in. X 0.035 in. 304 S.S. tube
5.	Cut valve stem, bottom
6.	Cut valve stem, top
7.	Adapter
8.	O-ring
9.	Top plate
10.	11/16 in. X 0.020 in. 304 S.S. tube

FIGURE 14 (CON'T)

The remaining five ball valves are B45S8s. Four of these are used as the inlet (9) and outlet (10, 11, 12) for the helium stream, while the fifth (8) valves the connection for the line vacuum pump.

The final valve (20) is a Vacuum valve used on the vacuum jacket pump down line.

Most of the repurifier piping consists of 1/2 in. O.D. seamless 304 stainless steel tubing. This was chosen to cut down on line pressure drop. The condensed air lines consist of 1/4 in. O.D. tube and the gas analyzer line is 1/8 in. O.D. tube. The 1/8 in. tube was chosen to create pressure and temperature drops in the line before entering the analyzer.

All repurifier internal fittings are stainless steel socket weld.

g. Vacuum Jacket

This is the outer jacket of the repurifier. It contains all other components. The other components are suspended and all feedthroughs go through the top of this jacket. The jacket is evacuated to thermally isolate the components. It is constructed mainly of stainless steel in order to minimize corrosion problems and outgassing problems due to the vacuum. The complete vacuum jacket is made of three parts, the upper jacket, lower jacket and transducer housing.

The upper jacket consists of a 30 in. O.D. 10 gage rolled 304 stainless steel tank, seven feet in length. At the top of this tank is welded a flange, 34 in. O.D., seen in Figure 15. The flange is used to bolt on the upper plate and as a seat for an o-ring.

The top plate, 5/8 in. thick, as seen in Figure 16, contains all the repurifier feedthroughs except the vacuum connection which is a 1 in. tube welded into the side of the upper jacket. The top plate also contains threaded holes for lifting eyes, and suspension rods. All connectors are made through this plate to facilitate repurifier assembly.

From Figure 16 we see that there are two types of weld preps. On the C and D holes an o-ring is used as a seal. An example of a C hole is shown in Figure 17. These holes are

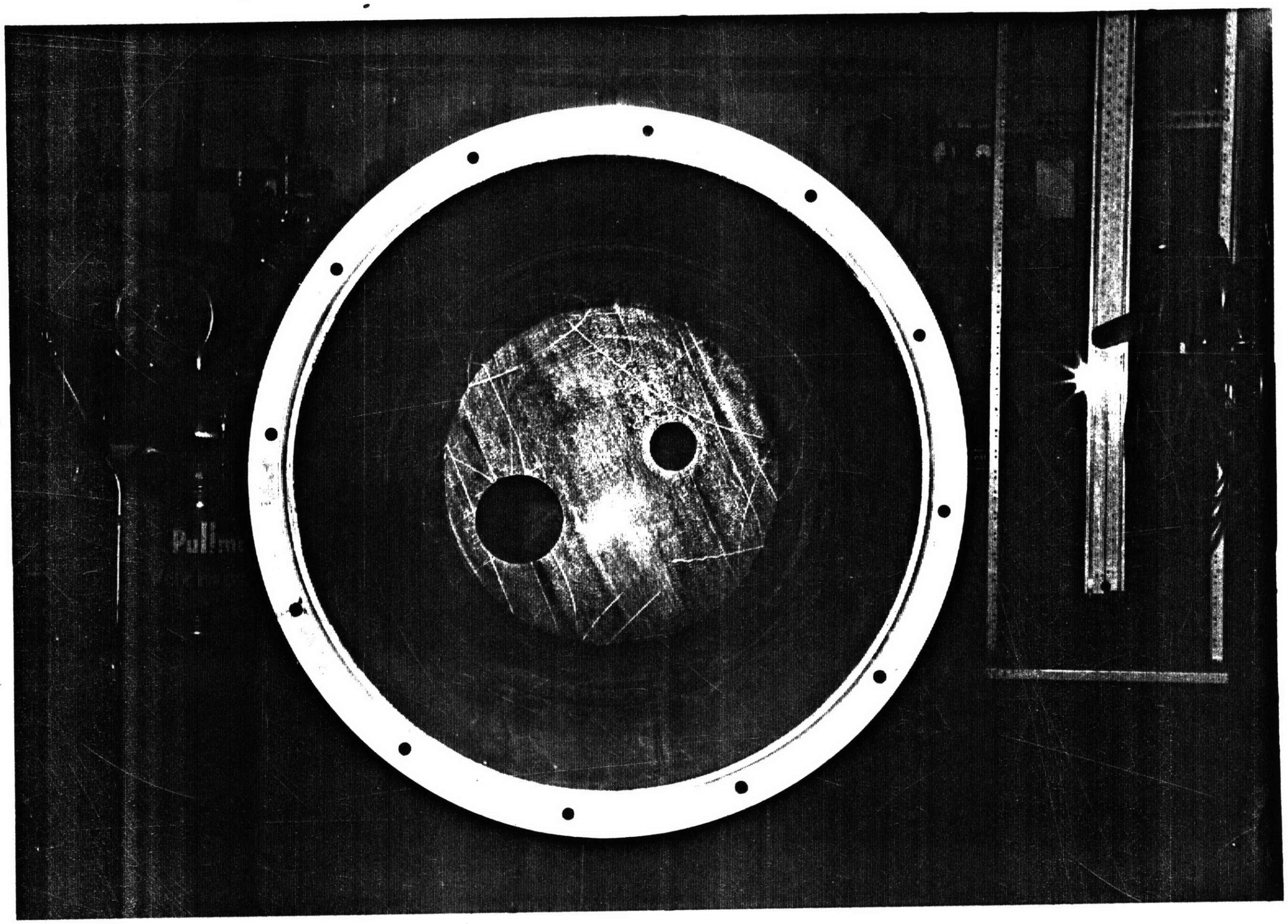

FIGURE 15 - TOP VACUUM FLANGE

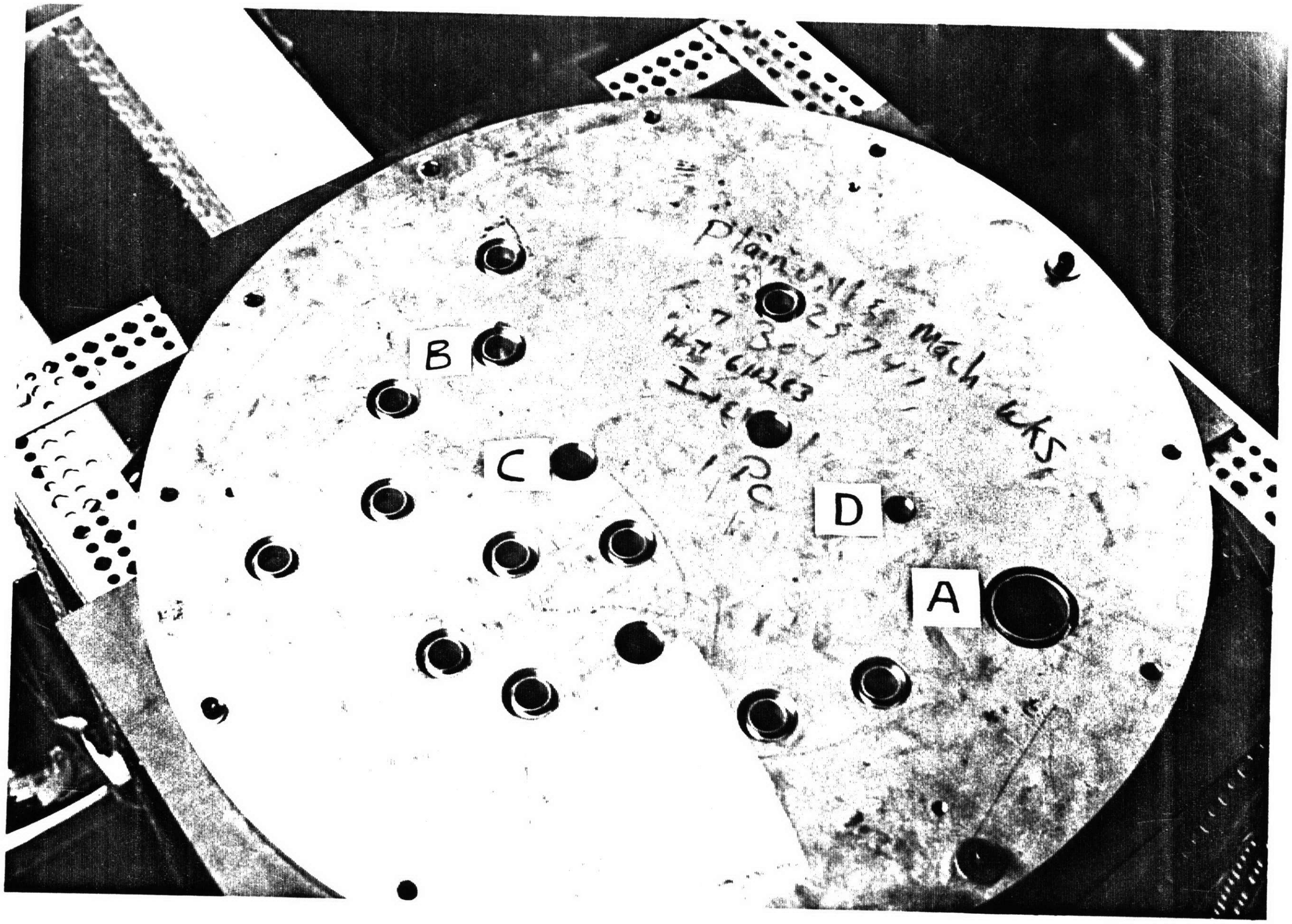

FIGURE 16 - TOP VACUUM PLATE

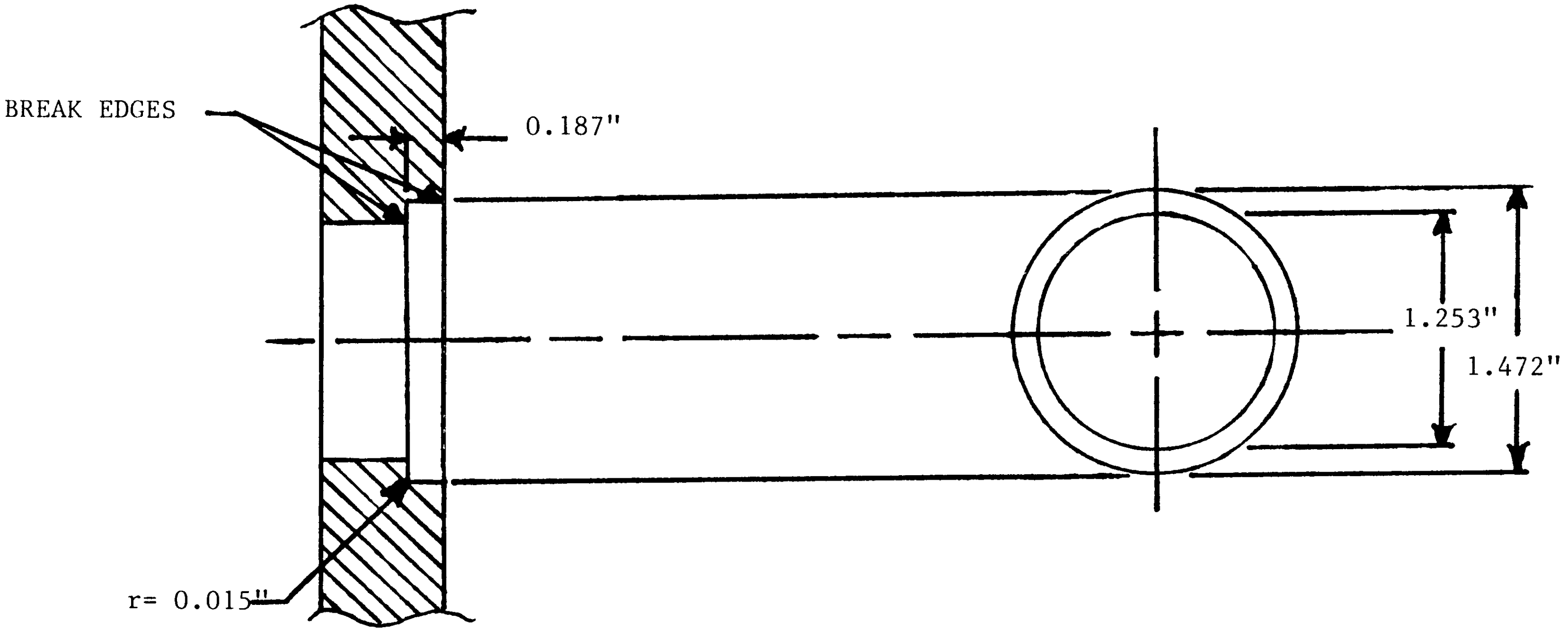

FIGURE 17- EXAMPLE OF A "C" HOLE

used for the extended valves. Their setup can be seen by referring back to Figures 13 and 14. This setup is used in order to allow for the possible removal of the valves at some later time. The valves can be easily assembled or disassembled by means of a tightening nut.

On the A and B holes, an example of an A hole is shown in Figure 18, grooves are machined and tubes are welded into the holes. On the top of the tubes are welded adapters which accept whatever is being fed through. These adapters are shown in Appendix F. This scheme isolates the feedthroughs to prevent freezeup of the plate. They are more permanent setups than the C and D holes since the removal of one of these feedthroughs calls for cutting or grinding of welds.

At the bottom of the upper jacket is welded a plate 5/8 in. thick shown in Figure 19. This plate contains two through holes, 4 in. and 7.75 in. O.D., with threaded bolt holes, 1/4 in.-20, 1/2 in. deep, where the lower jacket and transducer housing are attached.

The lower jacket is needed to jacket the 15 foot charcoal bed. It consists of a welded flange 10 in. O.D., shown in Figure 20, used to attach it to the upper jacket and as a seat for an o-ring seal. An 8 in. O.D., .12 in. thick 9.5 ft long stainless steel tube used as the lower tank, and a lower plate welded to the lower tank and shown in Figure 21.

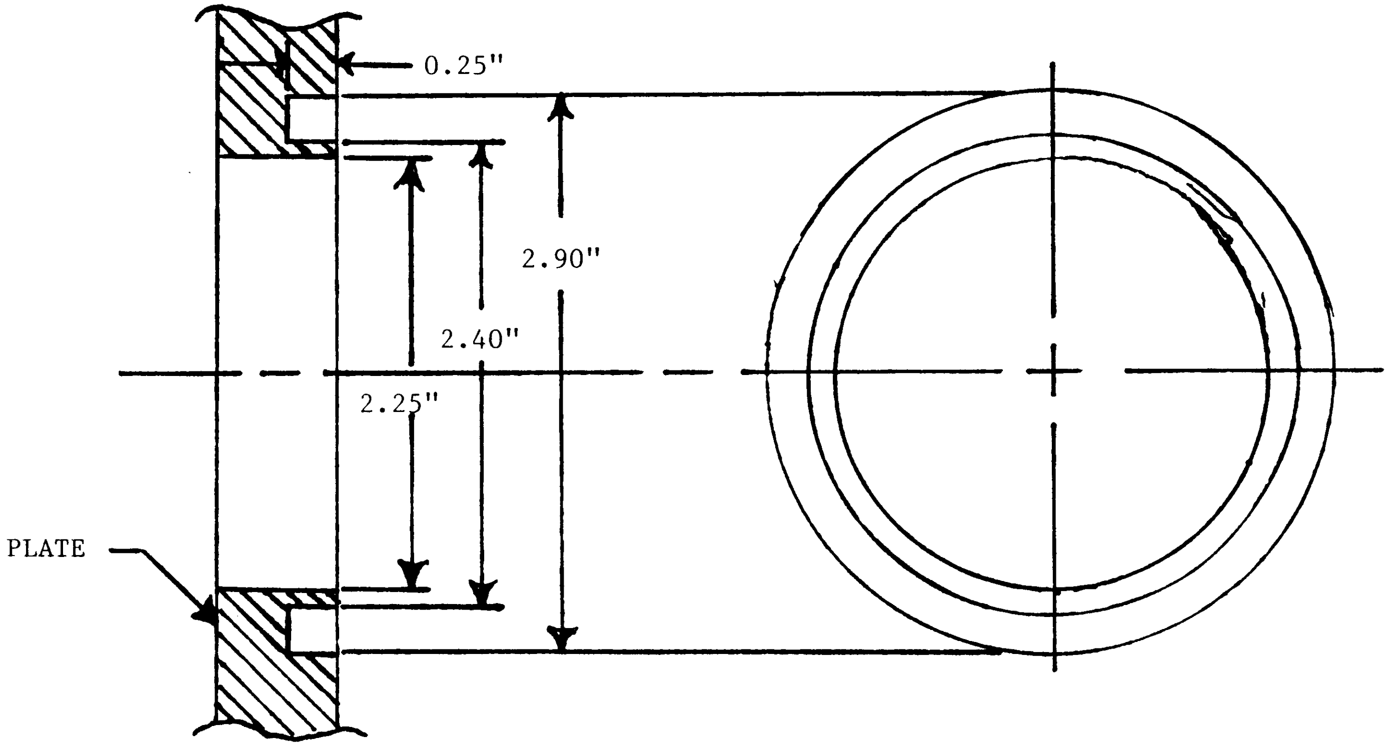

FIGURE 18- EXAMPLE OF AN "A" HOLE

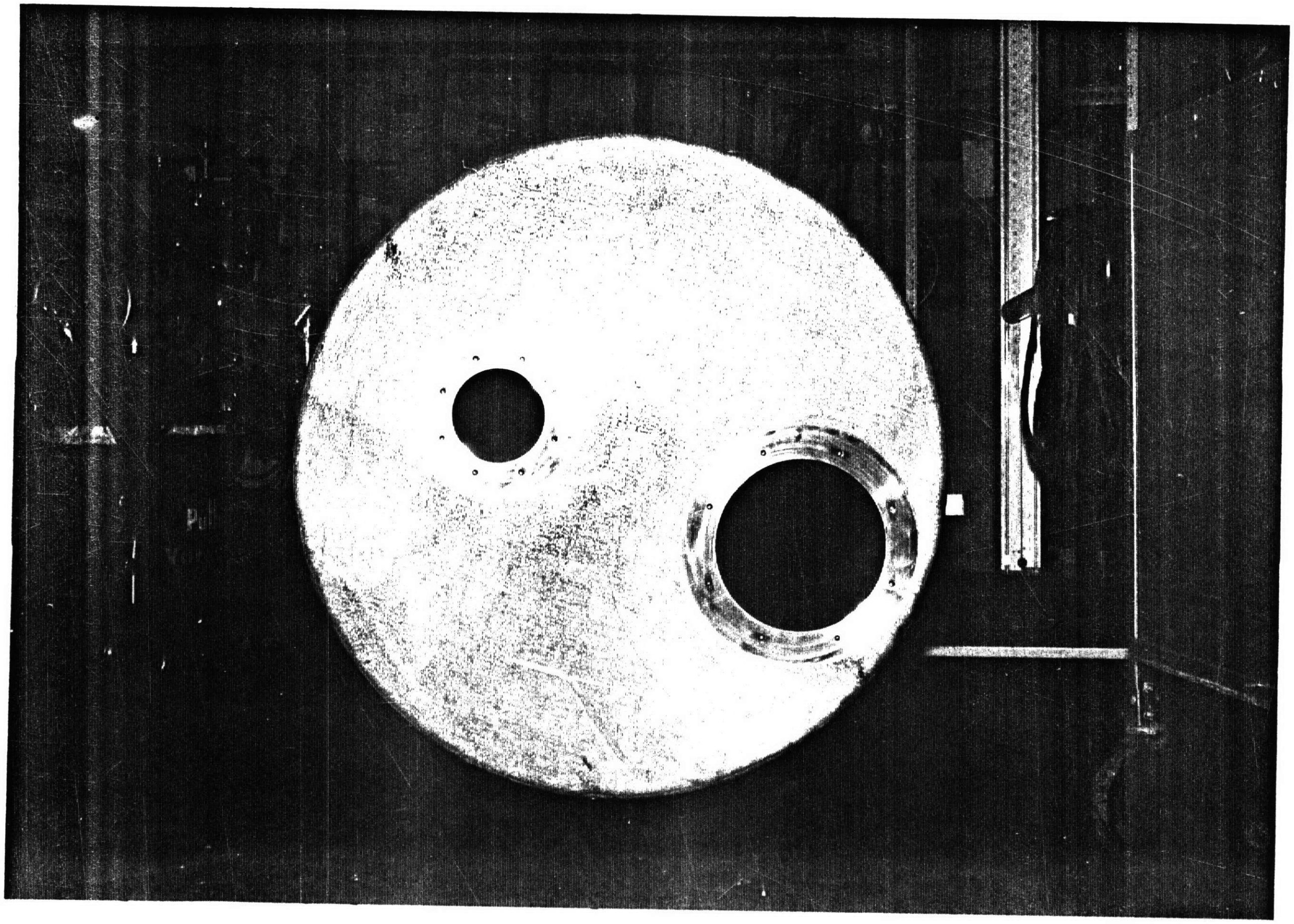

FIGURE 19 - BOTTOM VACUUM PLATE

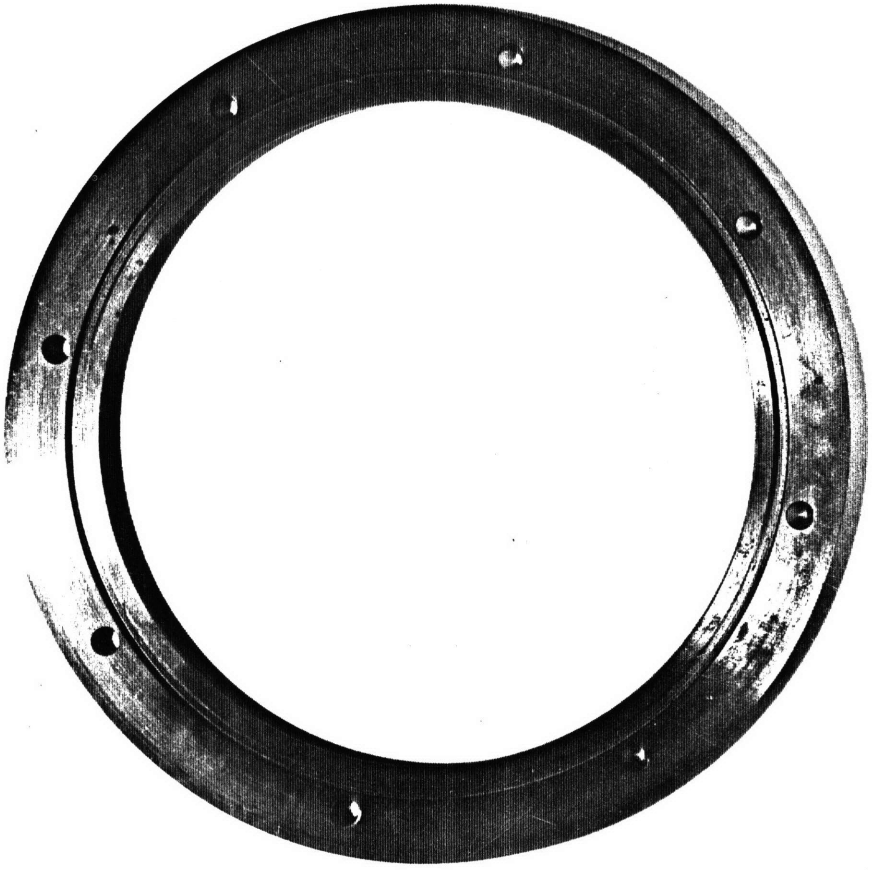

FIGURE 20 - LOWER VACUUM FLANGE

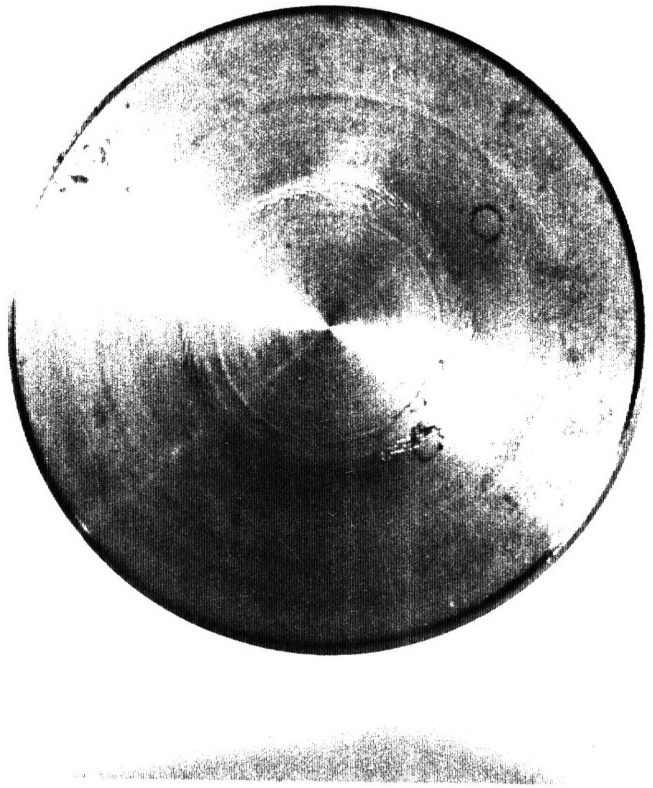

FIGURE 21 - LOWER VACUUM PLATE

The transducer housing is a separate, removable jacket which makes the load cell easily accessible in case of problems. It consists of a welded flange 6.5 in. O.D., shown in Figure 22, also used for attachment and an O-ring seal. A 4 IPS schedule 40, 5 1/2 in. length of stainless steel pipe used as the housing, and a lower plate welded to the housing and shown in Figure 23. In the lower plate is machined a groove where the load cell sits. This groove keeps the load cell from sliding in the housing. Load cell leads are fed through the lower plate.

Stress and collapse calculations for the vacuum jacket can be found in Appendix G.

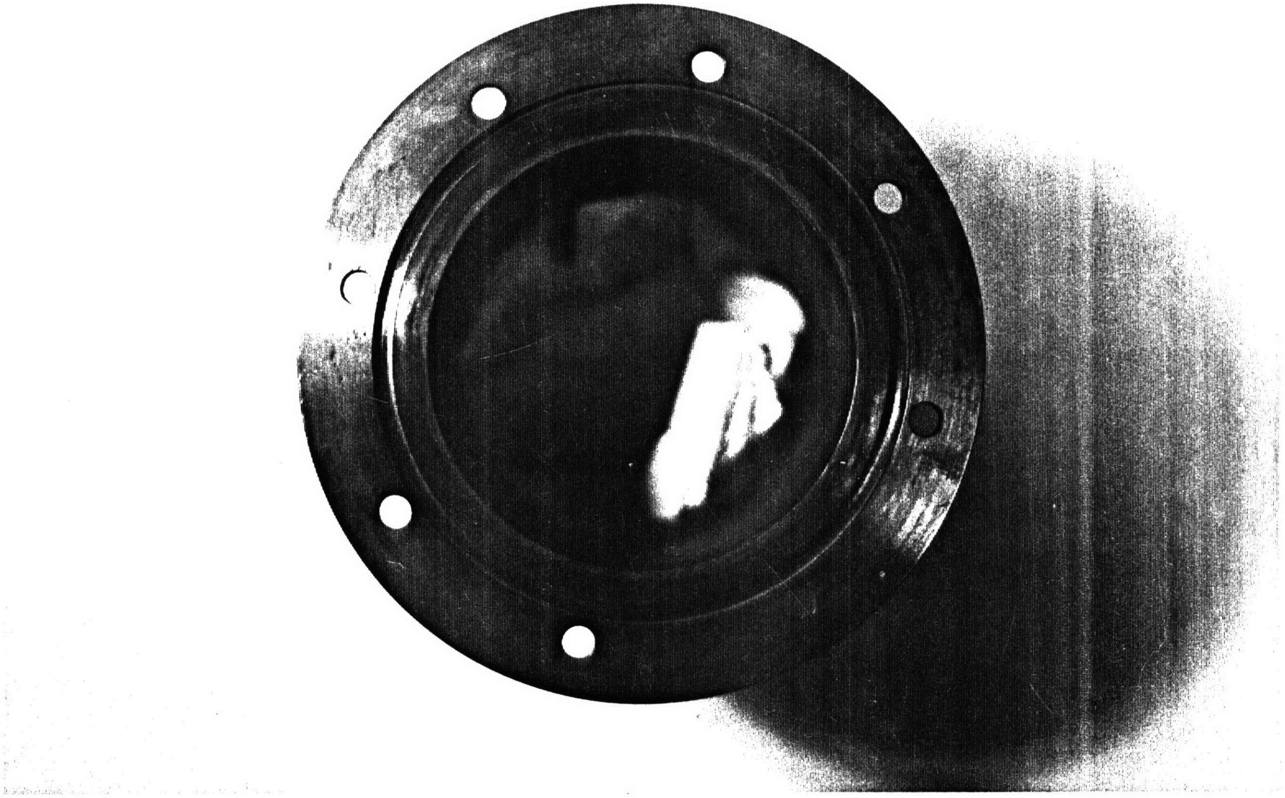

FIGURE 22 - TRANSDUCER HOUSING FLANGE

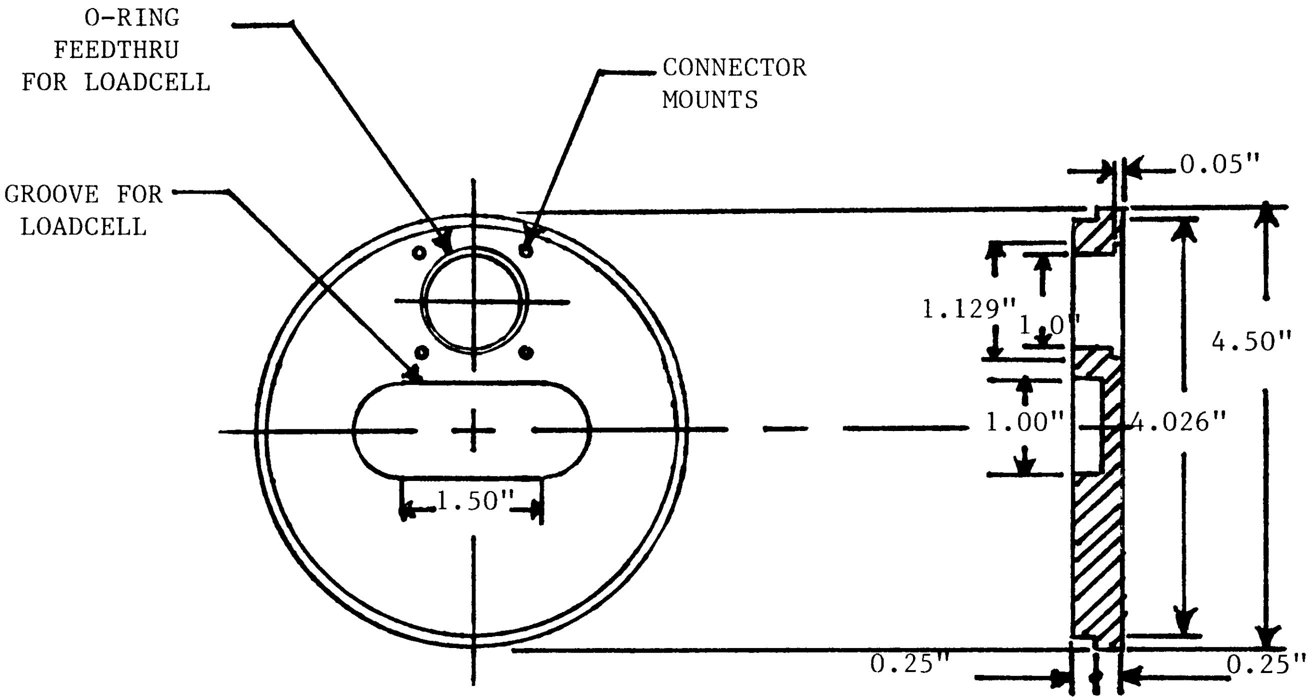

FIGURE 23- TRANS. HOUSING LOWER PLATE

3. Operation

Refer to flow diagram Figure 5.

a. Repurification System

The impure helium enters the repurifier from the drier through a ball valve (9). The helium then goes through two five foot lengths of Joy Tube heat exchanger (31). It travels through the outer annulus of the joy tube being cooled by N_2 vapor contained in an outside jacket and cold pure helium which is exiting the repurifier via the inner two joy tube annuli.

At this point the helium should be near LN_2 temperature. Its purity level can be checked by the gas analyzer (25) by opening the correct sample ball valve (23).

Now the helium proceeds to the LN_2 pot (28) and is cooled to LN_2 temperature in the cooling coil. Here the air contaminant will condense out of the gas and be carried into the separator (29) where the condensate is separated from the gas by gravity.

The helium exits the top of the separator and again can have its purity level checked by the manifold (23).

The helium now goes to the charcoal bed (30). A 2000 psi relief valve (17) is connected at the bed entrance to prevent overpressurization of the bed. Here all residual contaminants are removed from the helium. Upon exiting the bed helium purity can again be checked by opening the manifold (23). Another 2000 psi relief valve (6) is placed at the exit of the bed to prevent heat exchanger overpressurization in case of clogs.

The cold pure helium now enters the inner two annuli of the heat exchanger and cools the incoming helium. The warm pure helium exits the repurifier through a ball valve (10) and is sent to pure storage.

b. Cooling system

The cooling system begins with the LN_2 pot being filled from storage thru valve (1). Some of the LN_2 is vaporized by the incoming helium and pressurizes the cooling system. A low pressure 25 psi relief valve (33) is installed to prevent pot overpressurization. The LN_2 flows from the bottom of the pot through an extended stem control valve (13) to the separator cooling coil. Another 25 psi relief valve (19) is placed in the line here.

From here the N_2 enters the charcoal bed cooling coil. Upon exiting the bed the N_2 flow is again relieved by valve (36).

At this point the N_2 flow may either be sent back to the LN_2 pot via valve (3) or it can be sent on to the heat exchanger via valve (4).

If sent to the heat exchanger the N_2 vapor can be supplemented with air condensate from the separator by opening throttle valve (16). It can also be supplemented with more N_2 vapor from the top of the LN_2 pot via valve (2).

Whichever combination is chosen the cooling stream is relieved at the heat exchanger entrance, flows through the outer jacket and upon exiting is vented to the atmosphere.

c. Purging system

The purging system consists of a warming stream of nitrogen. This nitrogen can be at ambient temperature or heated. This stream enters the repurifier through a fill valve (5) and goes into the charcoal bed cooling coil. Valves (3) and (4) are closed to confine the purge stream to the charcoal bed. The stream goes through the coil warming the bed. When the stream exits the bed it is again forced, by the closing of valve (13), to exit the repurifier through valve (18) and vent to the atmosphere.

The warming stream is allowed only in the charcoal bed to minimize the mass heated up and therefore the mass needed to be cooled during the next run.

At this point all internal valves are opened and all other valves closed. Now the entire system is evacuated through a ball valve (8) in a branch of the helium inlet line. This evacuation lowers the partial pressure of the contaminant causing desorbtion and removes any other contaminant from the system.

After desorbtion is complete the repurifier is recooled and ready for normal operation. Purge flow rate and time are roughly 1 scfm of N_2 for 23 hours at ambient temperature. Calculations can be found in Appendix A.

B. Drier

1. Design Objectives

The design goals for the drier are:

1) To remove moisture from recovered helium gas at a rate of 50 scfm at 2000 psi.

2) To attain a contaminant level below 50 ppm by volume.

3) To regenerate adsorbers.

4) To run continuously by using 2 adsorbers in parallel.

These goals require the unit to be of adequate size and strength to accept the volume and pressure of gas specified. They require high quality adsorbent, to attain the desired purity level, along with piping connections and a secondary purging system which can be used by one adsorber while the other is in operation.

2. Components

A detailed flow diagram of the drier is shown in Figure 24. Each component will now be discussed.

a. Cylinders

As seen in Figure 24 there are two cylinders run in parallel. This is so that the drier can be run continuously by simply switching adsorber cylinders. It eliminates the problem of coordinating drier adsorber and charcoal adsorber regeneration cycles.

The cylinders used are Robbins Aviation Inc. purifier chambers model 10ASP with a maximum flow rate of 525 scfm and a maximum pressure of 10,000 psia. These cylinders are used because of their appropriate specifications and availability. A schematic of a cylinder is shown in Figure 25.

The cylinders have internal end threads at each end which accept threaded end plugs. These plugs have integral O-ring grooves used for sealing the cylinders. All connections are made in the top plug. It has inlet and outlet connections which use swagelok O-ring fittings for sealing.

On the cylinder side of the inlet in the top plug is another O-ring groove used for sealing an adsorbent canister. This canister is not used

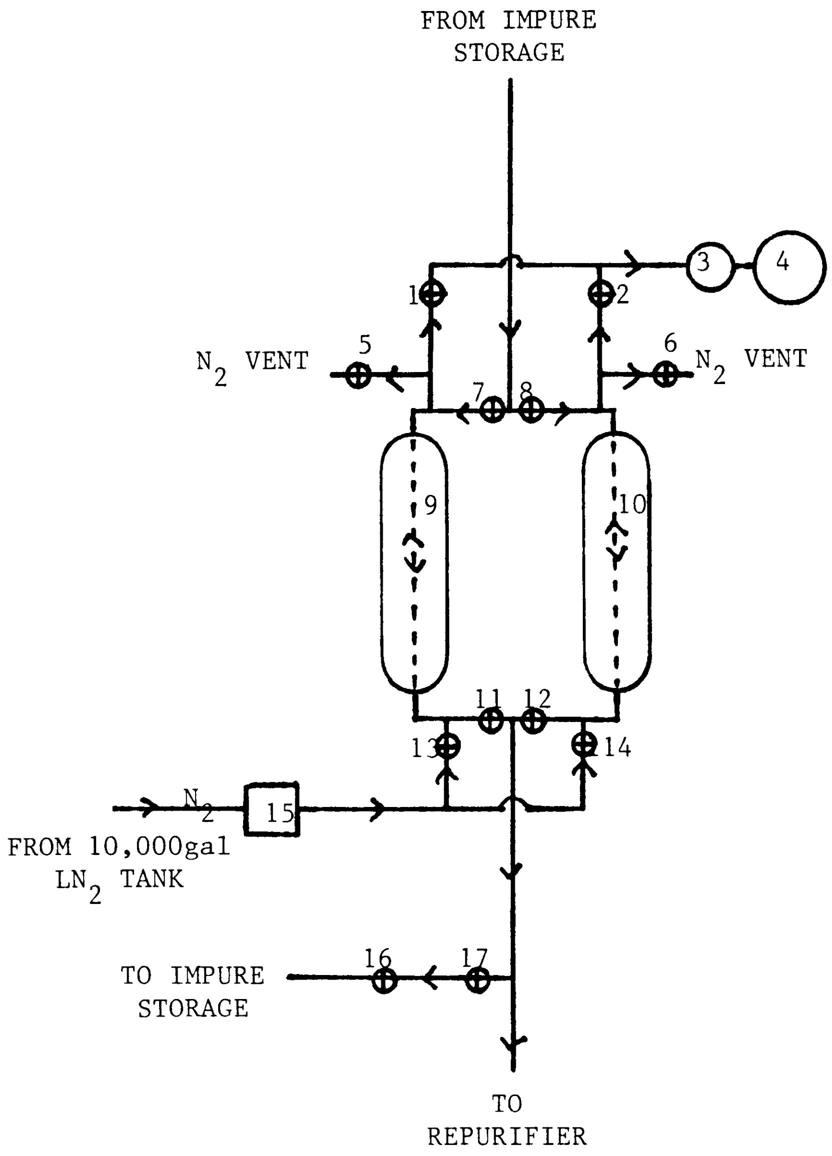

FIGURE 24- DRIER FLOW DIAGRAM

1,2.	Evacuation valve, Whitey B44S6 Ball valve, 3/8 in.
3.	Condensate trap
4.	Vacuum pump
5,6.	N_2 vent valve, Whitey B44S6 Ball valve, 3/8 in.
7,8.	Adsorber switching valve, TOP, Whitey B44S6 Ball valve, 3/8 in.
9,10.	Adsorber columns
11,12.	Adsorber switching valve, BOTTOM, Whitey B44S6 Ball valve, 3/8 in.
13,14.	N_2 inlet valve, high temp. Whitey 6TS6, 3/8 in.
15.	Heater, Hotwatt 12 in., 120 vac. 20 amps
16	Back pressure regulator, Grove S-91-W
17	Storage valve, Whitey B44S6 Ball valve, 3/8 in.

FIGURE 24 (CON'T)

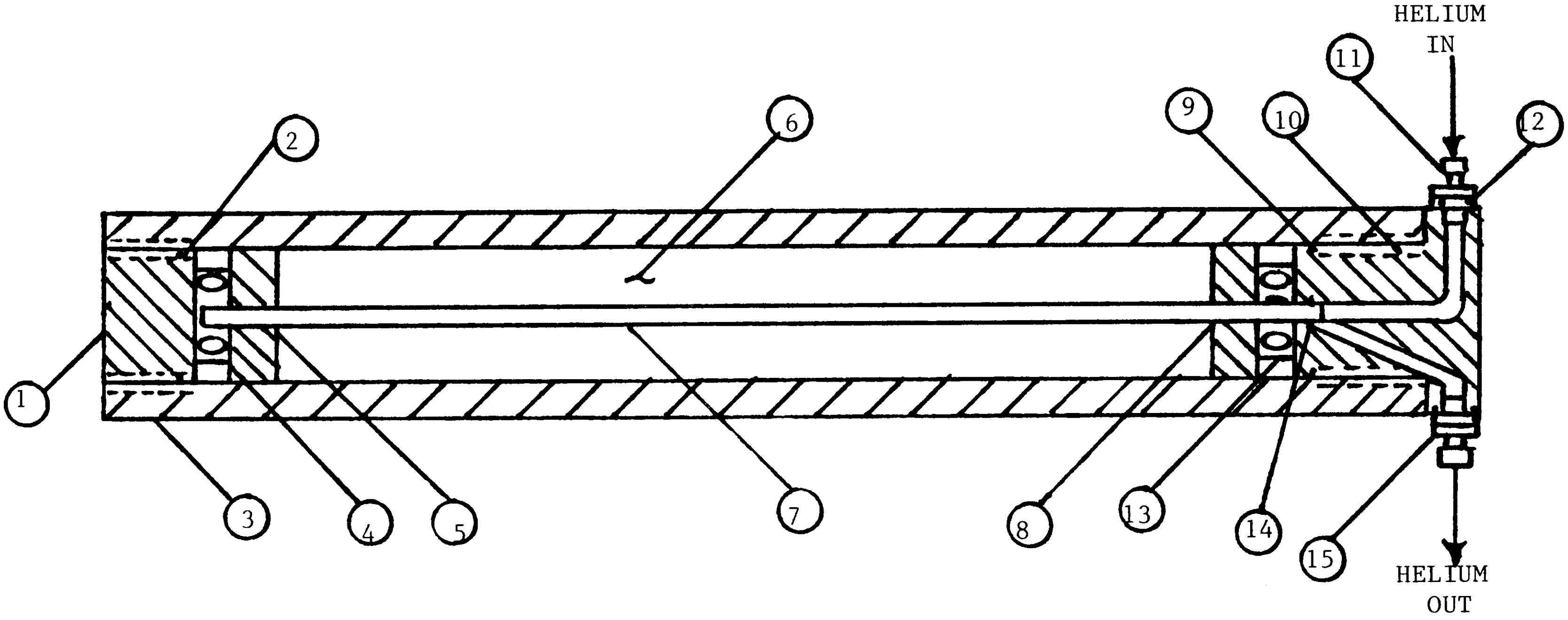

FIGURE 25- DRIER CYLINDER SCHEMATIC

1.	Bottom end plug
2.	O-ring
3.	Cylinders
4,13.	Spacers
5,8.	Filter material
6.	Molecular sieve
7.	1/2 in. tube
9.	O-ring
10.	Top end plug
11,15.	Swagelok O-ring fitting
12.	O-ring
14.	O-ring

FIGURE 25 (CON'T)

in the drier, instead loose molecular sieve pellets are used, but the O-ring will be used to seal the 1/2 in. helium inlet tube.

The cylinders will be mounted on a wall using unistrut members.

b. Molecular Sieve

Molecular Sieves belong to a class of compounds known as zeolites. Zeolites are naturally occuring, however they are scarce and therefore synthetic zeolites are generally used. They are crystalline metal alumino silicates that are activated for adsorbtion by removing their water of hydration with heat. This removal causes little change in compound structure and therefore a very porous adsorbent is formed with a strong affinity for water and certain gases. (see reference 4).

The pores of molecular sieve are uniform in size and of molecular dimensions. This allows for a high selectivity on the basis of molecular size. However once a molecule is admitted, its volitility, polarity and degree of unsaturation also play a part in how tightly the molecule is held. These properties along with a high adsorption capacity make molecular sieve a very efficient adsorbent.

The pores of molecular sieve type A which is used in this project are roughly spherical and about four angstroms in diameter (see reference 4).

This pore size makes this sieve especially good for water adsorption. These pores account for about half of the total adsorbent volume.

The strong adsorption forces in molecular sieves are due mainly to exposed cations in the crystal lattice. These cations strongly attract negative charges on polar molecules such as water and can induce dipoles in non-polar molecules. Of course the more polar the molecule the more strongly it is attracted. Molecular sieves are characterized by langmuir type isotherms in which adsorption capacity increases to a saturation point and then remains level. This saturation point corresponds to the filling of the sieve internal voids.

This type of adsorbent was chosen over silica gel etc. because of its high drying efficiency. It has been reported to dry gas to a water content of 0.05 ppm by volume.

An estimate of adsorption capacity is given by Union Carbide Linde Div. data sheet F-43A-1 as 20 lbs of water adsorbed per 100 lbs of molecular sieve type 4A pellets at drier conditions.

Using 10 lb/lb as a conservative estimate of breakthrough capacity, as explained in section IIIA, 1a, it is found that 15 in.^{3} of sieve is needed per hour of run at 50 scfm, water saturated helium. All molecular sieve calculations can be found in Appendix E. Therefore a full cylinder holding about 165 in.^{3} of sieve will last for 11 hours of operation before regeneration is needed.

The pressure drop through the drier bed is negligible compared to the 2000 psi working pressure.

Purging of this unit is done using heated dry nitrogen gas from the 10,000 gallon LN_2 tank @ 30 psi, and evacuation. When one of the cylinders is saturated the helium flow is switched to the other cylinder. The dirty cylinder is then heated by a counter-current flow of nitrogen at 5 scfm and 500^oF, regulated by the vent valve. The nitrogen is heated using a Hot Watt Inc. 2.4 kw, 12 in. standard air heater. Its temperature is controlled using a surface mount thermostat and relay as a thermoswitch. The temperature and flow of the nitrogen were recommended by Union Carbide. The bed reaches 500^oF after about 1.25 hours. At this point the nitrogen flow is stopped and the bed is evacuated. This method of regeneration is in principle the same as that used in the charcoal bed.

c. Cylinder Interior

Aside from the molecular sieve (6) the cylinder interior contains tubing, filtering material and spacers. These can be seen in Figure 25.

The tubing (7) is put on the interior inlet port and runs to the bottom of the cylinder. This tube, which is sealed by an O-ring (14), carries the helium to the bottom of the bed.

Filtering material (5,8) such as glass wool is put at the ends of the cylinder to filter out any oil that gets thru the oil separator and to keep the sieve from flowing out of the cylinder. Glass wool is needed due to the high bed purging temperature. Spacers (4,13) are provided to support the bed and to keep the inlet and outlet clear of glass wool.

d. Valving and Piping

There are twelve valves used with the drier. They can be seen in Figure 24. Nine of these valves are Whitey 3/8 in. swagelok Ball valves. These valves are used for storage, purge flow control and cylinder switching. There are two Whitey high temperature valves (13,14) also 3/8 in. swagelok. These are put on the purge lines where the hot nitrogen enters the cylinders. And the last valve (16) is a Grove back pressure regulator which holds the drier pressure when helium is being sent to impure storage.

The drier piping consists of 3/8 in. O.D. 304 stainless tubing for all lines that are at working pressure. The 3/8 in. lines match up with existing system lines. The purge lines consist of 1/2 in. copper lines. These lines are at low pressure. They extend up to the valves which separate them from the high pressure system.

Drier fittings are 3/8 in., stainless, swagelok for the high pressure line and solder fittings for the low pressure line.

3. Operation

Refer to flow diagram Figure 24 and Figure 25.

a. Drying System

The helium enters one of the drier cylinders (9 or 10) from the recovery compressor and oil separator thru a ball valve (7 or 8). The helium is carried to the bottom of the cylinder by an internal tube. From here it flows upward thru the filter material and molecular sieve and is dried. The dry helium flows from the cylinder thru another ball valve (11 or 12) and then either to the repurifier or to impure storage. This continues until the cylinder is saturated with water at which time the cylinder is valved off and the other cylinder is opened for operation.

b. Purging System

The N_2 vapor used for regeneration is from an existing 10,000 gallon LN_2 tank at 30 psi. The N_2 flow is regulated to 5 scfm and goes to the heater (15) where it is heated to 500°F. From here the N_2 enters the outlet of the cylinder thru a high temperature valve (13 or 14). The N_2 flows countercurrent to the helium flow so that in the event the bed is not fully regenerated the helium flow will be in last contact with that portion of the bed which is most fully regenerated. The N_2 flows thru the cylinder heating it, and then out and thru a ball valve (5 or 6) to be vented. The N_2 flows for about 1.25 hours at which point the entire bed is at 500°F. Now all valves are closed, except the vacuum pump ball valve (1 or 2), and the system is evacuated. The evacuated N_2 is passed thru a cold trap (3) in order to remove moisture before it enters the vacuum pump (4). After evacuation the bed is again ready for operation.

The reasons for heating and evacuating are the same as for the charcoal adsorber. Both processes lower the adsorption capacity of the adsorbent causing desorption. However one difference is that the warming flow in the drier is in physical contact with the adsorbent. As long as the nitrogen is free of water vapor this is fine since beside heating the adsorbent the nitrogen will also lower the partial pressure of water vapor causing more desorbtion.

Any residual nitrogen that might be left after heating will be displaced by evacuation.

C. Other System Components

1. Design Objectives

The design goals for peripheral system components are:

1) To integrate the drier and repurifier into the existing central liquefaction system.

2) To provide helium recovery capability.

3) To provide pure and impure helium storage capability.

Theses goals require expanding the use of some existing system components along with the addition of new components. They also require the matching of new and existing equipment.

2. Components

For a flow diagram of the helium recovery and repurification system refer to Figure 2. Each component will now be discussed.

a. Piping

The route of the main recovery pipeline from FBNML is shown in Figure 26.

The line ends at SGTF where it intercepts an existing line to CEL. The line from FBNML is a low pressure 1 in. O.D. soldered copper line, while the return line is a high pressure 1/2 in. O.D. welded stainless line.

Miscellaneous piping of components is done to match existing piping consisting mainly of 3/8 in. O.D. 304 stainless tubing. Fittings are generally 3/8 in. swagelok.

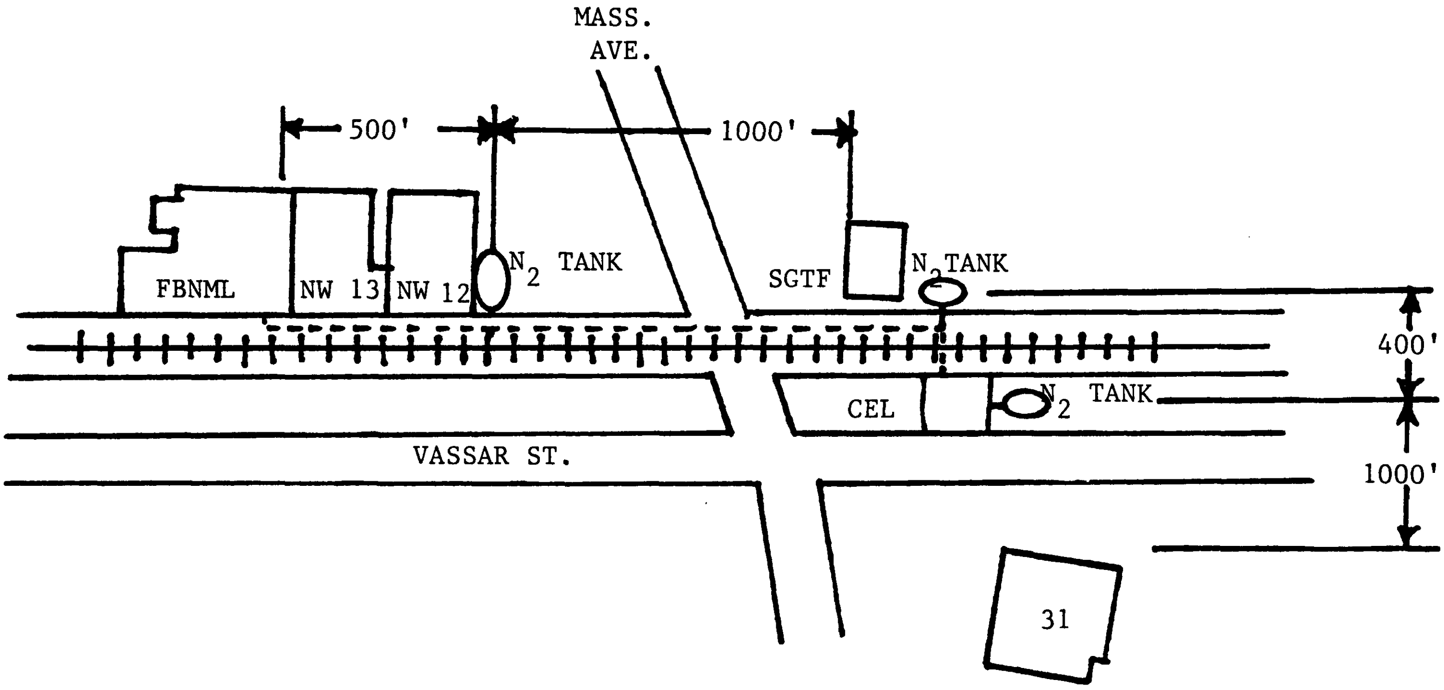

FIGURE 26- HELIUM RECOVERY

PIPE LINES AND STORAGE TANKS

b. Gas Bags

There are two gas bags. An existing small 200 scf bag (4), located in the basement of CEL, and a large 2000 scf bag (3). The large bag will be put in parallel with the small bag, as seen in the flow diagram Figure 2. It will be located in a shed on the roof of CEL. Both bags are used as low pressure impure storage which can be used to supplement a low impure helium flow from FBNML and SGTF.

The large bag will also be connected to other points in CEL, exactly where has not yet been decided. Valving of the large bag is done with 1 in. ball valves which allow the bag to fill and exhaust.

c. Compressors

There are two existing compressors at CEL which will be used. The first is a 30 scfm, 1 atm compressor (5) which works as a slave to the second, a 30 scfm, 2000 psi compressor (6). Since the compressor provides only 30 scfm it will have to be supplemented by stored high pressure gas if the operating flow of 50 scfm is desired.

The compressor is piped into the drier with 3/8 in. stainless tube.

d. New and Existing Storage

Total existing storage capacity is about 111,000 scf of pure helium. This storage is located at CEL. All helium storage is valved into an existing manifold.

Liquid nitrogen and N_2 vapor are supplied from an existing 10,000 gallon LN_2 tank (14). The LN_2 tank is used to fill a LN_2 dewar (13) which supplies the liquefier. This dewar will now also be used to supply the repurifier.

New storage capacity will consist of 9 "jumbo tubes" providing about 64,000 scf capacity. Three of the tubes will be used for pure helium storage, three will be used for impure storage and the remaining three will be valved so that they can be used as either pure or impure storage whichever is needed. This arrangement allows for the storage of the 5000 scf of impure helium, which is to be repurified per run. However it also allows for the storage of up to 40,000 scf of impure helium if necessary.

These new tubes will be located at CEL and will be added to the existing manifold. They will be stacked in a 3 X 3 square arrangement. They will rest on three sections of 9 X 7 railroad ties with sections of 2 X 10 between the tube layers. The tubes will be held on the wood by angle irons on the top and bottom of each end of each wood section.

3. Operation

Refer to diagram Figure 2 and section IIC.

Impure helium is recovered by the system installed at the FBNML, see Figure 3. The gas flows thru the pipeline (15) to SGTF where it intercepts an existing line and flows to CEL. At this point the gas is at low pressure and flows to the gas bags (3) and (4). It can either be stored in the bags to supplement the flow at a later time or it can flow on to the compressors. The slave compressor (5) passes 30 scfm of gas at 1 atm to the master compressor (6) which compresses the gas to 2000 psi. From here the gas passes through the drier (7) and then to impure storage (8) where it is metered using tank pressures and temperatures. When enough gas has accumulated for a repurification run, about 5000 scf, the gas goes again through the master compressor and drier to the repurifier (10). After purification the gas enters the manifold and can be stored in any of the pure storage tanks (11) or sent to FBNML or SGTF.

IV. RESULTS AND DISCUSSION

From the literature it appears that a contaminant level of about 50 ppm can be achieved by this repurification system. It uses the same methods that are used in other purification systems which achieve contaminant levels below 10 ppm.

It will operate at a 20% contaminant level using 1.2 liters of LN_2 per equivalent liquid liter of pure helium which is comparable to smaller available commercial purifier units.

V. CONCLUSIONS AND RECOMMENDATIONS

It is concluded, from data and operation of similar purification systems, that the system described will meet the design specifications.

It is recommended that throttling of the air condensate be automated by interfacing the existing load cell with an automatic valve actuator. (See reference 3). This should prevent problems with over and under filling of the separator.

It may also be useful to automate other repurifier actions such as the regeneration cycle and gas transfer between components in order to minimize the need for operator intervention.

VI. SUMMARY

A helium recovery and repurification system was designed. The system handles 50 scfm of helium at 2000 psi. The helium may be contaminated to a maximum of 20% water saturated air. The gas is recovered at low pressure at the Francis Bitter National Magnet Laboratory and piped to the Cryogenic Engineering Laboratory. Here the gas is compressed to 2000 psi and sent through one of two parallel 165 $in.^3$ molecular sieve adsorber beds to be dried. The gas is then stored in impure storage until enough has accumulated for a repurification run, this amount is about 5000 scf. At this point the gas is recompressed, redried and sent to the repurifier. Most of the air contaminant is condensed out of the stream by a 10 ft LN_2 cooled Joy Tube heat exchanger. The condensate is separated by gravity in a separator. This condensate is then used for cooling along with the LN_2. The gas continues through a LN_2 cooled 1.3 ft^3 activated charcoal bed where residual contaminants are removed. The pure, cold gas exits through the heat exchanger helping to cool the incoming warm stream. The pure gas is then stored until it is needed.

The system has purity monitoring and purge capabilities. Liquid nitrogen is supplied from an existing 10,000 gallon tank. Total LN_2 consumption is about 137 liters per 5000 scf run.

APPENDIX A

Activated Charcoal Bed

a. Amount of Charcoal

The amount of air that must be adsorbed by the charcoal bed is the amount that remains in the helium stream after condensation of most of the air contaminant. Assuming a stream of 3000 scfh of air saturated helium at 2000 psi and LN_2 temperature, the amount of air remaining in the stream is,

$$\frac{V \text{ @ } 2000 \text{ psi}}{v \text{ sat air @ } -320^{\circ}F} = 6.5 \text{ lb/hr} \tag{2}$$

where, $V=22.5\ ft^3/hr$

$v=3.47\ ft^3/lb$

Using a charcoal breakthrough capacity of 100 scf air/ft^3 A.C. or 7.6 lb air/ft^3 A.C., the amount of charcoal needed per hour is 0.85 ft^3. For a complete run of 1.6 hr, 5000 scf, about 1.3 ft^3 of charcoal is needed.

The above breakthrough capacity is basically an approximation of the shape of the adsorbtion wave through the bed. To see if it is a good approximation we must do the following.

Refering to Figure 27 we will try to approximate the value of

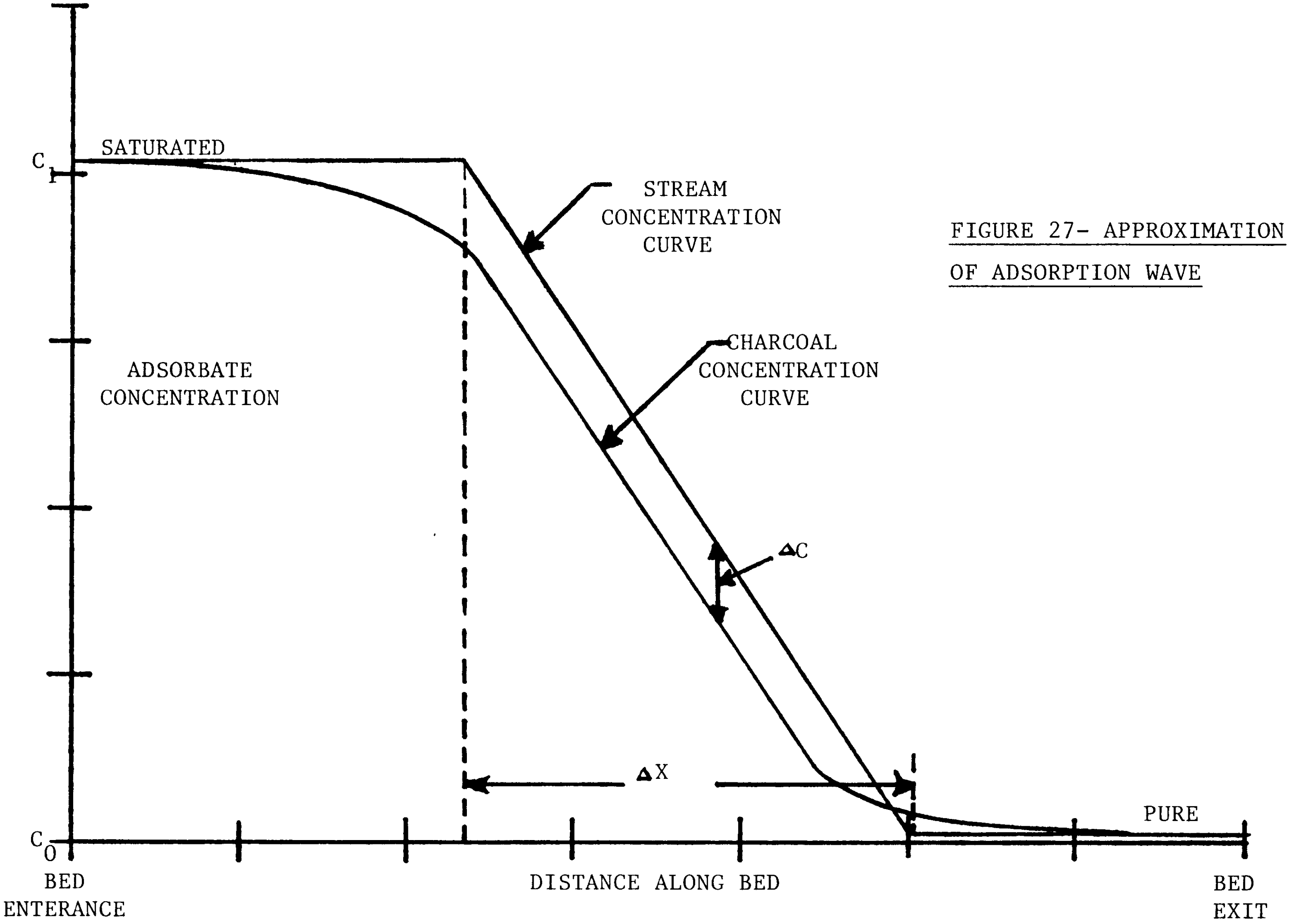

FIGURE 27- APPROXIMATION OF ADSORPTION WAVE

Δx, this is the length of bed used between saturation and breakthrough.

First we assume a linearly sloped stream concentration curve, this curve shows the concentration of adsorbate in the stream verses distance along the bed. Then we find the average driving concentration difference, Δc, between our assumed curve and a linear charcoal concentration curve.

This Δc will depend on the Δx used, therefore a Δx value is assumed and Δc is found. If the Δc is small then the charcoal curve follows our assumed curve closely. This means our assumed adsorption wave shape is accurate and that the Δx value assumed is also accurate. From here we can reasonably approximate the breakthrough capacity.

Using the equations,

$$\dot{m} = \frac{\dot{m}_H}{\rho_H} \frac{dc}{dx} \Delta x \tag{3}$$

$$\dot{m} = h_m A \Delta c \tag{4}$$

and the linear approximation,

$$\frac{dc}{dx} = \frac{c_1 - c_0}{\Delta x} \tag{5}$$

we equate the mass transfer from the stream to the mass transfer between the stream and charcoal. This is done by combining eqs. 3 and 4 to get,

$$\frac{\dot{m}_H}{\rho_H} (c_1 - c_0) = h_m A \Delta c \tag{6}$$

where, $\dot{m}_H$ = 24 lb/hr

ρ_H = 5.24 lb/ft^3 , @ 2000 psi

$c_1 - c_0$ = change in bed adsorbate concentration

h_m = mass transfer coefficient

A = mass transfer area

To find $c_1 - c_0$ we assume c_1 to be the total 6.5 lb of air in the incoming volume, which is 8.3 ft^3 at 2000 psi. This gives c_1= 0.783 lb/ft^3. The exit concentration, c_0, is considered negligible. Therefore $c_1 - c_0$ = 0.783 lb/ft^3.

To find A we assume the charcoal to be small spheres, in this case of diameter 0.0078 ft. We calculate the volume of the spheres, and the volume of the bed over the length. Δx. Now the number of spheres that fit in the bed volume is found and multiplied by the sphere surface area to get A = 88.4Δx.

The mass transfer coefficient is found using,

$$h_m = \frac{j_D V}{(Sc)^{2/3}} \tag{7}$$

see reference 1

where, j_D = Chilton-Colburn factor

V = stream velocity, ft/hr

Sc = Schmidt number

To find j_D we use,

$$j_D = 1.82\ (Re_d)^{-0.51} = 0.2 \qquad (8)$$

Re_d is given by,

$$\frac{\rho\ V\ D_p}{\mu} = 70.57 \qquad (9)$$

where, $\rho = 5.24\ \text{lb/ft}^3$, @ 2000 psi, -320°F

$u = 0.03$ lb/hrft

$D_p = 0.0078$ ft

$V = 24\ \text{lb/hr} \times \frac{1}{5.24}\ \text{ft}^3/\text{lb} \times \frac{1}{0.0884}\ \frac{1}{\text{ft}^2} = 51.8\ \text{ft/hr}$

Sc is given by,

$$Sc = \frac{\nu}{D} = 2.85 \qquad (10)$$

where, $\nu = 0.0057\ \text{ft}^2/\text{hr}$

$D = 0.002\ \text{ft}^2/\text{hr}$

Substituting these values into eq. 7 gives h_m = 5.13 ft/hr. Again substituting into eq. 6 gives,

$$\Delta c \Delta x = 0.008 \text{ lb/ft}^2 \tag{11}$$

Assuming Δx = 1 ft gives, Δc = 0.008 lb/ft^3, which as a percentage of the total $(c_1 - c_0)$ is, (0.008/0.783) X 100 = 1.0%.

Which means the actual charcoal adsorption wave closely follows our assumed wave when Δx = 1 ft. So this Δx value is a good approximation.

In this approximation we lose 1 ft of the adsorber bed leaving 14 ft. Using the adsorption capacity of 154 ft^3/ft^3 we arrive at a breakthrough capacity of 140 ft^3/ft^3. Which means the value used of 100 ft^3/ft^3 is conservative.

b. Coil

The O.D. of the charcoal coil was chosen so that equal volumes of charcoal would be on the inside and outside of the coil. Therefore using a 1/2 in. O.D. tube, and a 4 in. bed O.D., the O.D. of the coil is found to be 3.5 in.

To decide the number of coil turns needed, first the energy put into the helium by adsorption and therefore the energy which must be removed by the nitrogen is found. Adsorption is much like condensation so the energy added is,

$$\dot{m}_A h_{fgA} = 573.43 \text{ BTU/hr} \tag{12}$$

where, $\dot{m}_A = 6.5$ lb/hr

$h_{fgA} = 88.22$ BTU/lb

This added energy causes a rise in helium temperature. This temperature rise is found using,

$$573.43 = \dot{m}_H c_{pH} (T_1 - T_0) \tag{13}$$

which gives,

$$(T_1 - T_0) = 19^{\circ}\text{F} \tag{14}$$

where, $\dot{m}_H = 24$ lb/hr

$c_{pH} = 1.25$ BTU/lb^oF

If it is assumed, for approximation, that the adsorption all takes place in a short length at the bed entrance, then this temperature rise can be modeled as the inlet temperature difference of a parallel flow heat exchanger, holding the LN_2 temperature constant. Therefore the energy which must be removed by the nitrogen is given by,

$$Q = HA\Delta T_{LM} \tag{15}$$

where, H = overall heat transfer coefficient

A = total heat transfer area

ΔT_{LM} = LOG MEAN TEMPERATURE DIFF. $= \dfrac{\Delta T_{in} - \Delta T_{out}}{LN\ (\Delta T_{in}/\Delta T_{out})}$

The unknowns in eq. 15 are A and ΔT_{out}, Q = 573.43 BTU/hr, ΔT_{in} = 19^oF and H can be calculated. Therefore a reasonable value for A will be chosen and the corresponding ΔT_{out} will be found. If ΔT_{out} is considered reasonable then the A value will be used, if not the value will be iterated. First the overall heat transfer coefficient must be found. This is done assuming there are three resistances connected in series,

$$\frac{1}{H} = \frac{1}{h_{AC}} + \frac{1}{h_{SS}} + \frac{1}{h_i} \tag{16}$$

where, h_{A_C} = COEFF. from charcoal to tube

h_{SS} = COEFF. through tube

h_i = COEFF. from tube to N_2

h_{AC} is found using the Eckert equation for packed beds,

$$h_{AC} = 0.8\frac{k}{D_p}\left(\frac{D_pG_o}{u}\right)^{0.7} Pr^{1/3} = 95.4 \text{ BTU/hrft}^{2\,o}\text{F} \quad (17)$$

see reference 1

where, $k = 0.045$ BTU/hrft^{o}F

$D_p = 0.0078$ ft

$u = 0.03$ lb/hrft

$Pr = 0.7$

$G_o = 345$ lb/hrft^2

Properties for helium and air at 2000 psi and LN_2 temperature.

h_{SS} is found using the equation,

$$h_{SS} = \frac{k}{t} = 1852 \text{ BTU/hrft}^{2\,o}\text{F} \quad (18)$$

see reference 1

where, $k = 10$ BTU/hrft^{o}F

$t = 0.0054$ ft

h_i is found using the McAdams correlation,

$$h_i = 0.023\ Re^{0.8} Pr^{0.4}\ \frac{k}{D} = 45.5\ \text{BTU/hrft}^2\,{}^{\circ}\text{F} \quad (19)$$

see reference 1

where, $Pr = 0.73$

$k = 0.01$ BTU/hrft$^{\circ}$F

$D = 0.031$ ft

and Re is given by,

$$Re = \frac{GD}{Au} = 63550 \quad (20)$$

where, $G = 57.4$ lb/hr

$D = 0.031$ ft

$A = 0.008$ ft^2

$u = 0.035$ lb/hrft

properties for N_2 at boiling point.

Using these values of h and equation 16 we find, H = 30.3 BTU/hrft$^{2\circ}$F.

Using this H value and an A value of approximately 8.0 ft^2, corresponding to a coil pitch of 2.5 in., in eq. 15 gives ΔT_{out} as 0.005°F. This is negligible and therefore the A value is acceptable and calls for 69 coil turns.

c. Initial Cooling

The mass of stainless steel in the charcoal bed is, 161 lb. The mass of the charcoal is approximately 40 lb. The energy needed to cool this mass from ambient to LN_2 temperature is,

$$q = (m_1 c_{p1} + m_2 c_{p2}) \Delta T = 10{,}050 \text{ BTU} \qquad (21)$$

where, $m_1 = 161$ lb

$m_2 = 40$ lb

$c_{p1} = 0.095$ BTU/lb$^{\circ}$F

$c_{p2} = 0.25$ BTU/lb$^{\circ}$F

$\Delta T = 385^{\circ}$F

The amount of LN_2 vaporized to supply this energy is,

$$\frac{q}{h_{fgN}} = 116 \text{ lb} = 68 \text{ L} \qquad (22)$$

where, $h_{fgN} = 85.9$ BTU/lb

d. Pressure Drop

The pressure drop through the adsorber is found using the Ergun correlation for packed beds,

$$P = \left(\frac{150(1-e)\ u}{D_p G_o} + 1.75\right) \frac{L G_o^2\ (1-e)}{D_p e^3\ \ 5 \times 10^9} = 0.96\text{psi} \quad (23)$$

see reference 1,

where, $e = 0.5$, void fraction

$D_p = 0.0078$ ft

$G_o = 345$ lb/hrft^2

$u = 0.03$ lb/hrft

$L = 15$ ft

$\rho = 2.66$ lb/ft^3

$A = 0.087$ ft^2

and 5 X 10^9 hr^2/in. is used to arrive at the correct units.

Properties for helium at N_2 boiling point and 2000 psi.

e. Purge

The energy required to purge the bed is the energy needed to heat the stainless pipe and charcoal to ambient temperature. This energy is given by equation 21 and is 10,050 BTU.

This energy must be supplied by the 1scfm of nitrogen flowing through the bed coil. To determine the purge time, a steep wave model is used. In this simple model it is assumed that the exit purge stream remains cold until the entire bed is warm and then abruptly increases in temperature. For this model first we find the total purge gas mass needed to provide the 10,050 BTU. Then this mass is divided by the mass flow rate to arrive at the purge time. The equation,

$$q = m_N c_p \ (T_1 - T_0) \tag{24}$$

or,

$$m_N = \frac{q}{c_p \ (T_1 - T_0)} \tag{25}$$

where, $q = 10{,}050$ BTU

$c_p = 0.25$ BTU/lb$^{\circ}$F

$T_1 - T_0 = 385^{\circ}$F

gives the total gas mass needed as 104.4 lb. Therefore, the purge time is,

$$\frac{m_N}{\dot{m}_N} = 23 \text{ hr} \tag{26}$$

where, $\dot{m}_N$ = 1 scfm or 4.56 lb/hr

This model gives a lower limit to the purge time by assuming an infinite heat transfer coefficient. However the exact analysis, (see refs. 7 and 8) using calculated coefficients is closely approximated by this simple model.

APPENDIX B

Joy Tube Heat Exchanger

a. Flow in Gap

A flow gap, 10 mils wide, between the joy tube and pressure jacket was designed into the heat exchanger to increase the heat transfer rate. The gap flow is found by arbitrarily choosing a tube flow and subtracting it from the known total flow. Then the pressure drop through the tube is found. This pressure drop equals the drop in the gap, and from it can be found the gap flow. If the chosen tube flow plus the resultant gap flow do not equal the known total flow then the results are iterated until correct.

The total flow is 69.6 lb/hr, assuming a tube flow of 65 lb/hr the tube pressure drop is given by A.D. Little Inc. as,

$$\Delta P = \frac{0.05185\ f\ G_s^2}{D_p} = 0.169 \text{ psi} \tag{27}$$

where, G_s = 4.1 lb/s ft^2

D_p = 0.1 in.

ρ = 3.1 lb/ft^3

Properties are for air and helium at 2000 psi.

The value of f for the joy tube is given as 0.06 at a flow of

701b/hr. For the gap, f is estimated from the Reynolds number,

$$Re = \frac{DG}{Au} = \frac{V\rho D}{u} \tag{28}$$

using,

$$f = \frac{0.0791}{Re^{0.25}} \tag{29}$$

Using the tube pressure drop as the gap pressure drop, the gap flow velocity is found using,

$$\Delta P = 2f\ (L/D)\,\rho V^2/g = 0.169\ \text{psi} \tag{30}$$

where, $L = 120$ in.

$D = 0.02$ in.

$\rho = 0.0018\ \text{lb/in}^3$

$g = 386\ \text{in/s}^2$

and f is obtained by combining eqs. 28 and 29 to become,

$$f = \frac{0.0791}{(V\rho D/u)^{0.25}} = \frac{0.03}{V^{0.25}} \tag{31}$$

where, $u = 7 \times 10^{-7}$ lb/s in

Substituting eq. 31 into eq. 30 gives V=13.95 in/s which is equivalent to 4.3 lb/hr where the gap flow area is 3.3 X $10^{-4}ft^2$. The total flow that results is 69.3 lb/hr which is a little low, therefore we must iterate.

Assuming a flow of 65.25 lb/hr in the tube and doing the calculations gives a gap flow of 4.35 lb/hr, which is correct. Therefore about 6.7% of the total flow goes through the gap. This allows for a reasonable heat transfer rate through the gap.

b. Temperature Difference

The temperature difference between the incoming and outgoing balanced streams of helium, ignoring the air for now, is found using the relation,

$$LUA'\Delta T = \dot{m}c_p\ (T_1 - T_0) \qquad (32)$$

where, UA' = overall heat transfer coefficient with respect to area between the two streams

ΔT = the temperature difference between the two streams

$\dot{m}$ = pure helium flow rate, 24 lb/hr

$c_p = 1.24$ BTU/lb^{o}F

$T_1 - T_0 = 385^o$F

$L = 10$ ft

This leaves the heat transfer coefficient to be found. It is assumed the coefficient consists of three resistances, one copper wall and the inside and outside surfaces of the copper wall. This is shown in Figure 28. The equation becomes,

$$\frac{1}{UA'} = \frac{1}{A_1'h_1} + \frac{1}{h_2} + \frac{1}{A_3'h_3} \qquad (33)$$

where each coefficient has its own area.

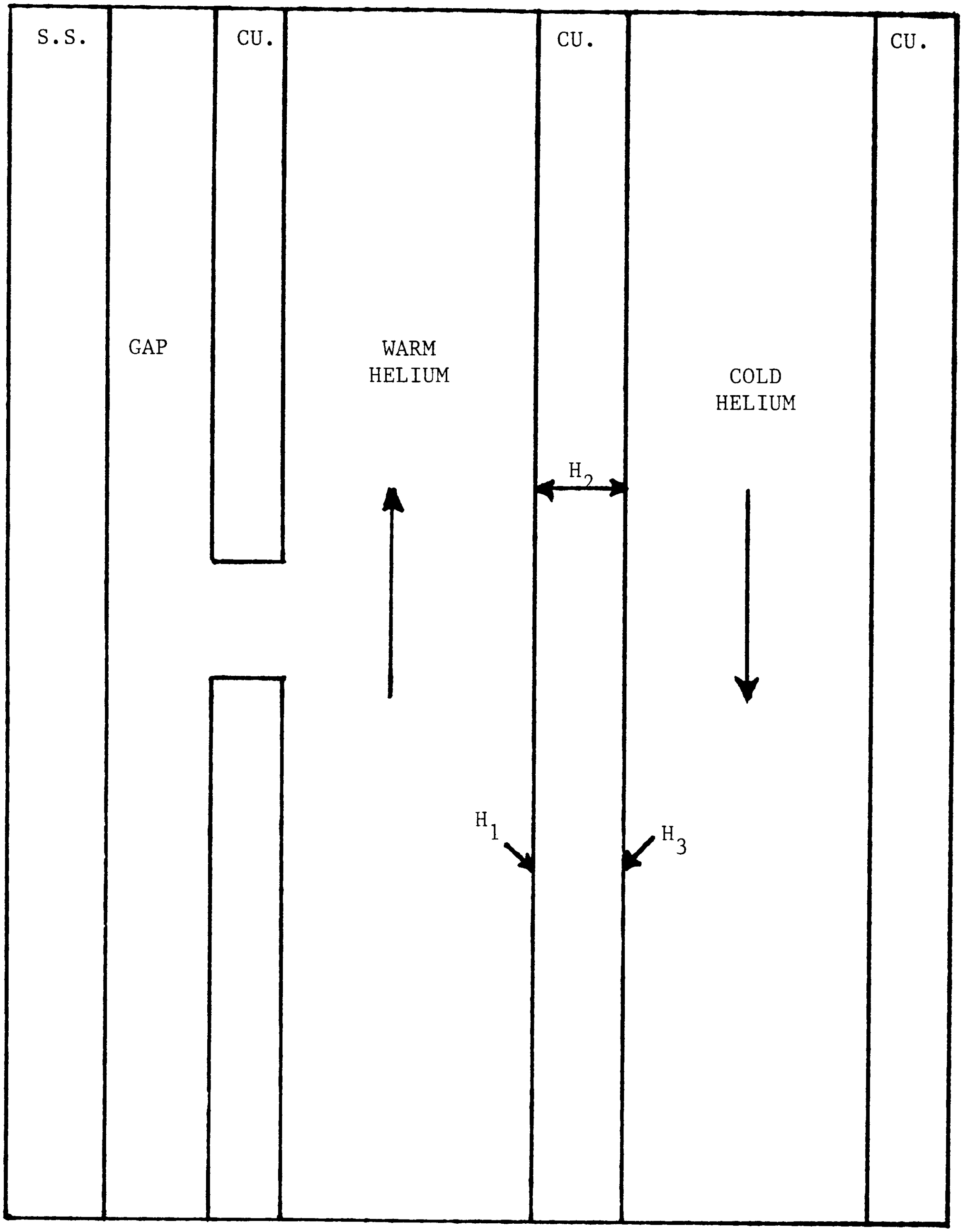

FIGURE 28- HEAT TRANSFER COEFFICIENTS BETWEEN HELIUM STREAMS

The equation for h_2 is,

$$h_2 = k/t = 16800 \text{ BTU/hrft}^{2\circ}\text{F} \tag{34}$$

where, $k = 70$ BTU/hrft$^{\circ}$F

$t = 0.05$ in.

For h_3, A.D. Little Inc. gives the equation for the "joy tube" as,

$$h_3 = \frac{0.118\ c_p G}{Pr^{2/3}\ Re^{0.3}} = 86.6 \text{ BTU/hrft}^{2\circ}\text{F} \tag{35}$$

where, $c_p = 1.24$ BTU/lb$^{\circ}$F

$G = 5454.5$ lb/hrft^2

$Pr = 0.7$

and RE is found using eq. 28 where,

$G = 24$ lb/hr

$A = 0.0044$ ft^2

$u = 0.03$ lb/hrft

$D = 0.00167$ ft

and is 3636.4.

Properties for helium at -320°F and 2000 psi.

The coefficient h_1 is given by eq. 35 as 180 BTU/hr ft^{2o}F where,

c_p = 1.0 BTU/lb^{o}F

G = 14829.5 lb/hrft^2

Pr = 0.7

and Re is found using eq. 28 where,

G = 65.25 lb/hr

A = 0.0044 ft^2

u = 0.03 lb/hrft

D = 0.0088 ft

and is 4345.

Properties for helium and air @ 2000 psi and -320^{o}F.

Substituting the h values into eq. 33 along with the values,

$$A_1 = 1.96 \text{ ft}^2$$

$$A_3 = 1.93 \text{ ft}^2$$

yields, UA' = 112.65 BTU/hr^{o}F.

Substituting UA' into eq. 32 gives T = 10.17^{o}F.

The amount of LN_2 which vaporizes to make up this temperature difference is given by,

$$\dot{m}_N = \frac{\dot{m}_H \, c_{pH} \Delta T}{h_{fgN}} = 3.5 \text{ lb/hr} \qquad (36)$$

where, $\dot{m}_H = 24$ lb/hr

$c_{pH} = 1.24$ BTU/lb^{o}F

$\Delta T = 10.17^{o}$F

$h_{fgN} = 85.9$ BTU/lb

c. Pressure Drop

The pressure drop through the joy tube is given by eq. 27. The parameters for the incoming stream are,

$G_s = 4.4$ lb/s ft^2

$D = 0.1$ in.

$\rho = 3.1$ lb/ft^3

$f = 0.06$

and the pressure drop is 0.194 psi/10ft.

The parameters for the outgoing stream are,

$G_s = 1.5$ lb/s ft^2

$D = 0.24$ in.

$\rho = 2.66$ lb/ft^3

$f = 0.05$

and the pressure drop is 0.01 psi/10ft.

APPENDIX C

Liquid Nitrogen

a. Steady State Consumption

The consumption of liquid nitrogen consists of three parts. First the LN_2 needed to make up the heat exchanger helium temperature difference found in Appendix B to be 3.5 lb/hr. Second, the LN_2 needed to liquify the incoming 20% air contaminant which is found using,

$$\dot{m}_N = \frac{\dot{m}_A \, h_{fgA}}{h_{fgN}} = 46.8 \text{ lb/hr} \tag{37}$$

where, $\dot{m}_A = 45.6$ lb/hr

$h_{fgA} = 88.22$ BTU/lb

$h_{fgN} = 85.9$ BTU/lb

And third, the LN_2 needed to make up the temperature difference between the air, ignoring the helium as we ignored the air before, and the N_2 stream. This temperature difference is found using eq. 32 where the only parameters that change are,

$$c_p = 0.235 \text{ BTU/lb}^{\circ}\text{F}$$

and $\dot{m}_N$ is the total nitrogen flow which we don't know yet. However we do know that the total flow is given by,

$$\dot{m}_N = \frac{\dot{m}_A\, c_{pA} \Delta T}{h_{fgN}} + 50.3 \tag{38}$$

where, $\dot{m}_A$ = 45.6 lb/hr

c_{pA} = 0.235 BTU/lb°F

h_{fgN} = 85.9 BTU/lb

and 50.3 lb/hr is the flow we already know we have, and ΔT is what we're looking for. Substituting these values and eq. 38 into eq. 32 yields,

$$\Delta T = \frac{1.13\Delta T + 453}{UA'} \tag{39}$$

therefore again we must find UA'.

The overall heat transfer coefficient consists of three resistances as shown in Figure 29. From Appendix B we know,

$$h_1 = 105.37 \text{ BTU/hrft}^{2\circ}\text{F}$$

h_2 is given by,

$$h_2 = k/t = 1000 \text{ BTU/hrft}^{2\circ}\text{F} \tag{40}$$

where, k = 10 BTU/hrft°F

t = 0.01 ft

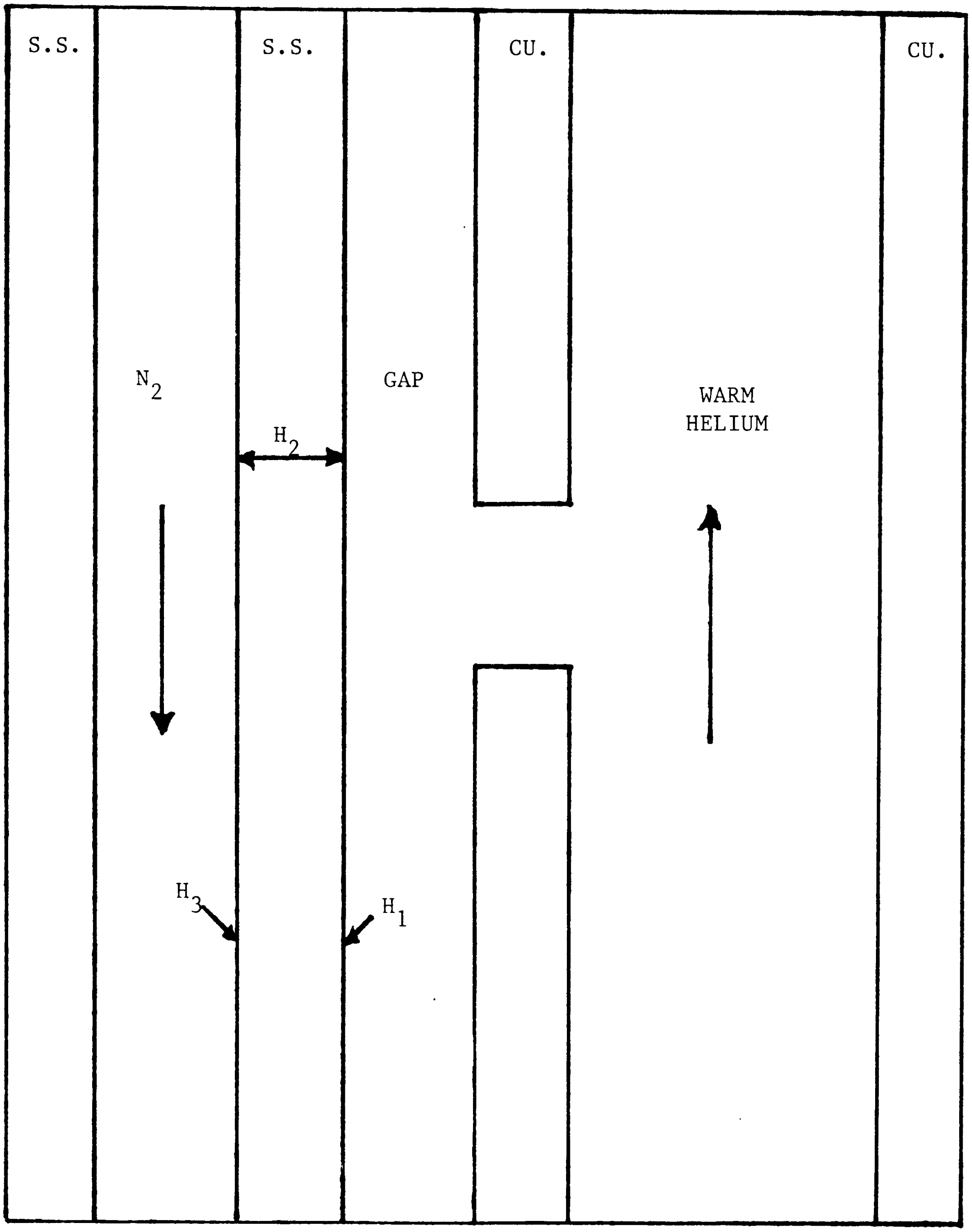

FIGURE 29- HEAT TRANSFER COEFFICIENTS BETWEEN N_2 AND HELIUM STREAMS

and h_3 is given by eq. 19 as 19.64 $BTU/hrft^2F$ where,

$k = 0.01\ BTU/hrft^{2o}F$

$D = 0.0125\ ft$

$Pr = 0.73$

and Re is given by equation 28 where,

$G = 60\ lb/hr$

$A = 0.003\ ft^2$

$u = 0.035\ lb/hrft$

and is 7142.8.

Substituting these h values into the equation,

$$\frac{1}{UA'} = \frac{1}{A_1'h_1} + \frac{1}{h_2} + \frac{1}{A_3'h_3} \qquad (41)$$

along with,

$A_1' = 0.398\ ft^2$

$A_3' = 0.458\ ft^2$

gives $UA' = 7.35\ BTU/hr^oF$.

Substituting UA' into equation 39 gives $T = 73^oF$.

The amount of LN_2 needed to make up this temperature difference is,

$$\dot{m}_N = \frac{\dot{m}_A \, c_{pA} \Delta T}{h_{fgN}} = 9.1 \text{ lb/hr} \qquad (42)$$

where, $\dot{m}_A = 45.6$ lb/hr

$c_{pA} = 0.235$ BTU/lb°F

$h_{fgN} = 85.9$ BTU/lb

$\Delta T = 73^{\circ}F$

Therefore the total steady state LN_2 consumption is 59.4 lb/hr, or 33.5 liters. For a complete run of 1.6 hours, 53.6 liters are needed.

b. Initial Cooldown Consumption

The LN_2 required for cooldown is approximately equal to the LN_2 needed to cool the charcoal bed and separator.

From Appendix A, for the charcoal bed, the LN_2 needed is 68 liters. The separator mass is 61.61 lb. The LN_2 needed to cool this is,

$$m_N = \frac{mc_p\ (T_1-T_o)}{h_{fgN}} \begin{array}{l} = 27.61\ \text{lb} \\ = 15.5\text{L} \end{array} \qquad (43)$$

where, $m = 61.61$ lb

$c_p = 0.1$ BTU/lb^{o}F

$(T_1-T_0) = 385^o$F

$h_{fgN} = 85.9$ BTU/lb

Therefore total LN_2 consumption for a 1.6 hr, 5000 scf, run is 137 liters.

c. Pressure Drop

The pressure drop through the N_2 jacket is given by eq. 30 as 0.855 psi, where,

$L = 120$ in.

$D = 0.15$ in.

$\rho = 5.8 \times 10^{-5}$ lb/in.^{3}

$V = 639.3$ in./s

and f is obtained from eqs. 27 and 28 where,

$G = 57.4$ lb/hr

$A = 0.003$ ft^2

$u = 0.035$ lb/hrft

and is 0.0087.

d. Pot Coil

The LN_2 pot coil was designed in the same manner as the charcoal coil. The pitch was chosen to be 1.0 in. The coil O.D. was chosen to be 10 in. and 16 turns was estimated to be appropriate. The coil turns are in the lower two feet of the pot so that they are always immersed in the LN_2.

APPENDIX D

Separator

a. Amount of Air

From eq. 2 the amount of air which remains in the helium stream after the separator is 6.5 lb/hr. Subtracting this from the assumed 20% (45.6 lb/hr) of air which enters in the helium stream gives 39.1 lb/hr as the amount of air condensing in the separator. Over the entire run of 1.6 hr, 5000 scf, the amount of air condensed becomes 62.6 lb or about 1.15 ft^3.

b. Throttling

The separator weighs 61.61 lb and the internal volume is 0.5 ft^3, from a. the condensed air weighs 62.6 lb. Assuming the condensate is released when the unit is half full, then the range of weights between the opening and the closing of the throttle valve is about 76 lb to 62 lb, which is an acceptable range for the sc-200 load cell. And the unit will have to be throttled about 5 times per run, every 20 minutes, or a continuous release of condensate at an appropriate rate can be used.

c. Coils and Springs

The separator coil was given the dimensions, 6.5 in. O.D., 2 in. pitch and 5 1/2 turns. These were found appropriate to cool the separator mass.

The springs which allow the separator to move freely in order to be weighed consist of 1 turn of tubing. This tubing will be coiled during construction and given an appropriate O.D. to allow full freedom.

APPENDIX E

Molecular Sieve

a. Amount of Sieve

As in Appendix A, at a flow rate of 3000 scfh, at 2000 psi and ambient temperature the amount of water remaining in the helium stream is,

$$\frac{V \text{ @ } 2000 \text{ psi}}{v_{sat,\ H_2O \text{ @ } 80^{o}F}} = 0.036 \text{ lb/hr} \qquad (44)$$

where, $V = 22.5 \text{ ft}^3\text{/hr}$

$v_{sat} = 633.3 \text{ ft}^3\text{/lb}$

Assuming a breakthrough capacity of 10 lb of sieve per pound of water adsorbed, the amount of sieve needed is, 0.36 lb/hr, or using a density of 41 lb/ft^3, about 15 $\text{in}^3\text{/hr}$.

Adsorption wave approximation can be done as in Appendix A. However the breakthrough capacity used, 50% of the adsorption capacity, is quite conservative.

Using the two 165 in^3 cylinders as the drier unit will provide capability for 11 hr running time per cylinder or at 1.6 hr per run per day about 7 days per cylinder.

b. Pressure Drop

The pressure drop through the bed is estimated by eq. 23 as, 0.4 psi, where,

$e = 0.5$

$D_p = 0.0052$ ft

$G_o = 1420.4$ lb/hrft^2

$u = 0.03$ lb/hrft

$L = 2.25$ ft

$\rho = 3.1$ lb/ft^3

$A = 0.049$ ft^2

c. Purging

Purging is done using a 5 scfm flow of dry nitrogen at 500°F. This nitrogen must supply the energy to heat the sieve and cylinder to 500°F. The energy required for heatup is,

$$(m_1 c_{p1} + m_2 c_{p2})\ (T_1 - T_0) = 3075 \text{ BTU} \tag{45}$$

where, $m_1 = 50$ lb

$m_2 = 5$ lb

$c_{p1} = 0.12$ BTU/lb$^{\circ}$F

$c_{p2} = 0.23$ BTU/lb$^{\circ}$F

$(T_1 - T_0) = 430^{\circ}$F

The purge time is found as in Appendix A from

$$m_N = \frac{q}{c_p\ (T_1 - T_0)} = 28.6 \text{ lb} \tag{46}$$

where, $q = 3075$ BTU

$c_p = 0.25$ BTU/lb$^{\circ}$F

$(T_1 - T_0) = 430^{\circ}$F

And the purge time is given by,

$$\frac{m_N}{\dot{m}_N} = 1.25 \text{ hr} \tag{47}$$

where, $\dot{m}_N$ = 22.8 lb/hr.

Again this is a simple model which gives a lower limit to the purge time.

d. Purge Pressure Drop

The pressure drop through the bed during purging is given by eq. 23 as 7 psi where,

$e = 0.5$

$D_p = 0.0052$ ft

$G_0 = 465.3$ lb/hrft^2

$u = 0.068$ lb/hrft

The pressure drop through approximately 100 ft of tube from the LN_2 tank is given by eq. 30 as 0.017 psi where,

$L = 1200$ in.

$D = 0.25$ in.

$\rho = 4.4 \times 10^{-5}$ lb/in^3

$V = 37.5$ in./s

$g = 386$ in./s^2

and f is given by eqs. 28 and 29 where,

$G = 22.8$ lb/hr

$A = 0.049$ ft^2

$u = 0.043$ lb/hrft

Therefore the total pressure drop is acceptable compared to the 30 psi LN_2 tank pressure.

APPENDIX F

Weld Preparations

The weld preparations for the LN_2 pot and separator are shown in Figure 12. Weld preparations and adapters for the top vacuum plate are shown in Figures 17, 18, 30-32 and examples of their uses are shown in Figures 33-35.

The preparations and adapters allow tubes to be fed through the top vacuum plate without touching it, thereby minimizing thermal stresses.

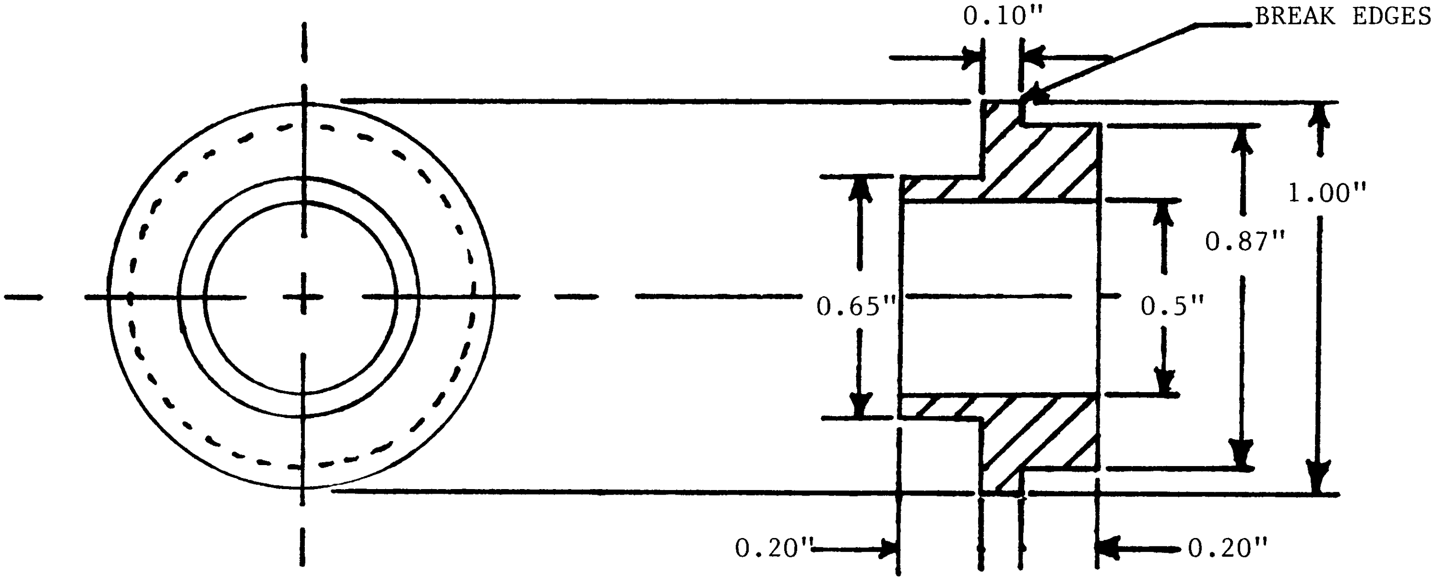

FIGURE 30- TOP VACUUM ADAPTER (½" TUBE)

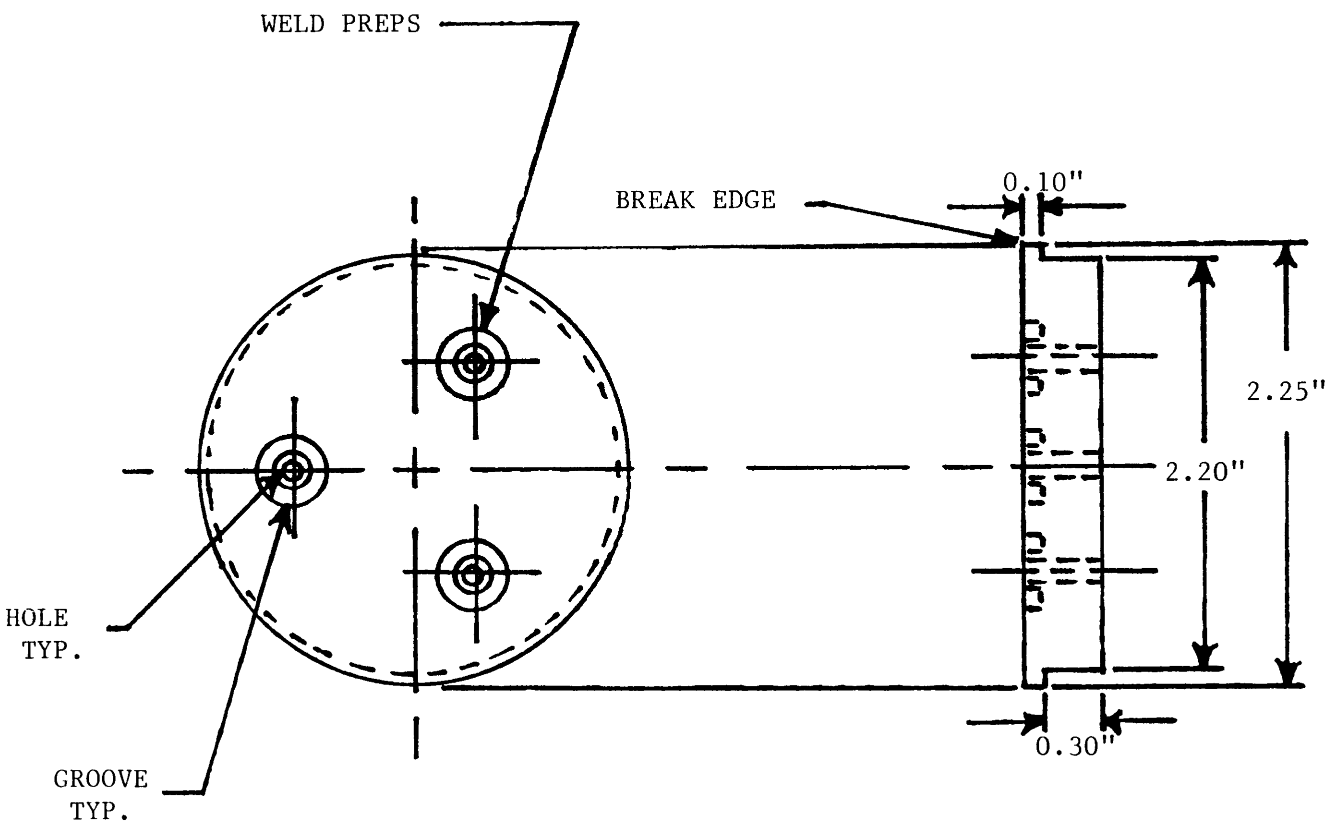

FIGURE 31- TOP VACUUM ADAPTER (GOW MACK)

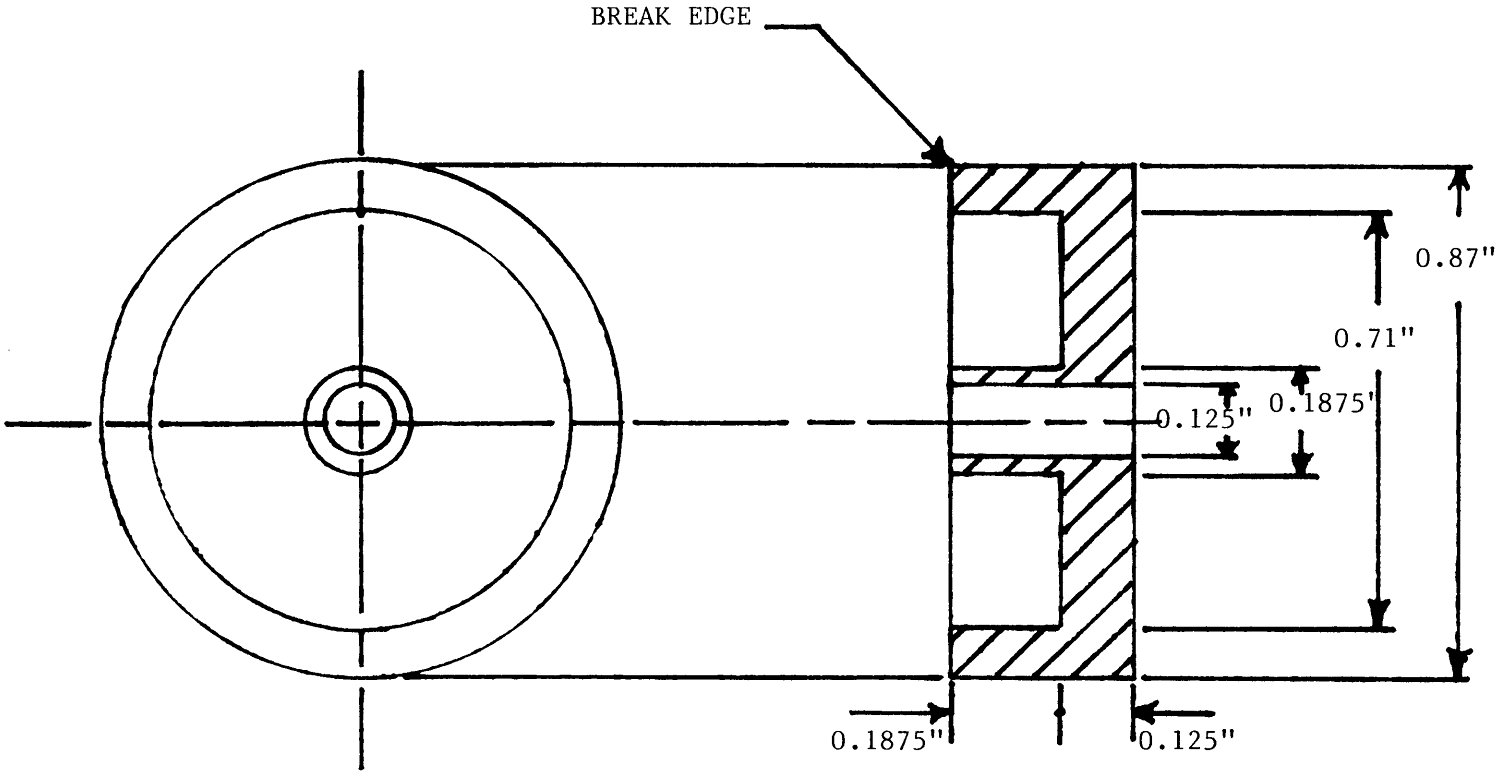

FIGURE 32- TOP VACUUM
ADAPTER (VPT)

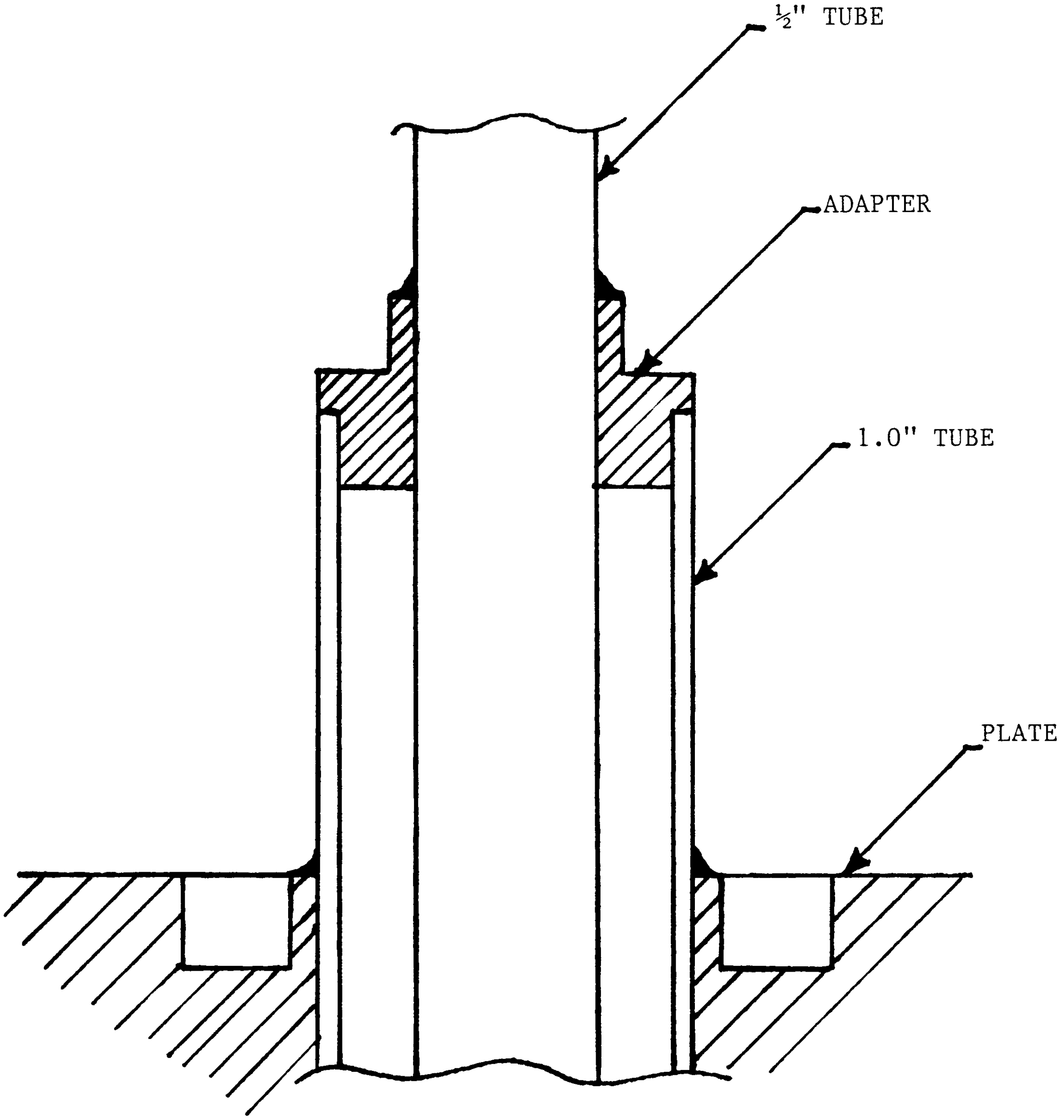

FIGURE 33- USE OF

WELD ADAPTER ½" TUBE

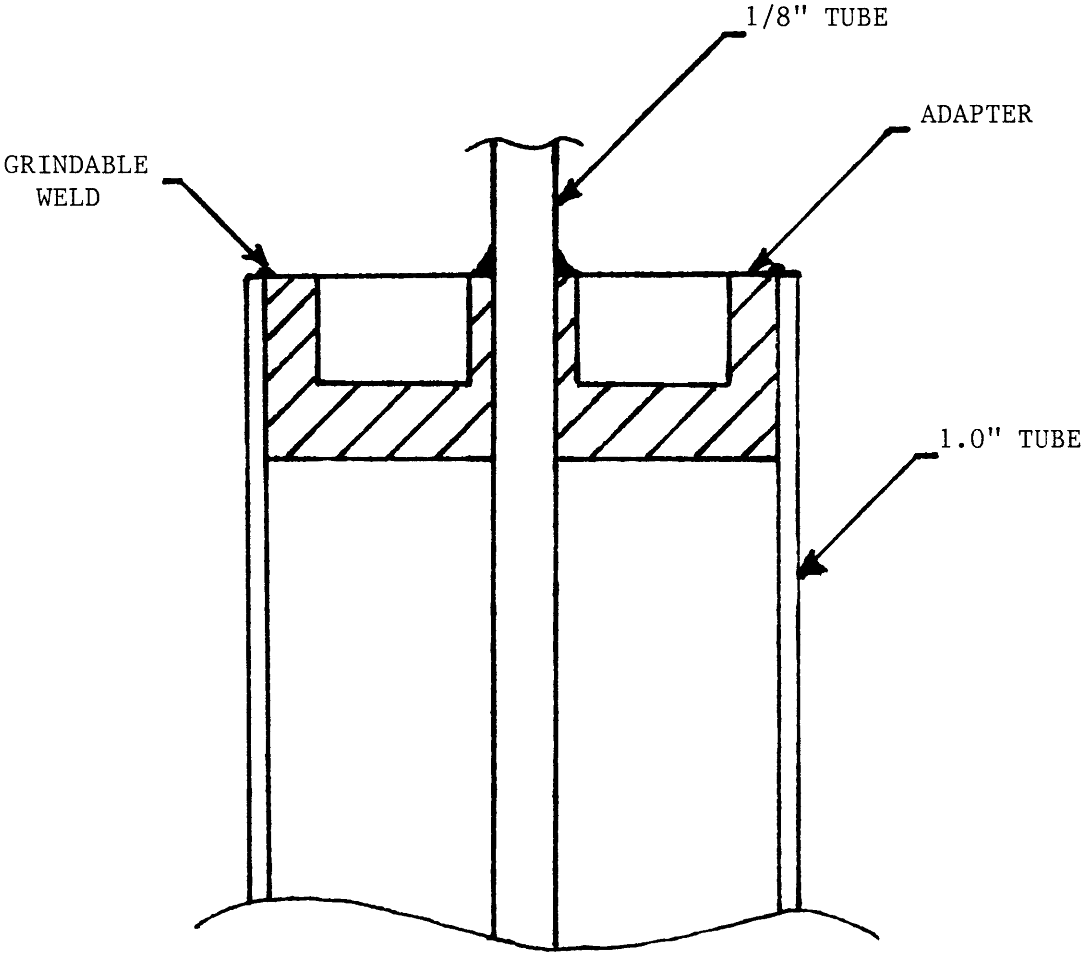

FIGURE 34- USE OF

WELD ADAPTER VPT

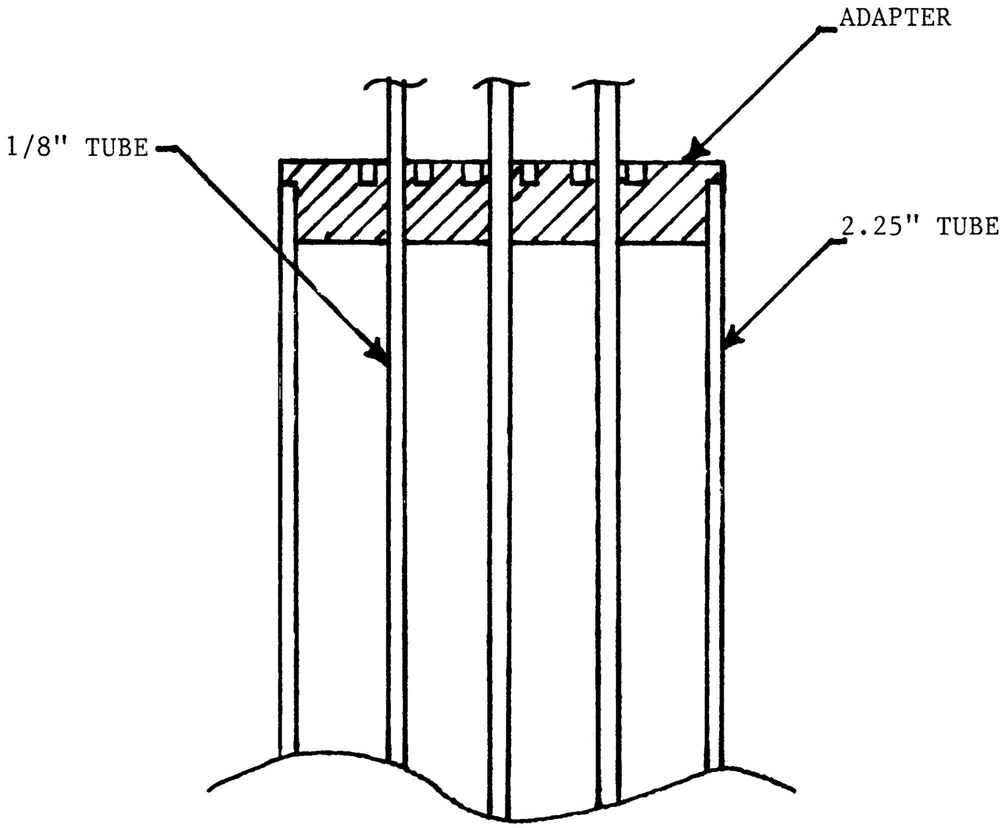

FIGURE 35- USE OF

WELD ADAPTER GOW MAC

APPENDIX G

Vacuum Jacket Stress

a. Vacuum Jacket

The collapsing pressure for the vacuum jacket is given by the Southwell equation for a thin shell. Using,

$E = 29 \text{ X } 10^6$ psi

$V = 0.3$

the equation becomes,

$$P = 70.9 \text{ X } 10^{6} \, \frac{T}{L} \, \frac{T}{d} \, \frac{T}{d}^{\,1/2} = 34 \text{ psi} \qquad (48)$$

see Figure 36,

where, $T = 0.134$ in.

$L = 84$ in.

$d = 30$ in.

This gives a safety factor of two for the vacuum jacket with an internal vacuum.

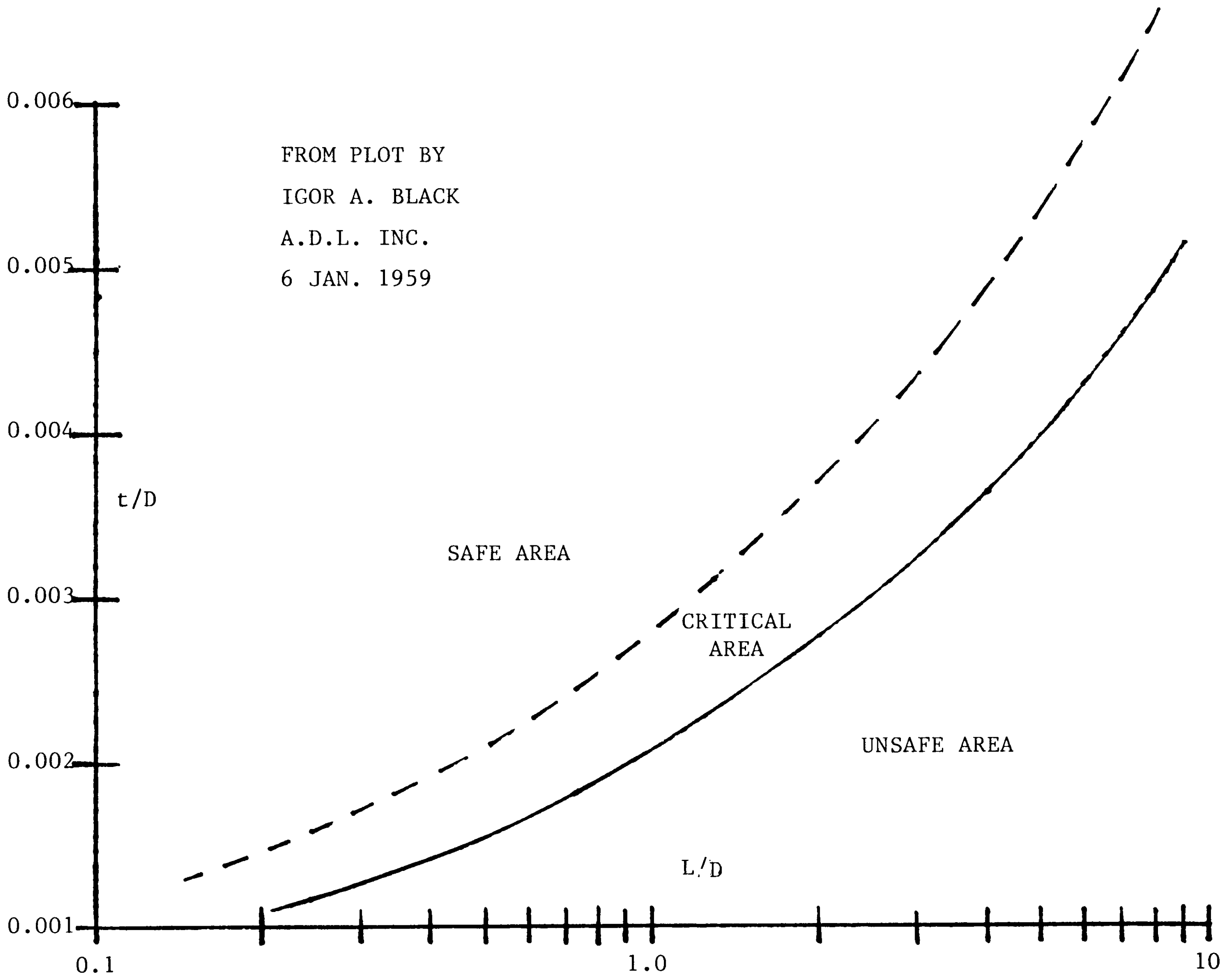

FIGURE 36- PLOT OF SOUTHWELL EQUATION FOR INTERNAL VACUUM

b. Top Vacuum Plate

The stress in the top plate is found using the formula for the bending moment and its relation to the stress,

$$M = PR^2 (3 + V)/16 = 569.5 \text{ lb in./in.} \tag{49}$$

$$\sigma = 6M/t^2 = 8747.4 \text{ psi} \tag{50}$$

where, $P = 15$ psi

$R = 15$ in.

$V = 0.3$

$t = 0.625$ in.

see reference 2.

This stress is calculated considering only the vacuum loading assuming the plate and component weight to be small over the plate area.

Since the top plate contains tubes it is important to know what the plate deflection will be in order to assure that feedthrough welds will not be overstressed. The center deflection of the plate is given by,

$$y_c = \frac{PR^4}{64D} = 0.0095 \text{ in.} \tag{51}$$

where D is given by,

$$D = \frac{Et^3}{12\ (1-V)^2} = 1245615.4 \text{ in.lb} \tag{52}$$

where,$E = 30 \times 10^6$ psi

see reference 2.

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