FERMILAB-UPC-177

R.J.Walker
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THE CENTRAL HELIUM LIQUEFIER

I. Introduction

a. Relationship to the Overall Refrigeration System:

The refrigeration system of the Energy Doubler consists of several parts which work together for maximum output. The various parts can also work independently to carry a reduced load. The major components which contribute to the refrigeration are as follows:

1. The nitrogen refrigerator, with dewar.
2. The Central Helium Liquefier, with dewar, pump, and subcooler.
3. The Satellite refrigerators, with assorted transfer lines and subcoolers.

The nitrogen reliquefier will produce 50 tons of liquid nitrogen per day into the 14,000 gallon dewar. It is operating in a closed cycle and collects warm nitrogen gas from the magnet shields, the transfer lines, the helium cold box, purifiers, and satellites. The liquid will be transported in vacuum insulated transfer lines from the dewar to all use points.

Liquid helium from the Central Liquefier will be collected in a 5000 gallon dewar and pumped to each of the 24 satellites and subsequently distributed to the ring. Each satellite will use 111 liters for lead cooling and satellite "boosting". The boosting action results in 690 watts of 4.9°K refrigeration being delivered to the magnet string and the 111 liters from the Central being warmed to ambient temperature and recompressed for delivery back to the Central and use in the high pressure stream to the cold box.

This system has the advantage of extracting the available refrigeration from the stream at the satellite location, reducing the size and cost of the necessary transfer lines.

b. <u>General Equipment Plan</u>:

The equipment consists of a mixture of reconditioned Air Force surplus and newly designed and purchased components. Figure 1 shows the layout of the major components in the new 50 ft x 180 ft building which is equipped with a five ton crane. The following equipment is located inside the building (numbered as in Figure 1):

1. Two 4000 hp surplus air compressors which have been reconditioned, restaged, and converted to helium service.
2. One similar compressor in process of being prepared for future service in a nitrogen reliquefier.
3. Three 4000 hp synchronous motors for these compressors (also surplus).
4. 4 kV switchgear and solid state field supplies.
5. Helium refrigerator cold box, 4875 liters/hour.
6. Local valve and instrument cabinet for refrigerator.
7. Two level control room structure.
8. Motor control center for auxiliary motors.
9. Oil removal system.
10. Seal gas cleanup system.

The following equipment is located outside:

11. 15MW transformer for main motors and 1.5MW substation for utility power.
12. Air cooled heat exchangers.
13. Cold box for nitrogen refrigerator.
14. 14,000 gallon liquid nitrogen storage vessel.
15. 5,000 gallon liquid helium storage vessel.
16. 30,000 gallon gas storage vessel rated at 250 psig.

II. Interior Structures

a. Compressor Foundations: To be assured of a successful compressor operation, it is necessary to build adequate mountings for them. The compressors which we are using weigh 185,000 lb each, plus another 50,000 lb for the motors. Since the machines are reciprocating and have large cylinders (see specifications), substantial shaking forces are developed by the 277 revolutions per minute of the motors. Typical shaking forces are about 10,000 lb and couples are about 130,000 ft lb.

The foundations were designed by Dames and Moore. Figure 2 shows a sketch of the model which they used for computer analysis. The main support is a 3 ft thick reinforced slab, 90 ft long and 35 ft wide. The top of this slab was at normal floor level. The main crankshaft frames were elevated 54 inches to permit bringing suction pipes in the bottom of the cylinders without the use of pits, underground piping, and other complications. This foundation was separated from the building floor around it by soft padding. The pad was supported on 60 piles driven to a depth of about 36 ft and a loading of 30 tons each. The piles were 12-3/4 inches in diameter with 3/8 inch walls and were filled with concrete.

The total amplitude of vibration expected is less than .003 inches. This amplitude is expected to be noticeable, but not troublesome to persons or machinery.

b. <u>Cold Box Pit</u>: A steel-lined pit 13 ft in diameter and 36 ft deep was constructed under the helium liquefier. This was necessary to permit the assembly of the various components of the cold box and to make it possible to make repairs in the future with a minimum of delay and expense.

c. <u>Control Room Enclosure</u>: This is a two story prefabricated industrial office type structure. It is 20 ft wide by 40 ft long. The lower level serves as a maintenance and storage area and contains the gas analysis equipment and the sanitary facilities. The upper level houses the control consoles and all of the remote readout and automatic logic. It also has space allotted to prints and records. The upper level is designed to provide convenient access and view downward toward the compressor system, on the second level to the cold box maintenance valves, and upward to the third level platforms which permit access to the valve operators, transfer lines, and turbines on top of the cold box.

III. Helium Compressors

a. Compressor Redesign: The redesign of the seals and the flow calculations were performed by Commercial Machine Works, using standard techniques, as well as the shop work and assembly of the compressors.

1. Introduction

Two Worthington six cylinder, 4000 hp reciprocating air compressors were reviewed for determination of performance characteristics when applied to helium service. Several alternates were considered in an effort to obtain a flow rate and hp usage consistant with the system requirements and compressor capability.

2. Design Criteria

Existing compressors are five stage, six cylinder units as follows:

First stage	-	34-1/4inch	2 cylinders
Second stage	-	27 inch	
Third stage	-	15 inch	
Fourth stage	-	9 inch	
Fifth stage	-	6 inch	

New design conditions call for a three stage application. Therefore, performance of existing cylinders has been reviewed and based on this requirement, initial inlet pressure of 15.435 psia and final discharge pressure of 180.81 psia are the parameters of the design review. Effort has been made to maximize the mass flow through the unit, requiring consideration of different cylinder and interstage pressure arrangements.

Four basic alternate design criteria were evaluated. The option selected was to utilize all existing compressor cylinders with adjusted interstage pressures to allow maximum mass flow throughput. The crank end of one first stage cylinder is unloaded. The 15 inch, 9 inch, and 6 inch cylinders operate in parallel as the third stage of compression.

3. Performance

The unit is expected to perform as shown in the Table below:

TABLE I

UNIT PERFORMANCE

Item	Stage of Compression 1	2	3
Cylinders used	2-34-1/4"	1-27"	1-15", 1-9", 1-6"
Type of gas	Helium		
Piston displacement-cfm	7903	3268	1441.3
Compressor speed-rpm	277		
Altitude	Sea level		
Intake temperature-F	80	100	100
Intake pressure-psia	15.435	38.57	87.97
Discharge pressure-psia	39.337	89.73	180.81
Discharge temp.-F	325	325	287
Volumetric efficiency-%	84.88	85.28	84.95
Actual capacity-cfm	6708	2787	1224.4
Equivalent capacity #/hr - dry	4286.5	4286.5	4286.5
Bhp/stage	610.7	536.3	501.8
Total	1648.9		

Notes: Frame and shaft loading changes resulting from the new design conditions are not of a significant order of magnitude, therefore, no modification or changes in original cylinder configuration is required.

Shaking forces will be the same as the original design values.

First stage discharge pressure should not exceed 40-41 psia.

b. Compressor Modifications

1. Introduction

Compressor component and cylinder modifications required to adapt this air unit to helium service are outlined in detail showing both the physical and material changes required.

Other repair and/or replacement requirements were covered under a separate contract. All installation and alignment work has been completed. The compressors are fully grouted and mounted with special tiedown bolts. Extensive motor rework has also been completed, including testing, new windings as required, re-insulating, new bearings, installation and grouting.

2. Compressor Valves - Feather

All feather valves have been rebuilt using new valve strips.

The following work has been performed:

Grind and lap valve seats.

Grind guard to reduce lift.

3. Compressor Valves - Plate

All plate valves were rebuilt using new wear components as indicated. Valve lift was reduced for helium service.

The following work has been performed:

Grind and lap valve seats.

Replace plate springs and provide glass-filled Teflon buttons for springs.

4. Valve Types

The cylinders are equipped with feather or plate valves of various sizes as shown in Table II.

TABLE II

NUMBER AND VALVE TYPE PER CYLINDER

Stage	Quantity	Size	Type
First	12	13"	Feather
First	12	13"	Feather
Second	20	8-1/2"	Feather
Third (15")	12	6-1/2"	Plate
Third (9")	8	5-1/4"	Plate
Third (6")	8	4-1/4"	Plate

5. Piston Rider Rings

All pistons were modified to accept graphite-carbon-filled Teflon rider rings, Compressor Products Type FOF31 or approved equal.

Rider rings are solid, uncut type prestretched for installation. Two rings per piston.

Rider ring projection is .050". Piston o.d. have been turned where required.

Remachining of the babit rider rings in the ring carrier for replacement by Teflon rider rings was not successful for the first stage 34-1/2 inch pistons due to previous modifications and repairs in this area. All new first stage cast iron ring carriers were machined to fit.

6. Piston Compression Rings

All pistons are equipped with carbon-graphite-filled Teflon rings, Compressor Products Type FOF31 or approved equal. First and second stage rings are one piece angle cut with contained stainless steel expansion ring. All other rings are one piece angle cut, no expansion ring required.

7. Number of Rings Per Piston

First stage	2
Second stage	2
Third stage (15")	4
Third stage (9")	5
Third stage (6")	6*

*Piston machined with eight grooves. Center two grooves will not be required. No modification necessary.

8. Piston Rods

All piston rods were ground to a common diameter in the packing area. It was necessary to remove .020" of stock to attain cleanup at common diameter. Two rods were replaced. A 12-15 microinch finish was used.

9. Piston Rod Packing

New packing cases and packing were furnished with provision for oil and vent connection.

First and second stage packing has a minimum of five rings, Compressor Products Type 114-5, or approved equal using Type FOF-31 material with lapped bronze backup rings.

10. Distance Piece

A new oil scraper gland seal was added to prevent helium leakage into crank case. The unit seals in both directions and is specified as Compressor Products Type 140.

Access openings on each distance piece were enclosed, with covers of 3/4 inch steel plate.

Existing lube oil and vent connections on distance piece housing were used in making all internal connections.

11. Cylinders

All cylinders were final honed to produce a 15-18 micro-inch finish.

12. Gaskets

Garlock Type 7021 gaskets were used throughout.

IV. Piping and Flow Systems

a. Compressor Piping: The entire piping system for both helium compressors has been completed. The instrumentation and valve control systems are also in place. A portion of the piping to the cold box is still in progress, but the compressors are essentially ready to run and require only the final check of the switchgear. Figure 3 shows the gas management system for one compressor.

b. Air Cooled Heat Exchangers: The after coolers are also ready to run. These are also surplus and were reconditioned at Fermilab. The helium gas flows through bronze tubes with aluminum fins which are cooled by air blown upward by 14 ft diameter fans. The tube cores were completely redesigned and rebuilt to fit in the original duct towers and use the original 30 and 40 hp fans and duct towers.

c. Main Warm Gas Flow System: The routing of the main flow of helium gas is shown in Figure 4. It is evident that either compressor can circulate gas independently. The setpoint for the control loops shown in Figures 3 and 4 for suction and discharge pressure can be monitored and adjusted in the usual manner from the control room. The charcoal trap and the demister are both rated for the full flow of the two compressors. See Table III for specifications. The piping from the charcoal trap to the cold box has not yet been completed.

TABLE III

Specifications for the Monsanto Mist Eliminator

Gas	Helium
Flow rate	10,1086.1b/hr
Operating pressure	235 psia
Inlet mist loading	100°F
Oil	Rarus 427

Specifications for the Charcoal Vapor Trap

Operating pressure	180 psia
Temperature	100°F
Charcoal bed	300 cu ft
Flow	10,000lb/hr helium gas

d. Seal Gas Cleanup System: The seal gas is the leakage past the piston rod packings on each cylinder of the main helium compressors. This gas leaks into a low pressure volume between the cylinder and the crankcase and tends to be somewhat contaminated with air due to air being carried in from the crankcase by the piston rod. Seal gas is collected in a manifolding system and brought to the suction of the screw compressor and on to the scrubber. The guaranteed leakage rate is 50 SCFM per compressor, which should be well within the capacity of the cleanup system. The main specifications of the scrubber are given in Table IV. Figure 5 shows the main flow of the seal gas system.

TABLE IV

Specifications for the Gardner Low Temperature Purifier (Dual)

Flow	300 lb/hr
Composition	99% helium, 1% air (by weight)
Pressure	250 psig
Temperature	100°F
Output purity	5 ppm air for 12 hours
LN_2 requirements	45 lb/hr at 15 psig

Specifications for the Seal Gas Screw Compressor

Size	46 1/2" x 35" x 65" high
Weight	~2200 lb
125 hp motor	440 V 30 60 Hz
Full power estimated at	93 kW
Cooling water	40 GPM at 40 psig 85°F maximum supply temp.
Rotor	127 mm x 152 mm - female driven by 3600 rpm motor
Rotor displacement	233 cfm

Expect 70 to 75% volumetric efficiency

Expected throughput	180 scfm at 16.5 psia suction
Volume ratio	4.5

Oil removal system expected to reduce carry-over to less than 1 ppm by weight

V. Control System

a. General Plan: In designing the control system for the compressors a major factor was an attempt to make the system compatible and integrated with the helium reliquefier supplied by Helix Process Systems. In addition, as much information and logic as possible was centralized in the control room to facilitate operations as well as debugging. Thus, the main feature of the control system is a Texas Instruments Model 5000 programmable sequencer which controls the logic for trips, interlocks, alarms, timers, and status displays. Figure 6 shows a simplified block diagram of the control system used on the helium compressors. The control system for the cold box is independent and has essentially the same block diagram except that it does not have an analog alarm system.

b. Data Display Panel and Control Consoles: The cold box system has the sequencer, process controllers, data and alarm display panel all mounted in a custom-built cabinet. This cabinet also contains all the necessary control and selector switches and digital readouts for pressure, temperature, and flow. The data panel is illuminated and various process flows can be displayed in various colors. Valve status and alarm indicators also light under sequencer control. An identical cabinet has been installed to control the compressor and gas system. Furthermore, a data display panel of similar construction and function has also been installed so that the corresponding process flows displayed on the two consoles match. Figure 7 shows a photograph of the console installation.

c. Process Control: The most common control loop used consists of the following elements:

1. A sensing probe which transmits an electric signal to the control room, which is proportional to the process variable.
2. A Fisher process controller in the control console which compares the electrical signal representing the process variable with an operator adjusted set point and generates a correction based on the difference of the two input signals. This correction signal is transmitted back to the vicinity of the valve.
3. An "E to P" unit converts this electric signal to an air signal which is transmitted to a pneumatically operated control valve.
4. An operator-positioner package attached to the valve moves the valve stem an appropriate amount.

VI. Helium Reliquefier

a. Introduction to the System: This liquefier, with its control panel, is designed to liquefy helium into a remote dewar. Cold gas from the dewar will be returned to the system through the cold box.

The reliquefier uses four stages of refrigeration: liquid nitrogen and three oil bearing turboexpanders designed and manufactured by Sulzer. Heat exchangers are manufactured by the Trane Company. Design liquefaction rate is 4875 liters/hour at 4.6K.

1. Cold Box

The cold box assembly is 37 feet high and consists of: a 10 ft diameter vacuum shell; a supporting frame that attaches to the top head of the vacuum shell; three oil bearing turboexpanders; a vacuum pumping system; and an instrument panel. Components inside the vacuum shell are: the heat exchanger system and interconnecting cold piping, turbine inlet filters, control and shutoff valves, and connections to the three turbines. Figures 8 and 9 are views of the reliquefier.

2. Control Console

The main control console (see Figure 7) contains all the controls for one-man operation. A display panel contains a system flow diagram, indicator lights, and all instrument identification necessary for system operation.

Digital readouts in the appropriate units are used for temperature pressure, flow, and elapsed time.

b. Theory of Operation: The process cycle for the Fermilab Central Helium Reliquefier is shown on the TS diagram, Figure 10 and the flow diagram, Figure 11. Compressors, provided by Fermilab, will deliver 1267.7 grams per second (g/s) of pure helium gas at 11.9 atm pressure to the cold box.

Liquid nitrogen, provides the first stage of refrigeration by counterflowing with high pressure helium in heat exchanger HX1, 1A (E16). A flow of 588.6 g/s (2665 liters/hour) of liquid nitrogen at 1.3 atm, together with 1109.3 g/s of low pressure return helium, will cool 1267.7 g/s of helium from 311.1K to 80.7K.

In heat exchanger HX2 (E17) the high pressure helium is cooled to 45.67K by the low pressure return gas.

At the entrance of HX3 (E17) the flow divides with 916.7 g/s going to the turbines. Some gas, 0.7 g/s, is extracted and injected into the labyrinth seal isolating the oil from the helium in the turbine cartridge. The remaining 916 g/s flows through the first turbine (T-1) where helium is expanded from 11.5 atm to 6.0 atm at 37K. Power developed by the turbine in the work extraction process, is 42.0kW. Exhaust gas will pass from the turbine (T-1) through HX4 (E17) where it is cooled by the low pressure return gas to 25.66K. The flow is again divided with 471.9 g/s going to turbine T2, and 444.1 g/s of the remaining flow going to turbine T-3.

Gas, 0.2 g/s, is injected into the labyrinth seal of turbine T-2. The remaining 471.7 g/s flows through T-2 expanding from 5.9 atm to 1.3 atm at 16K resulting in turbine power of 23.3kW. Low pressure, 1.3 atm, helium exhausting from the turbine, returns via the low side exchanging refrigeration with the high pressure stream.

The 444.1 g/s at 5.8 atm is cooled by the return flow in heat exchanger HX5 and HX6 to 12.88K. Gas, 0.1 g/s, is injected into the labyrinth seal of turbine T-3. The remaining 444 g/s expands through turbine T-3 from 8-5 atm to 1.37 atm at 8K. The turbine power developed in the work extraction is 9.5 kW. Turbine exhaust gas exchanges its refrigeration with the high pressure gas flowing to the J-T valve in heat exchanger HX7.

When the flow divided to the turbine circuit the remaining high pressure helium flow of 351 g/s went directly to the J-T valve (PCV183). High pressure helium is cooled to 6.16K by the return stream in the heat exchangers HX3, 4, 5, 6, 7 and 8 (E17, E18, E19) before isenthalpically expanding to 1.397 atm, and 4.6K producing 4875 liquid liters/hour (l/h) of helium.

The liquid/gas mixture will separate in the Fermi dewar, 193.5 g/s of gas at 4.6K will return to the low side of the system.

c. Description:

1. Cold Box Assembly

The vertical cold box assembly consists of a carbon steel vacuum shell that encloses the heat exchangers, three turbines, turbine filters, interconnecting piping and valves; most of these components are covered with multilayered insulation.

The vacuum shell includes upper and lower flanges with O-ring seals. The top head of the vacuum shell contains all penetrations to the internal components. A support frame with legs is attached to the top head which allows the vacuum shell to be lowered into a pit to expose the cold box internal components for maintenance.

The overall dimensions of the cold box are 37 feet high by 12 feet square.

2. Heat Exchangers HX1, 1A (E16) HX2, 3, 4 (E17) HX5, 6 (E18) HX7, 8 (E19)

There are four brazed, aluminum, heat exchanger blocks in the system, all manufactured by the Trane Company. The cores are the plate-fin type using 1/8-inch serrated fins, and constructed of 3003 aluminum alloy. The headers and nozzles of the assemblies are made of 5083 aluminum alloy.

The heat exchangers, are all mounted vertically with the cold end down, and are interconnected with aluminum piping, except where stainless steel elements, such as valves, are required. Connections to stainless steel elements are made through aluminum to stainless steel transition joints.

Schedule 5, 304 stainless steel and schedule 40 6061-T6 aluminum pipe are used for interconnections.

The high pressure passages of all the aforementioned exchangers are designed to operate at a maximum pressure of 300 psig and were tested to 600 psig. The medium pressure passages of the exchangers are designed for 100 psig maximum operation and were tested to 200 psig, while the low pressure passage is designed for 50 psig maximum operation and was tested to 100 psig. The heat exchanger configurations are as follows:

HEAT EXCHANGER	DIMENSIONS	TYPE
HX1, 1A (E16)	36" x 23" x 170" long	Three-pass
HX2, 3, 4 (E17)	25" x 23" x 260" long	Three-pass
HX5, 6 (E18)	25" x 21" x 254" long	Three-pass
HX7, 8 (E19)	17" x 12" x 222" long	Two-pass

The heat exchangers are supported from their top end by stainless steel rods extending down from the top head of the vacuum shell. The heat exchangers are interconnected with lateral stainless steel angle supports and micarta sapcers. The supports are rigid from side to side but are somewhat flexible in the principal shrinkage direction. The heat loss via conduction through the supports between components is negligible.

Heat exchanger HX1, 1A can be decontaminated with solvent. If the high pressure section of heat exchanger HX1, 1A becomes contaminated with oil, connections are provided for attaching a pump to circulate solvent through the heat exchanger.

3. Turbines (T-1, T-2, and T-3)

The turboexpanders are single stage turbines of the centripetal type with oil bearings and oil braking. The turbine rotor is vertically mounted and is carried radially and axially in two oil lubricated bearings. Between the two bearings is the oil brake which dissipates the mechanical work performed by the turbine as heat. An oil-to-water heat exchanger removes the heat generated. A speed-sensing device is incorporated into the turbine which insures safe operation.

3.1 Low Temperature Housing. - The stainless steel turbine housing is installed in the cold box turbine mounting plate. This housing is covered by the turbine vacuum cover. All cryogenic helium pipework is assembled to this turbine housing. All turboexpander maintenance can be performed outside the cold box. (See Figures 12 and 13.)

3.2 Turbine Cartridge (Figure 14). - The fully equipped turbine cartridge includes the following parts:

- impeller (7) and impeller shaft (9)
- thrust (71) and journal (35)
- oil brake (42)
- labyrinth seal
- slinger ring (8)
- speed sensor (61)
- oil and seal gas connections

The cartridge is shop assembled, tested, and ready for assembly into the turbine housing from the lower side. All necessary connection unions for oil and seal gas lines are circular at its mounting flange.

3.3 Turbine Lower Casing. - The turbine lower casing contains an oil reservoir for the oil leaving bearings and brake. From the collector the oil leaves through an oil return line to the oil vessel. The ring space of the lower casing is part of a buffer volume to ensure safe working conditions in case of heavy process pressure changes. In this case, gas from the buffer volume will be injected to the labyrinth to guarantee a correct flow of gas to the oil-wetted parts.

3.4 Speed Measuring System. - The speed of the turbines is measured by an inductive pick-up. A speed indicator with the necessary safety contacts is installed in the control console.

3.5 Speed Indicator Type TMA 3. - The speed safety trips are adjusted as follows:

	Turbine No. 1 (T33B-60) (rps)	Turbine No. 2 (T22B-60) (rps)	Turbine No. 3 (T21B-50) (rps)
Warning Trip	1417	1583	1583
Shut-down Trip	1500	1667	1667

The speed switch system is based on a photo-optical circuit. The speed setting is made by means of an adjustable brake oil supply valve to the oil brake of the turbine.

VII. Cryogenic Fluid Flow System

The input and return for the helium portion of this system comes from the cold end of the reliquefier shown on the righthand side of Figure . Figure shows the main parts of this flow system. At the present time, the helium dewar is complete but the phase separator and transfer lines are in construction. It is our intention to complete the cold box acceptance test without the use of the 5000 gallon helium dewar. The test will be conducted using the phase separator, its pressure control loop, and the concentric line to the reliquefier. The liquid nitrogen dewar will be connected with temporary foam insulated transfer lines, and we intend to use the scrubber to clean up the plant inventory.

We are scheduled to test the compressors in November and the reliquefier in March and April.

FIGURE CAPTIONS

Figure 1. Approximate layout of major plant equipment.

Notes:
1. Main helium compressors.
2. Main nitrogen compressor.
3. 4000 hp synchronous motors.
4. 4kV switchgear for main motors.
5. CTi-Helix helium refrigerator.
6. Valve cabinet.
7. Control room, second level.
8. 1200 ampere motor control center.
9. Oil removal equipment.
10. Seal gas cleanup system.
11. Transformers for incoming power.
12. Air-cooled heat exchangers.
13. Nitrogen cold box.
14. Liquid nitrogen dewar.
15. Liquid helium dewar.
16. Intermediate pressure gas storage.

Figure 2. Footing and machine model used for computer analysis.

Figure 3. Simplified flow system for a single helium compressor.

Notes:
1. First stage of compression.
2. Second " " "
3. Third " " "
4. Stage unloading valves. These must be open to start compressor.
5. Discharge pressure control (kickback valve).
6. 2 micron particle filters.
7. Intermediate pressure storage tank.
8. Inventory control valve, from gas storage.
9. Inventory control valve, to gas storage.
10. Isolation valve.
11. Main suction relief valve, 16 inch.
12. Air-cooled heat exchangers.

Figure 4. Main gas flow system.

Figure 5. Seal gas cleanup system.

Figure 6. Block diagram of control system for helium compressors.

Notes:
1. Indicates multiwire connections.
2. Two-way data bus.

Figure 7. Control consoles for compressor and helium cold box.

Figure 8. Taop of helium cold box.

Figure 9. View of heat exchangers in helium cold box assembly.

Figure 10. TS diagram for helium liquefaction cycle.

Cont'd.

FIGURE CAPTIONS (Cont'd.)

Figure 11. Main helium flow in helium cold box.

Notes:

1. Liquid nitrogen in
2. ambient temperature nitrogen gas return.
3. 12 atm. helium gas in
4. 1.1 atm helium gas return.
5. 6.2°K, 11.2 atm cold helium gas.
6. 4.6°K liquid, 4875 liters/hr.
7. Cold gas return, 1.4 atm, 4.6°K.
8. Refrigerated gas delivered by turbine 3, 1.3 atm and 8.0°K.

Figure 12. View of turbine inlet filters.

Figure 13. Turbine access and gas ports.

Figure 14. Cross sectional view of the Sulzer oil bearing turbine.

Figure 15. Cryogenic transfer line system.

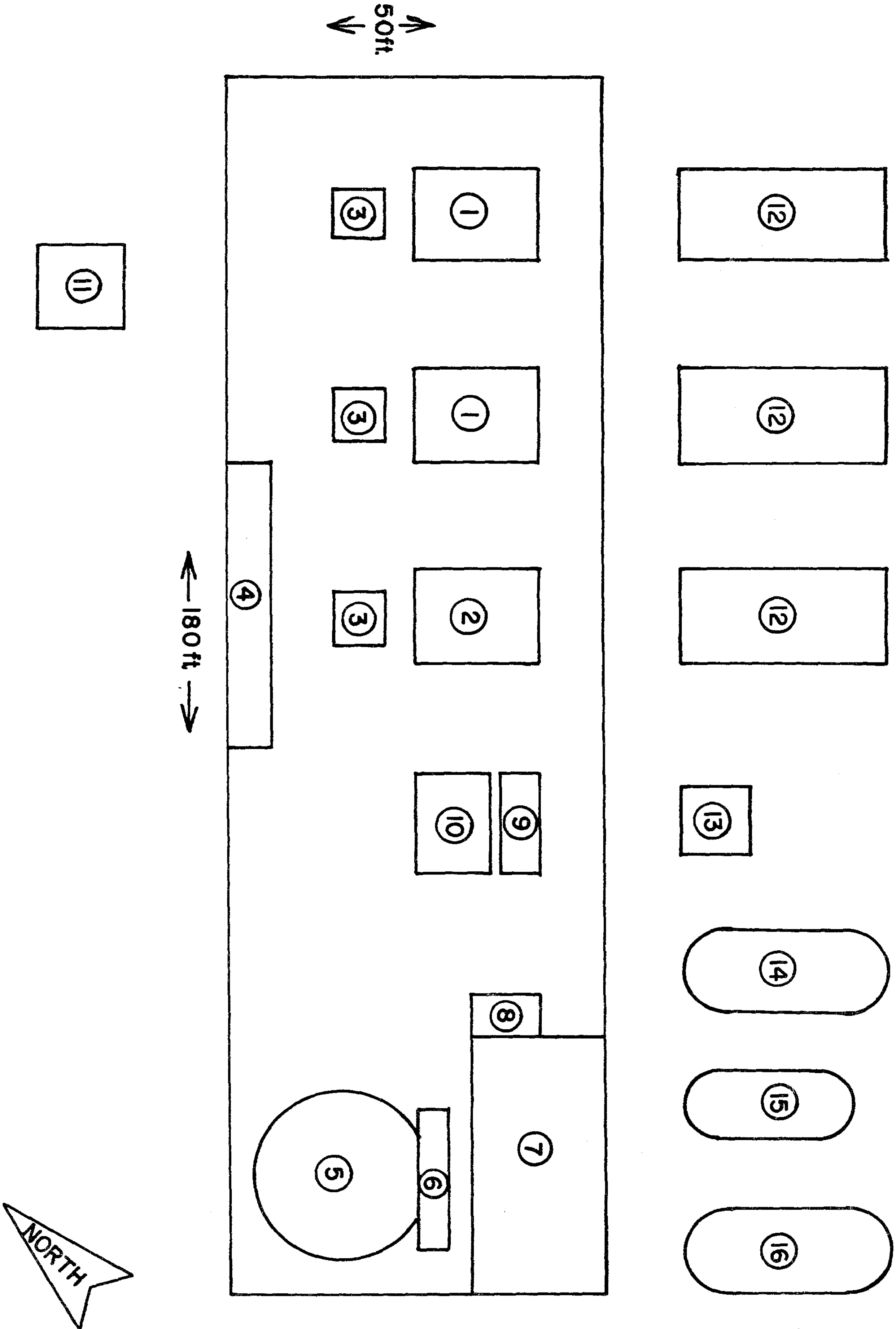

Figure 1. Approximate layout of major plant equipment.

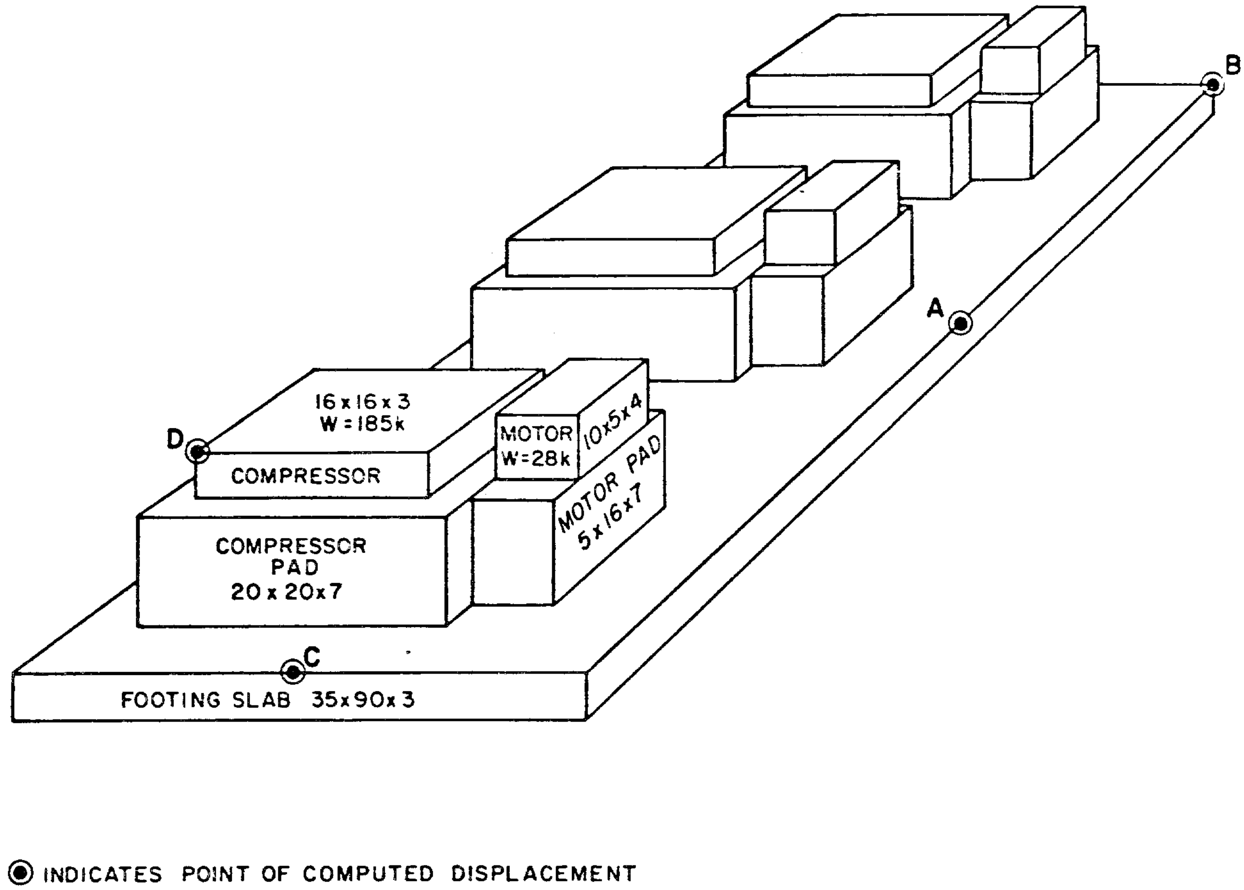

Figure 2. Footing and machine model used for computer analysis.

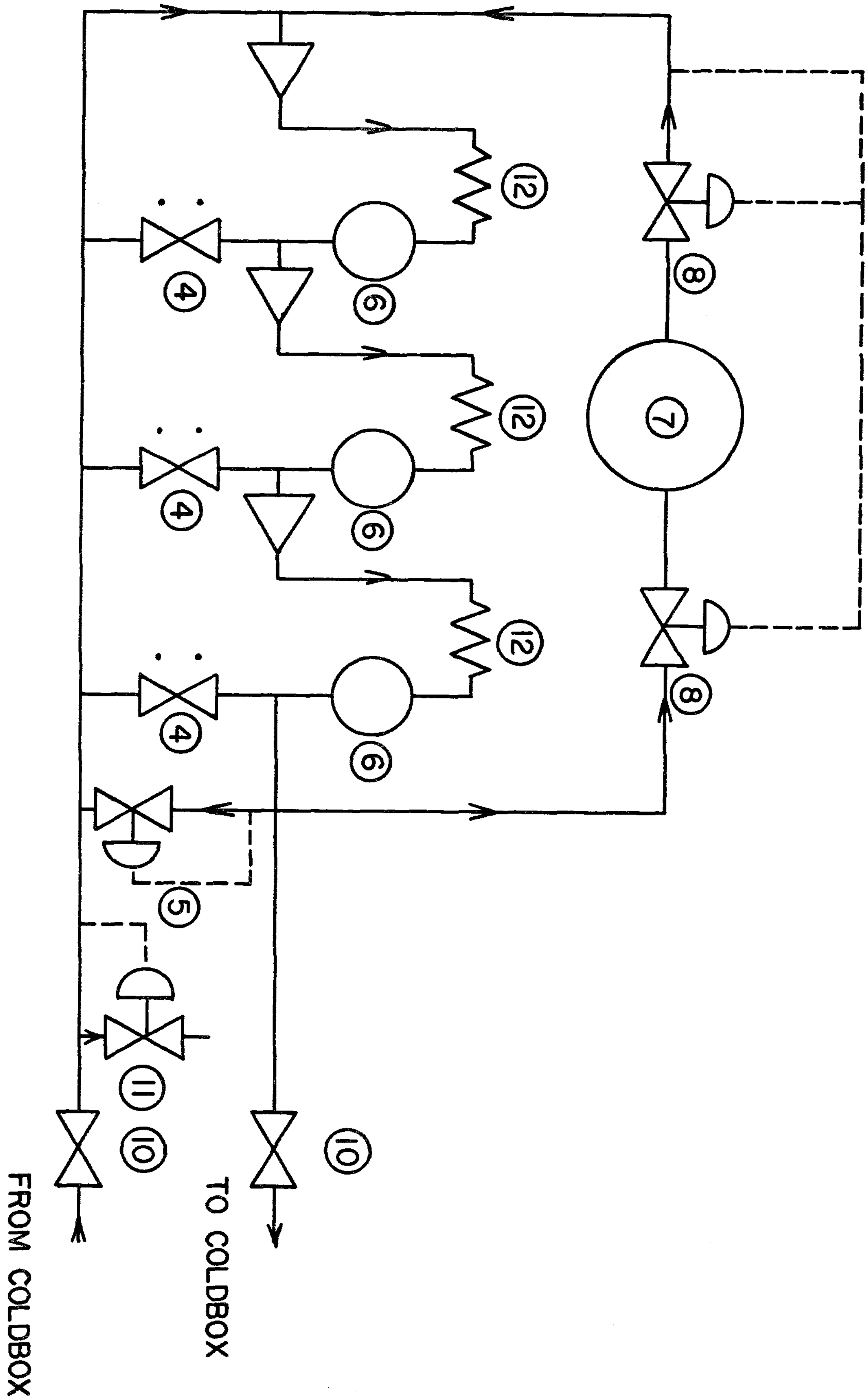

Figure 3. Simplified flow system for a single helium compressor.

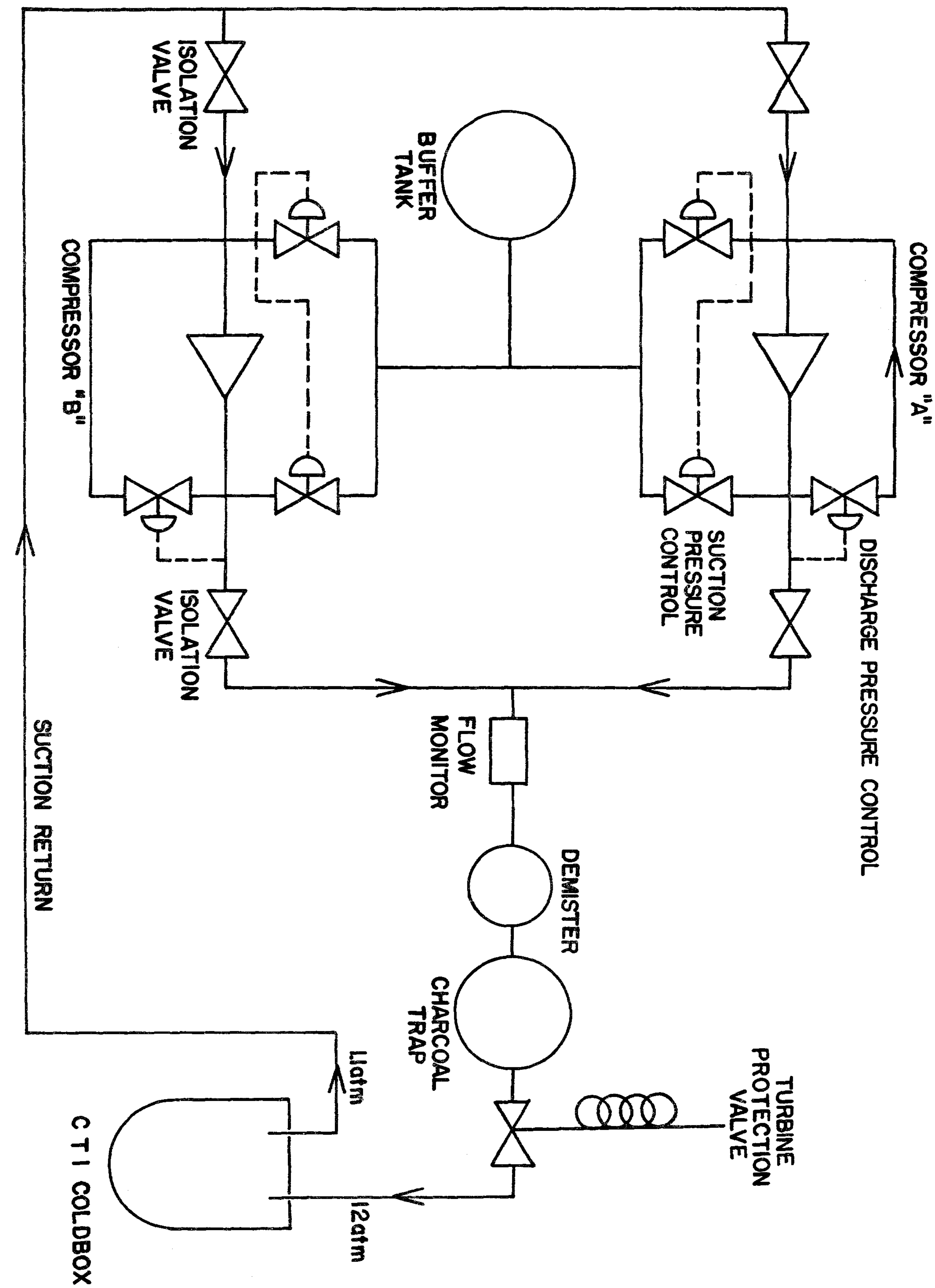

Figure 4. Main gas flow system.

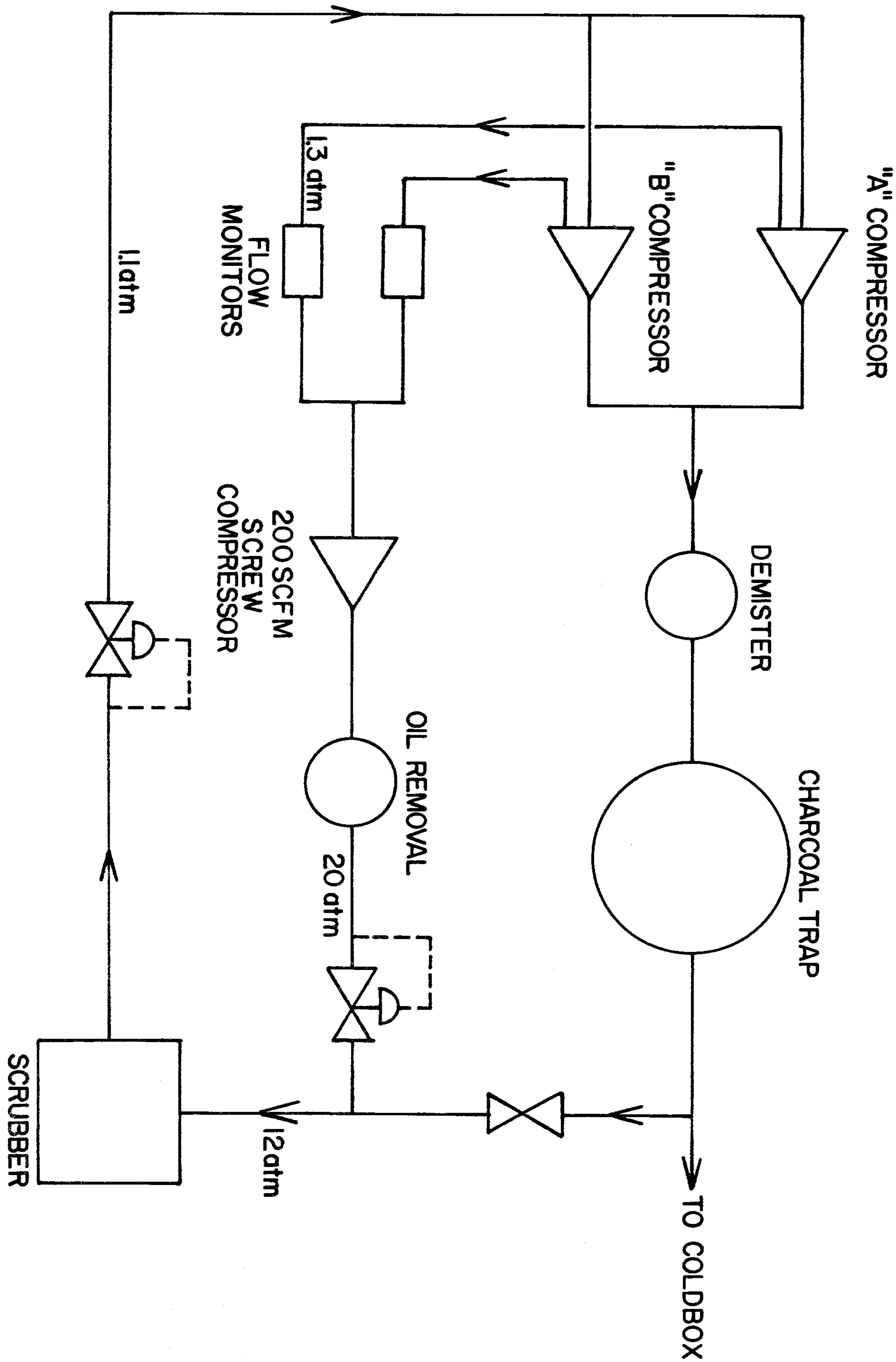

Figure 5. Seal gas cleanup system.

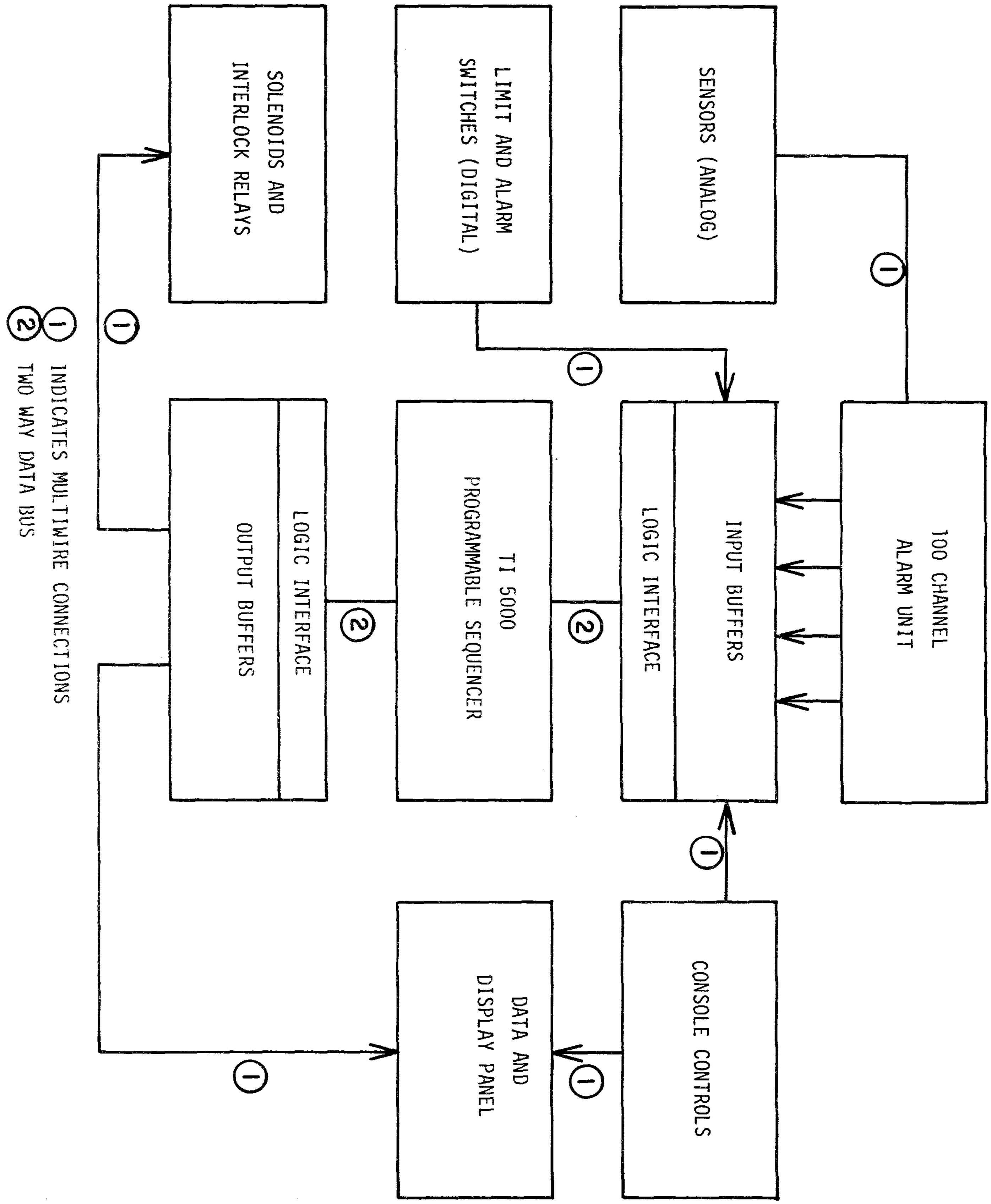

Figure 6. Block diagram of control system for helium compressors.

Notes: 1. indicates multiwire connections.
2. two-way data bus.

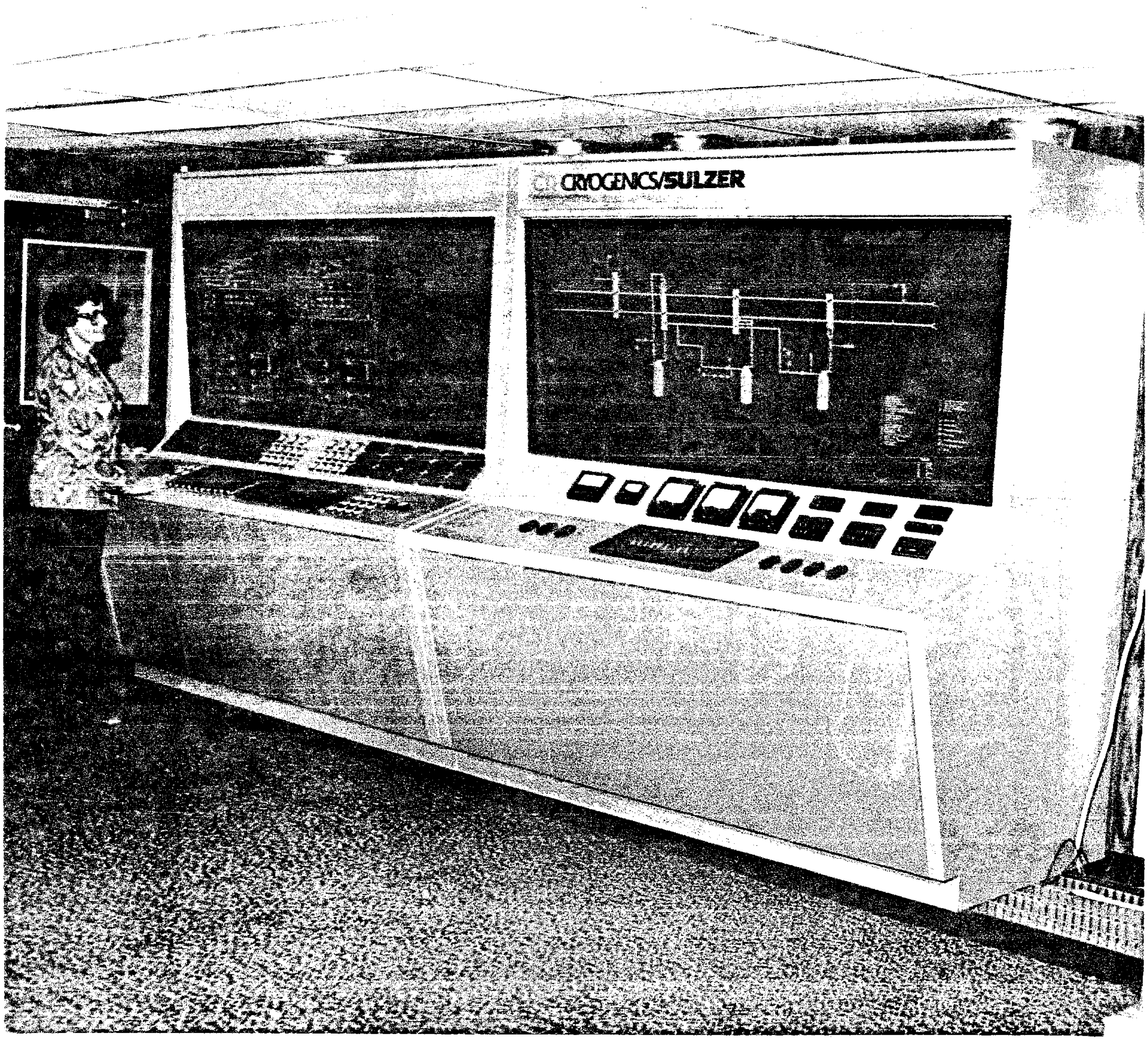

Figure 7. Control consoles for compressor and helium cold box.

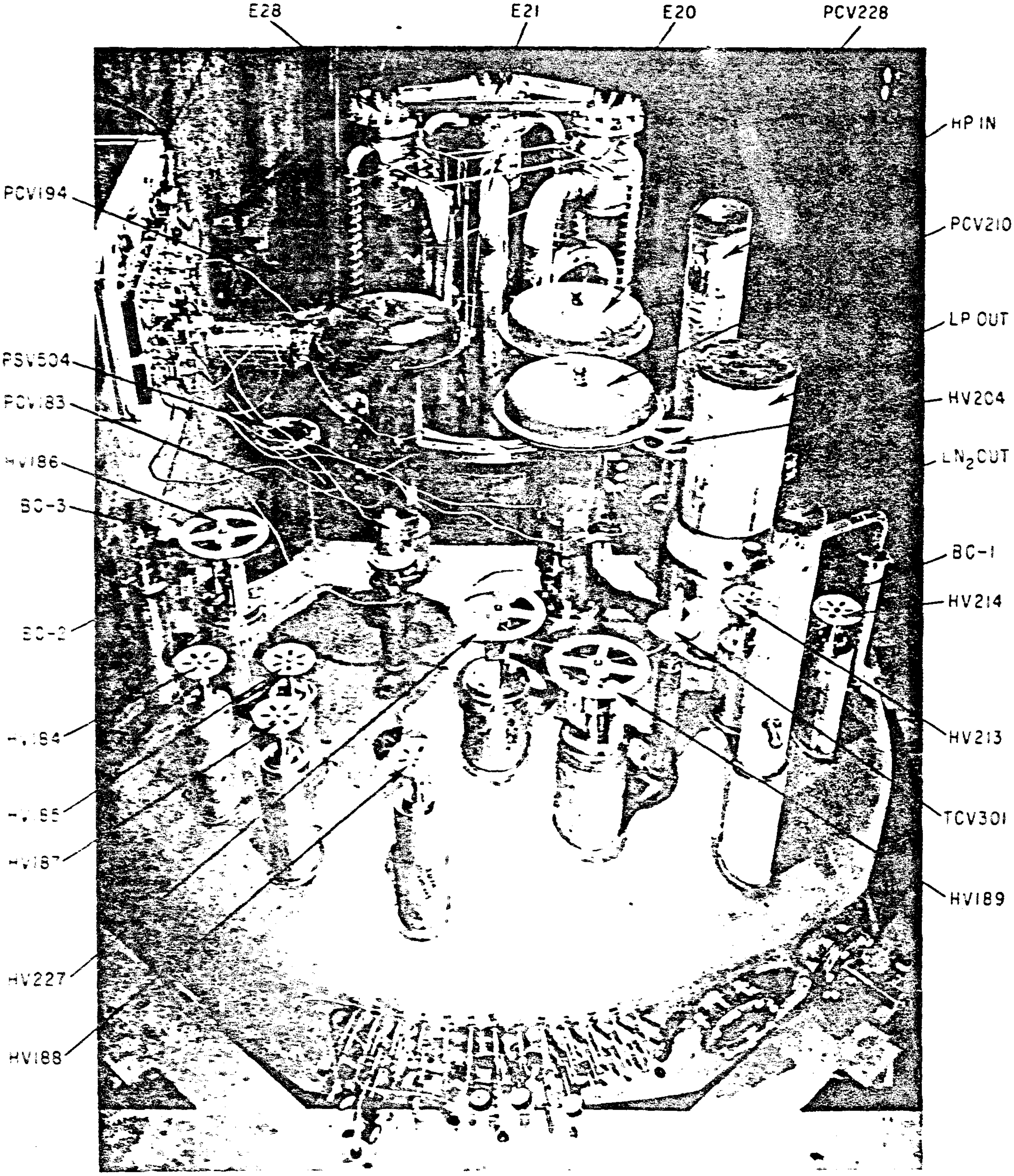

Figure 8. Top of helium cold box.

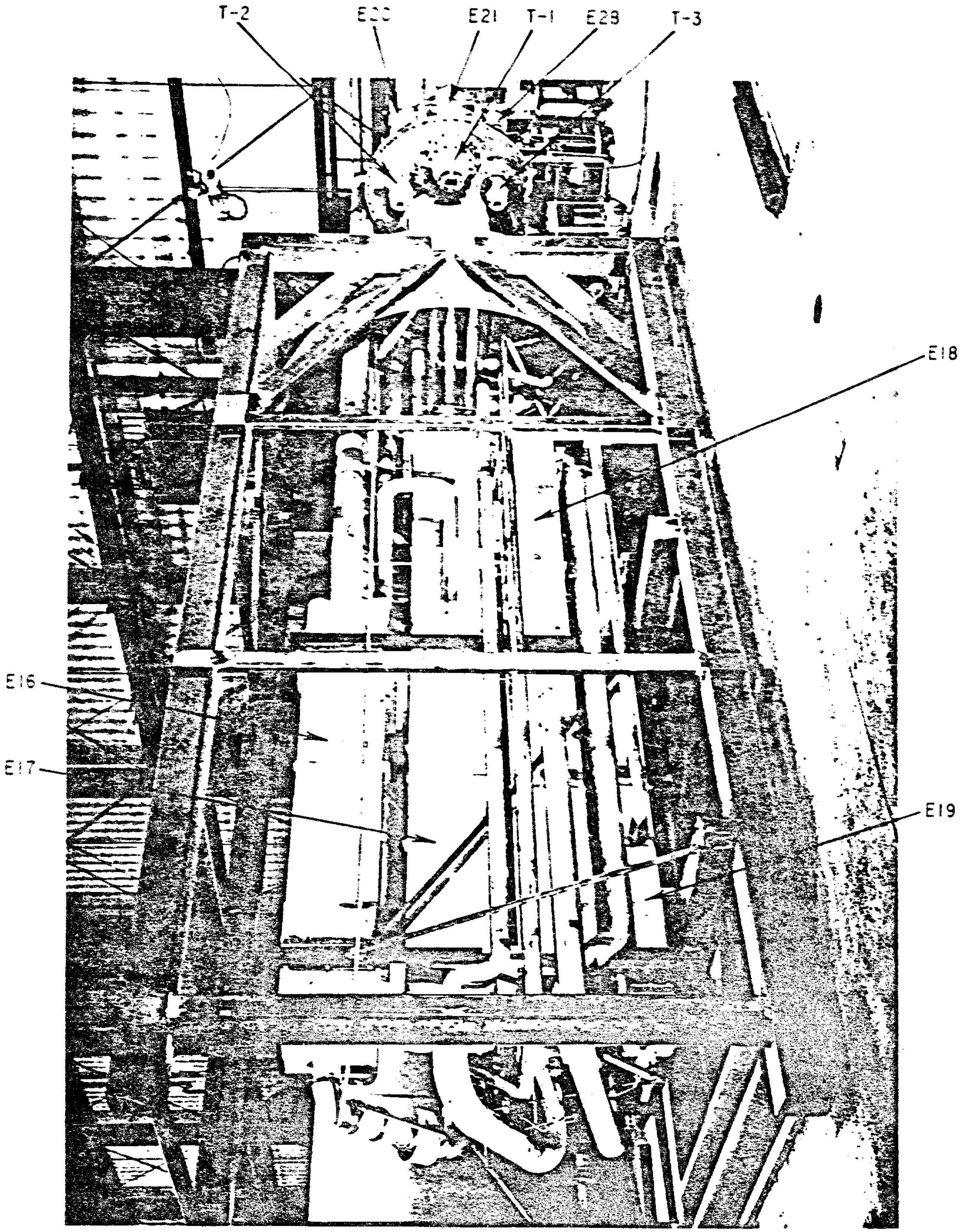

Figure 9. View of heat exchangers in helium cold box assembly.

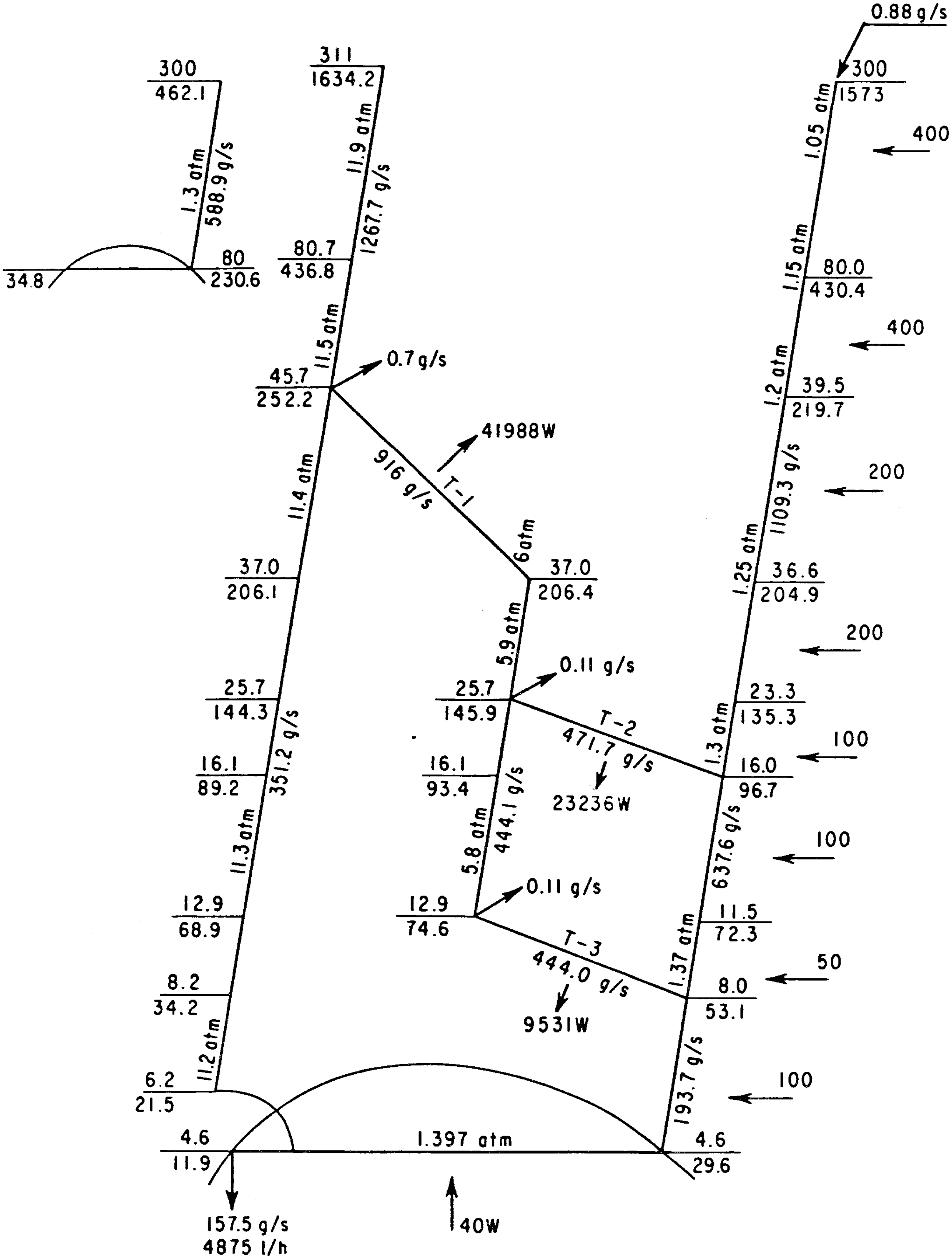

Figure 10. TS diagram for helium liquefaction cycle.

Figure 11 is missing.
(RJW is correcting.)

Correct page numbers

from here on

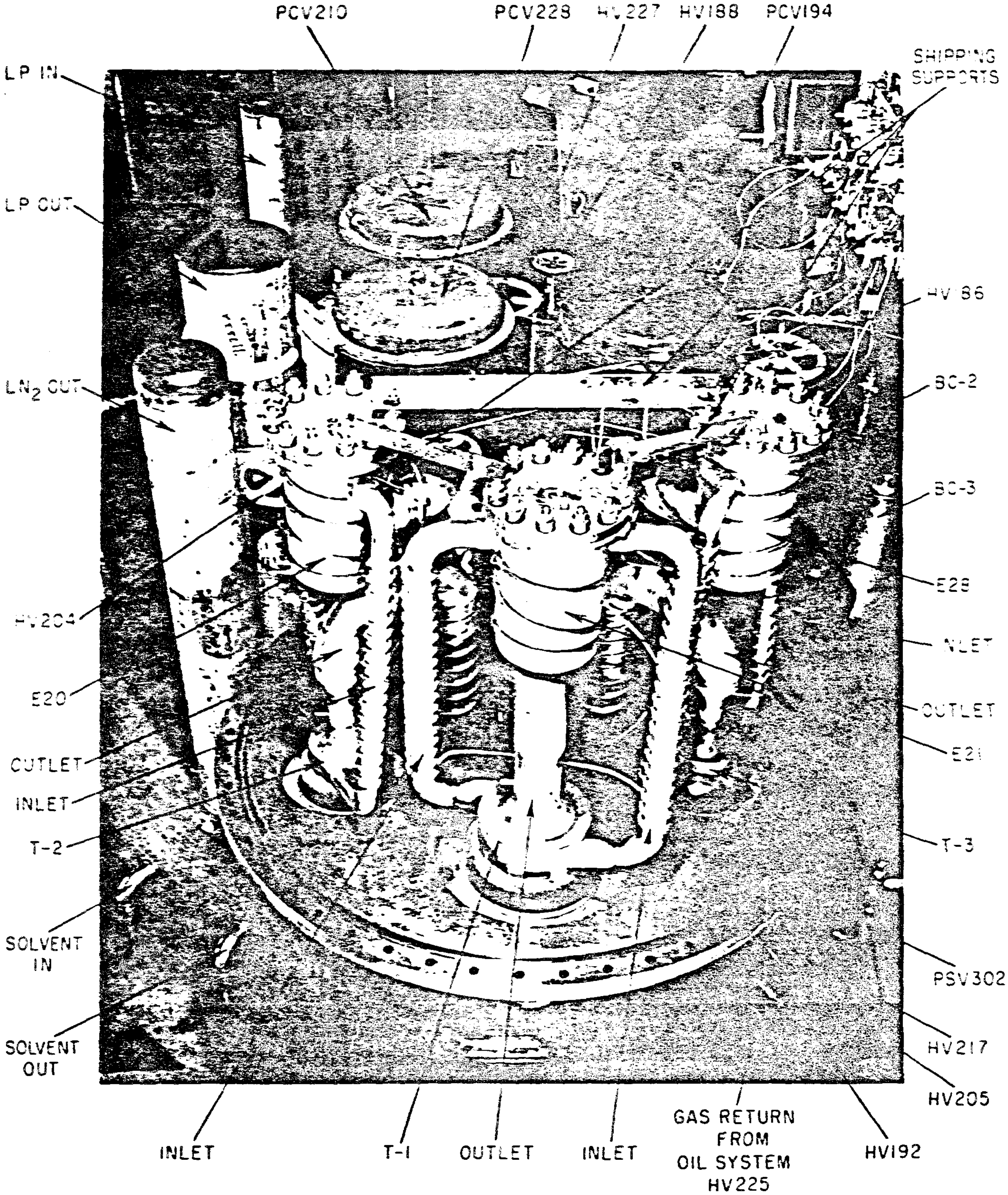

Figure 12. View of turbine inlet filters.

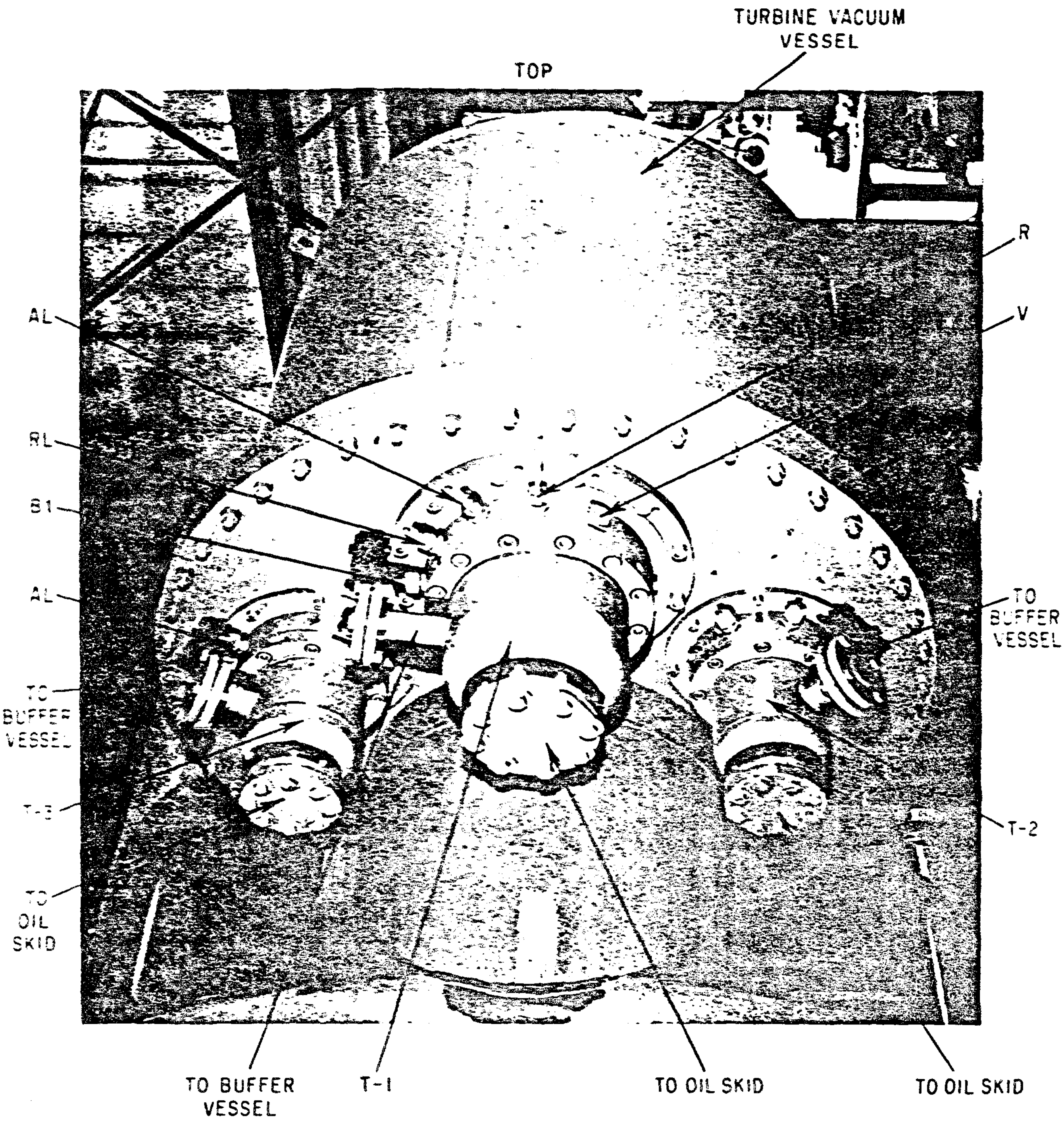

Figure 13. Turbine access and gas ports.

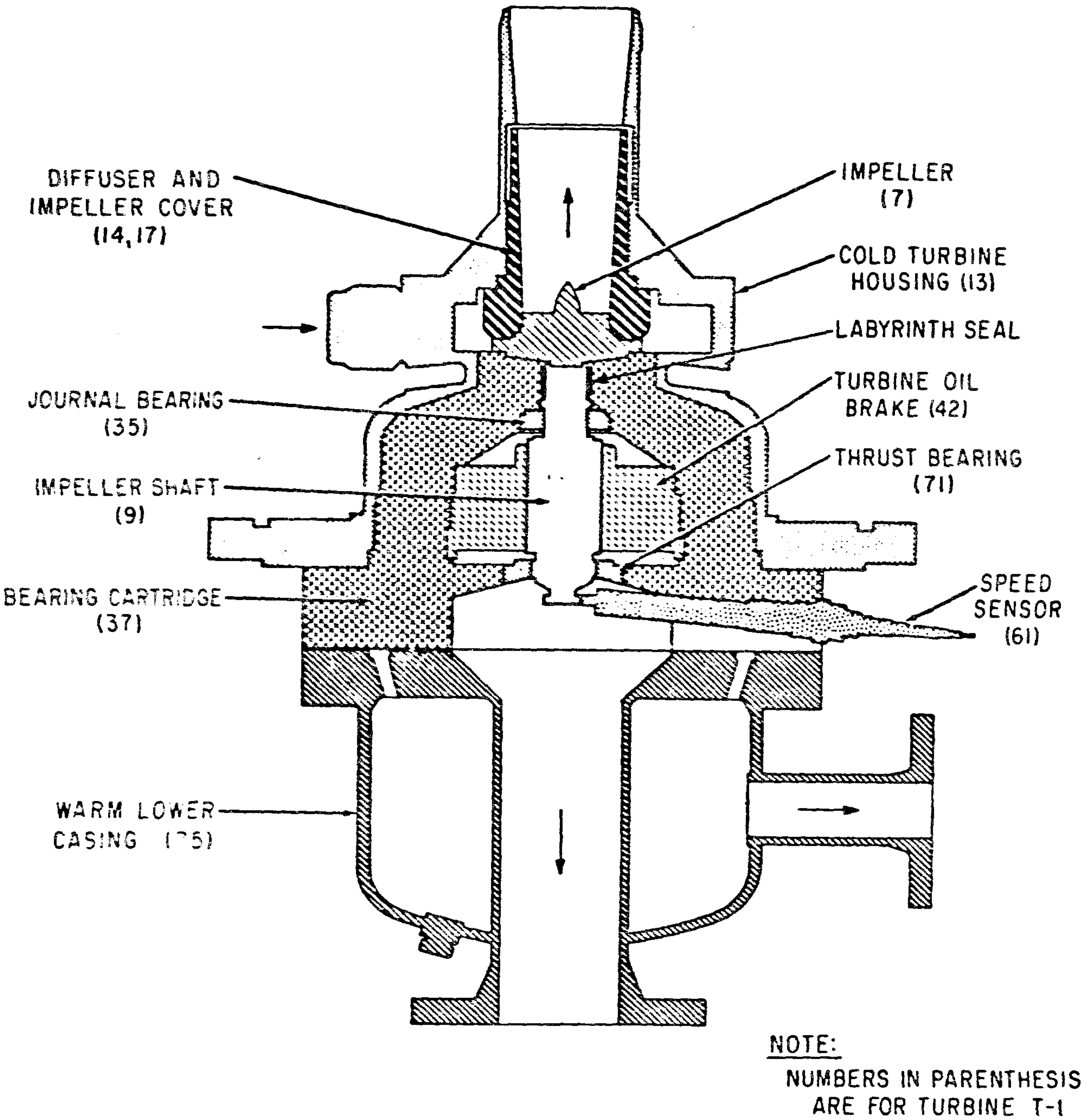

Figure 14. Cross sectional view of the Sulzer oil bearing turbine.

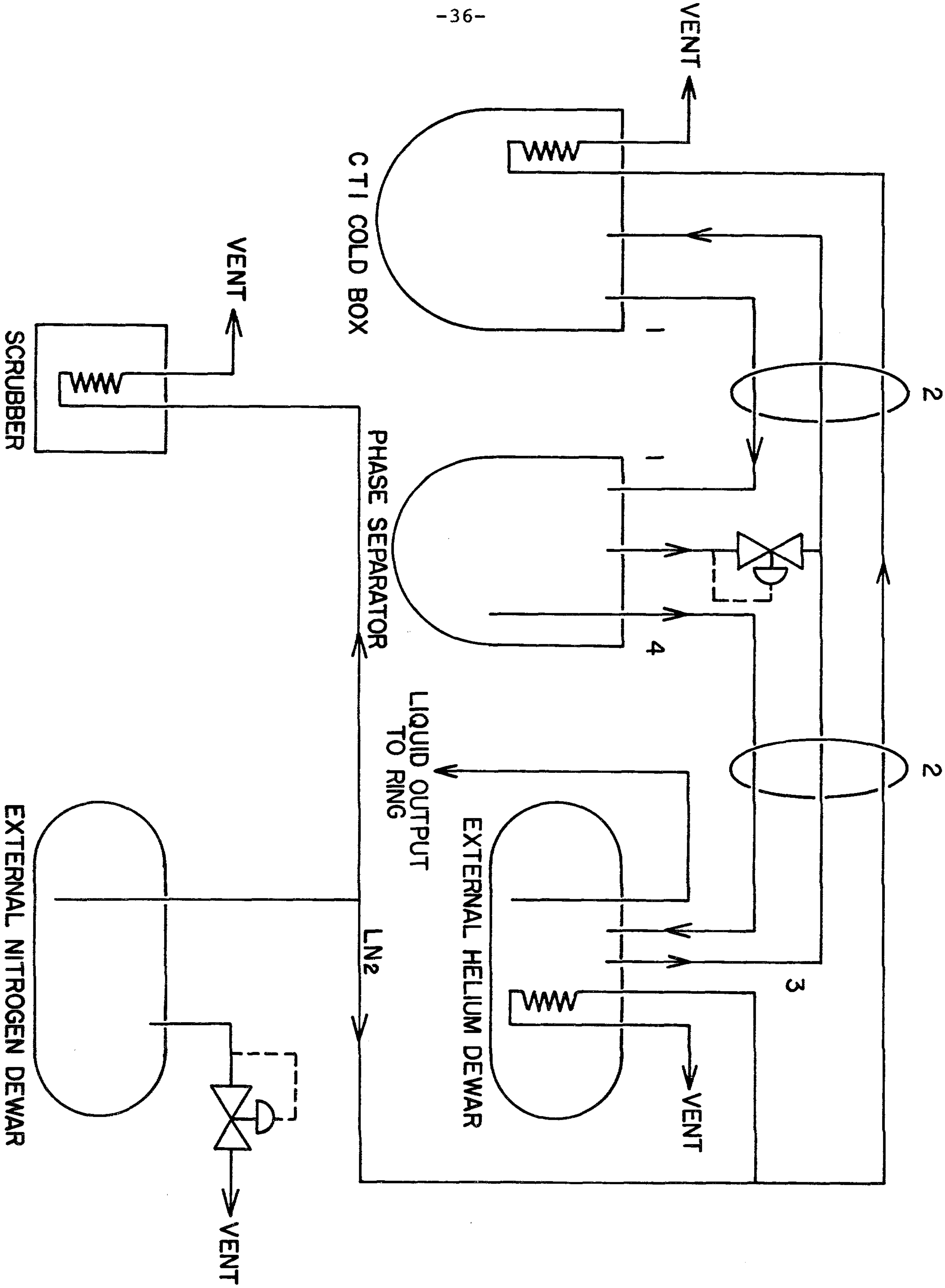

Figure 15. Cryogenic transfer line system.