CRYOGENIC SYSTEMS FOR THE MIRROR FUSION TEST FACILITY

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ABSTRACT

This paper will include an in-depth discussion of the design, fabrication, and operation of the Mirror Fusion Test Facility (MFTF) cryogenic system located at Lawrence Livermore National Laboratory (LLNL). Each subsystem will be discussed to present a basic composite of the entire facility. The following subsystems are included.

- 500kW nitrogen reliquefier, subcoolers, and distribution system.
- 15kW helium refrigerator/liquefier and distribution system.
- Helium recovery and storage system.
- Rough vacuum and high vacuum systems.

INTRODUCTION

The cryogenic system supporting the Mirror Fusion Test Facility (MFTF-B) at Lawrence Livermore National Laboratory (LLNL) provides liquid and gaseous helium and nitrogen at various temperatures to meet the requirements of the superconducting magnets, cryopanels, and numerous small loads. MFTF-B is one of two major government supported experiments in magnetically confined plasmas. The other experiment is located at the Princeton Plasma Physics Laboratory, Princeton, New Jersey, and is a Tokamak type reactor. The primary purpose of these experiments is to obtain physics data that will lead to the fabrication of machines capable of providing fusion energy.

The cryogenic system at MFTF-B consists of a number of subsystems. The subsystems are as follows:

- Two helium refrigerators.
- Two nitrogen subcoolers.
- A nitrogen reliquefier.
- A helium recovery system.
- An extensive helium distribution system with a rather unique forced-flow cooling system.
- A nitrogen distribution system.

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MFTF-B was preceded by an earlier experiment MFTF-A, that was supported by one of the above mentioned refrigerators and subcoolers and a portion of the helium nitrogen distribution systems. MFTF-A successfully completed the required technical demonstration as a full operational cryogenic system in 1982.

The MFTF-B operating system uses this equipment plus new and larger equipment. Two subcontracts were involved in developing this system; one for the earlier MFTF-A equipment and one for the additional equipment needed for MFTF-B. CVI Corporation in Columbus, Ohio, was awarded both of these contracts.

As of July, 1985, most subsystems had been tested and proven successful. Topics covered in this paper include

1. Cryogenic system requirements and specifications.
2. A systems overview.
3. A discussion of each major subsystem including equipment lists, cycle information, and block diagrams.
4. A summary of analysis completed.

Cryogenic System Requirements

MFTF-B cryogenic system requirements are to provide

- liquid helium refrigeration at 4.35K to 42K to superconducting magnets having a total weight of 1.05mkg (2.3m lbs).

- liquid helium refrigeration at 4.35K to cryopanels having a total area of 900 m^2.

- liquid helium at 4.5K to approximately 40 small loads requiring a total refrigeration of 1060 W. These loads include ten external cryopod pumps, 22 small cryopanels (about 10 m^2) used to locally pump neutral beam tanks, beam dumps, and a number of small loads associated with electronic and diagnostic equipment.

- liquid nitrogen at 80K to 90K for shielding of helium surfaces and for system cooldown refrigeration from ambient to 100K.

The entire system is to be cooled from ambient to operating temperature in less than ten days. In addition to the above heat loads, the system must also satisfy neutron heating generated from deuterium/deuterium reactions during 30s plasma pulses. The system must operate in the magnetic field and radiation environment assoicated with MFTF-B systems.

Tables 1 and 2 summarize the various helium and nitrogen heat loads resulting from the MFTF-B system requirements.

Cryogenic Systems Overview

Figure 1 is a block diagram of the complete helium cryogenic system. The crosshatched areas designate components of the MFTF-A system. Both systems are required during full operation of MFTF-B.

However, the system could be sustained in a standby mode (no shots fired) by only the 8kW refrigerator. Interconnecting lines are provided for this purpose between the 8kW and 3kW systems. The interconnection is accomplished using only two lines: one between the 8kW and 3kW cold gas return to the coldbox and the other between the 60,000 and 25,000 liquid helium dewars for liquid transfer between systems. Normally the two systems are operated independently. The 3kW refrigerator coldbox, located at the east end of Building 431 on the fourth floor, supports the east Yin-Yang magnet and vessel cryopanels.

The larger 8kW refrigerator system can operate at a reduced capacity in the event of failure of any one compressor skid or any one turbine. Consequently, failure of any one compressor or turbine would allow operation of MFTF-B in a standby or ready mode until repairs are completed.

A 500kW, 80K, extensive liquid-nitrogen system is employed. A nitrogen reliquefier eliminates the logistic problems of trucking liquid nitrogen to support the 500kW load. Providing this load by outside supplies would have required most of the liquid nitrogen available in the San Francisco, California area. Consequently, shortages were anticipated. Additionally, the simple payback period for the reliquefier is between one and two years of normal MFTF-B operation.

Table 1. Summary of Estimated LHe (4.35K) Heat Loads

ITEM	HEAT LOAD (W)	BLEED STREAM HELIUM TO GAS BAG (g/s)	
Magnets	Natural Convective Loop	Magnet Leads	Loads on 2 Phase Loop
Normal conduction and radiation	2332		
Neutron heating	744		
X-ray heating	30		
Current leads	--	10.0	
Magnet piping in vessel	200		
Cryopanels			
Normal conduction and radiation	2600		570
Microwave heating (0.1x2000)	270		105
Neutrons	7		30
X-rays	29		20
High, low and sloshing beams	--		
Plasma dump thermal radiator	50		
Cryopanel lines in vessel	170		
ECRH, gyrotrons, beamlines and diagnostics			110
External piping (non-shielded feeds)	1084		265
LHe dewars	426		
Valves and valve boxes	550		50
Cryopumps			50
Subtotal	8492	10.0	1200
Reserve Capacity	1995		20.8
Total Required	10,487		
Less Existing Capacity	3,075		
Total New Capacity	7,412		

Table 2. Summary of Liquid Nitrogen (85K) Loads

Magnet Shields (1000 m^2 area)		Load kW
Normal conduction and radiation (E-0.3)		161.0
Microwaves		2.0
Plasma dump thermal radiation		3.0
Neutrons and x-rays		Negligible
Cryopanel Shields		
Normal conduction and radiation		90.0
Microwaves		2.0
Plasma dump thermal radiation		50.0
Neutron and x-rays		Negligible
Storage tank		2.0
Cryopumps		4.0
Purifier		11.0
He refrigerator		20.0
Subcooler pumps		40.0
Dewar and LHe piping shields		5.0
LN piping and valves		8.0
		398.0
	Reserve	102.0
	Total	500.0

Figure 2 is an isometric showing the general layout of cryogenic equipment. The equipment is shared between Buildings 431 and 433. Building 431 houses the MFTF-B vessel and cryogenic equipment including

- o 8kW helium refrigerator.
- o 3kW helium refrigerator and compressors.
- o Helium recovery system including.
  - Recovery compressor.
  - Gas bag.
  - Dual cryogenic purifier.
- o Liquid nitrogen subcoolers.
- o Nitrogen and helium distribution systems.

Building 433 and ajacent areas house the 8kW-system helium compressors, the nitrogen reliquefier coldbox, high pressure helium storge, and a 150,000-litre nitrogen dewar.

Figure 3 is a photograph looking southeast over the top of the fusion chamber. Supply dewars for the west-end Yin Yang, west-end cryopanels, and some central-cell magnets are shown. Also, shown are cryogenic piping racks running the length of the vessel. These racks were preassembled in five sections at CVI Corporation to substantially reduce the amount of field fabrication.

Figure 4 is a photograph facing west from the control panel located on the fourth floor of Building 431. On the left is the 8kW coldbox. The 60,000-litre helium dewar is on the right.

Figure 5 is a photograph of the control console located in Building 431 (fourth floor west). A substanial portion of the console is devoted to the helium distribution system. The console is layed out pictorially. Near the center is a schematic of the MFTF-B vessel with valve controls, valve indicators, etc. Also, included on the console are controls for the 8kW coldbox and compressors, helium forced-flow system refrigerator and compressors, and the west-end liquid nitrogen distribution system. The 8kW refrigerator without simultaneous liquid production of 30.8 g/s would produce as estimated 10.7kW.

Figure 6 (facing east) shows Building 433, the new compressor building. In the foreground are overhead pipe racks leading to Building 431. This piping includes the 8kW-coldbox-to-compressor piping, cold nitrogen gas return from loads in Building 431 to the reliquefier, and liquid nitrogen supply lines to Building 431. Immediately in front of Building 433 is the nitrogen reliquefier coldbox and the vertical tanks for helium high-pressure storage.

Figure 7 shows the 8kW refrigerator compressor skids located in Building 433. All together Building 433 houses eight compressor skids totaling 12,900 HP, a 800kW induction generator used in conjunction with the nitrogen reliquefier expander, and a small control room.

Figure 8 is a photograph of a supervisory control and diagnostics system (SCDS) console . SCDS includes a number of these consoles for controlling all aspects of the MFTF-B experiment. One of the five screen consoles, as shown, is dedicated to the cryogenic system. SCDS is located in Building 439, approximately 30 metres from the northwest corner of Building 431 and is connected to the various local control panels by fiber-optic links. Its purpose is twofold:

- o It provides a central control area for the overall experiment
- o It permits operation, remote from Building 431, where neutron radiation limits personnel-exposure periods.

By use of the lower touch-control screens or a "mouse" on the upper screens, any portion of the cryogenic distribution system can be called up and controlled or monitored.

Subsystems

The following subsystems will be presented in this section:

- o 8kW refrigerator system.
- o 1200W forced flow helium refirgerator.
- o Nitrogen reliquefier.
- o Helium recovery and distribution systems.

8kW Refrigerator System. Figure 9 is a simplified schematic of the 8kW system showing the compressors, the oil removal equipment (located in Building 433), the coldbox and MFTF-B loads in Building 431. In addition to the 8kW of load at 4.35K the system must simultaneously provide 30.8 g/s of liquid helium: ten g/s is used for cooling magnet-current leads and the other 20.8 g/s is supplied to the forced-flow refrigerator. The 30.8 g/s is returned directly to the compressor suction at 300K.

Figure 10 is the T-S diagram for the 8kW system. Major components are described in Table 3. The overall efficiency of the system is approximately 19% of carnot. An 8% safety factory has been incorporated which does not enter into this estimate.

Table 3. 8kW Refrigerator Major Components

First Stage Compressors:

Three each, Howden 321/1.93/2.6, 400 HP drive, assembly made by CVI, Inc.

Second Stage Compressors:

Two each, Howden Model 321/1.93/5.0, 2250 HP drive, assembly made by CVI, Inc.

Oil Separator:

Three stages Brink/Monsanto coalescers (maximum impingement velocity-12ft/min) plus one charcoal -absorber/filter.

First Turbine:

Air Liquid C6 gas bearing turbine.

Second Turbine:

Air Liquid C5 gas bearing turbine.

Third Turbine:

Roto flow oil bearing turbine.

<u>1200W Forced-Flow Helium Refrigerator</u>. As a result of these proposal calculations, the difficulty of small load cooling was realized. In many cases the routing of pipe between these loads and supply dewars could not be direct enough to permit natural convection cooling. CVI Corporation then proposed and designed a forced-flow loop to supply these loads. LLNL accepted their proposal, resulting in the present system.

Figure 11 presents a simplified schematic of the forced flow system. Flow to the loads is provided by a conventional screw compressor (255/2.2/2.6 Howden). The source of the refrigeration is liquid helium supplied by the 8kW refrigerator. Consequently, no additional turbines are required. The high-pressure helium passes through an oil removal system similar to the 8kW refrigerator, through the heat exchangers, and through individual control valves to the various loads. The helium is expanded from 3.5 atm to slightly over 1 atm through the control valves, resulting in about 10% quality. After absorbing heat from the loads it returns to the coldbox at about 53% quality. The addition of LHe to the two-phase return provides cooling to the relatively warm high pressure helium to be liquefied. The excess helium, 20.8 g/s at full load, is removed from the forced-flow system prior to compressor suction and after it exits the coldbox. Figure 12 presents the T-S diagram for this cycle.

Nitrogen Reliquefier. This system takes nitrogen gas near saturation temperature from the loads and reliquefies it. The liquid is then returned to the loads, completing the cycle.

Figure 13 shows a simplified schematic of the system. In operation, saturated gas boil-off from the subcoolers passes through the liquefier heat exchangers, thus recovering sensible heat before entering the feed compressor. Both the feed and recirculating compressors are controlled to permit a large variation in feed rate. This allows the system to operate over a wide range of loads. The recirculating loop liquefies the nitrogen in a conventional manner. Major components are described in Table 4.

Table 4. Major Components of Nitrogen Reliquefier

Feed Compressor:	
	Joy two stage centrifugal with 1200 HP drive.
Recirculating Compressor:	
	Joy four stage centrifugal with 5500 HP drive.
Turbine:	
	Rotoflow, oil bearing driving 800kW induction generator which back feeds power line.

Helium Recovery System and Distribution System. A block diagram of the recovery system is shown in Figure 14. The system is the same as used for MFTF-A except six large tanks were added to the high pressure storage, increasing storage capacity from 1800kg to 7800kg. With this new storage about 80% of the MFTF-B liquid inventory can be stored as high pressure gas. The recovery system receives gas from the magnet current leads (10 g/s), leaks or vents from relief valves, compressor blow down vents, and gas returned during MFTF-B system warmup. Returning gas goes to the gas bag. The recovery compressor then pumps from the gas bag through the purifier to high-pressure storage. Online analysis ensures gas going to storage is pure. Table 5 describes major components of the system.

Table 5. Helium Recovery System Components

Gas Bag:	
	45,000 ft^3, vinyl, contained in air inflated tent.
Compresser:	
	Ingersol Rand, four stage, air compressor, 450 HP, modified by LLNL for helium service, 50 g/s, 2500 psi.

Table 5. Helium Recovery System Components (con't.)

Purifier:	
	Dual bed, charcoal, at LN temperature, 2500 psi operating pressure, made by CVI Corporation.
High-pressure storage:	
	6 tanks each 1700 ft^3 (5.6' dia by 100" long) 1890 psi. 60 tanks each 50 ft^3 (24" dia by 30' long) 2200 psi. Total storage 7800kg helium.

System Analysis

The purpose of this section is to direct the reader to references detailing some of the more significant or interesting analyses done in conjunction with the design of MFTF-B. Some of these references are already published papers, others are engineering notes and internal memorandums.

Magnet and Cryopanel Natural Convection Flow. Flow over the vessel between the magnets and cryopanels and their liquid helium dewars is established by natural convection due to heat addition at the load magnet or cryopanel. Two independent analyses were done to determine this flow, the resultant quality of helium in the load, and the required pipe sizing between the load dewars. The details of these are reported in Refs.1 to 6. The system was then designed to limit helium quality (vapor content) at the tops of the loads to about 2.5%.

Magnet Quench Vent Pressure. A quench in one or more of the 42 magnets of MFTF-B would result in rapid pressure buildup as the helium vents from the magnet because of resistive heating in the coil. Two independent analyses were done to determine pressure buildup based on magnet geometry and size of the vent piping. The details of these are reported in Refs. 7 to 10. In summary, it was assumed in one analysis that the magnet quenched instantaneously and all heat went to the helium. This is the worst case condition. In reality, the quench will propagate through the coil, resulting in a slower vent rate.[6-8] The other analysis assumed a quench propagation based on calculated and empirical information.[10] The system was then designed with quench vent-relief piping system capable of handling the quench of all the magnets together.

Steady State Heat Loads. Analyses of heat loads for both 4.35K and 80K loads were done for all MFTF-B systems, including magnets, cryopanels, piping, dewars, etc. These values were calculated based on radiant and conductive heat loads. The results were compared to empirical information taken from similiar systems. The MFTF-A heat loads were measured during operation of that system in 1982 and these served as valuable guides in determining heat loads for MFTF-B. Details are reported in Refs.10 to 13.

Pulse Heat Loads. Plasma shots up to 30s duration are planned when MFTF-B is in full operation. During shots, significant neutron-radiation heat will be deposited in the magnets. Microwaves used to heat the plasma will also deposit significant amounts of heat on the cryopanels. Average heat loads during the pulse have been calculated as up to 50% of the steady state loads. These calculations are reported in Refs. 10, 13, 14, 15, and 16.

Pulse Heating Effect on Main Helium System and Forced Flow Loop. The helium systems are designed with sufficient thermal capacity to absorb 30s of pulse heat without excessive pressure rise or other detrimental effects. Details are reported in Refs. 17 to 20.

Helium and Nitrogen Refrigerator Capacities. Capacities and liquefication capabilities of the helium main refrigerators, the helium forced-flow refrigerator, and the nitrogen reliquefier were calculated by CVI Corporation, using proprietary codes.

CONCLUSIONS

The MFTF-B cryogenic system is presently in the middle of an acceptance test. Most systems have tested successfully and been accepted by LLNL. So far the original budgeting and schedule estimates have been met, plus or minus a few percent. Final testing and evaluation can only be done on a fully operational MFTF-B system. Future reports will keep the community abreast of developments.

ACKNOWLEDGMENTS

The completion of the MFTF-B cryogenic system can be attributed in large part to the effort and attitude of CVI Corporation and to individuals within that organization. The company policy has not only been to meet contractural requirements but to provide equipment that best serves the MFTF-B project. To this end several highly qualified and dedicated individuals have been involved with the project. These include Bill Chronis, Charles Hood, Howard Altman, David Raymond, and Dallas Gittins. Robert L. Nelson is well known to most of us in the Cryogenic community. As Project Engineer for the MFTF-A and MFTF-B, he has brought a rare combination of technical knowledge, analytical capability, and practical hands-on experience to the project.

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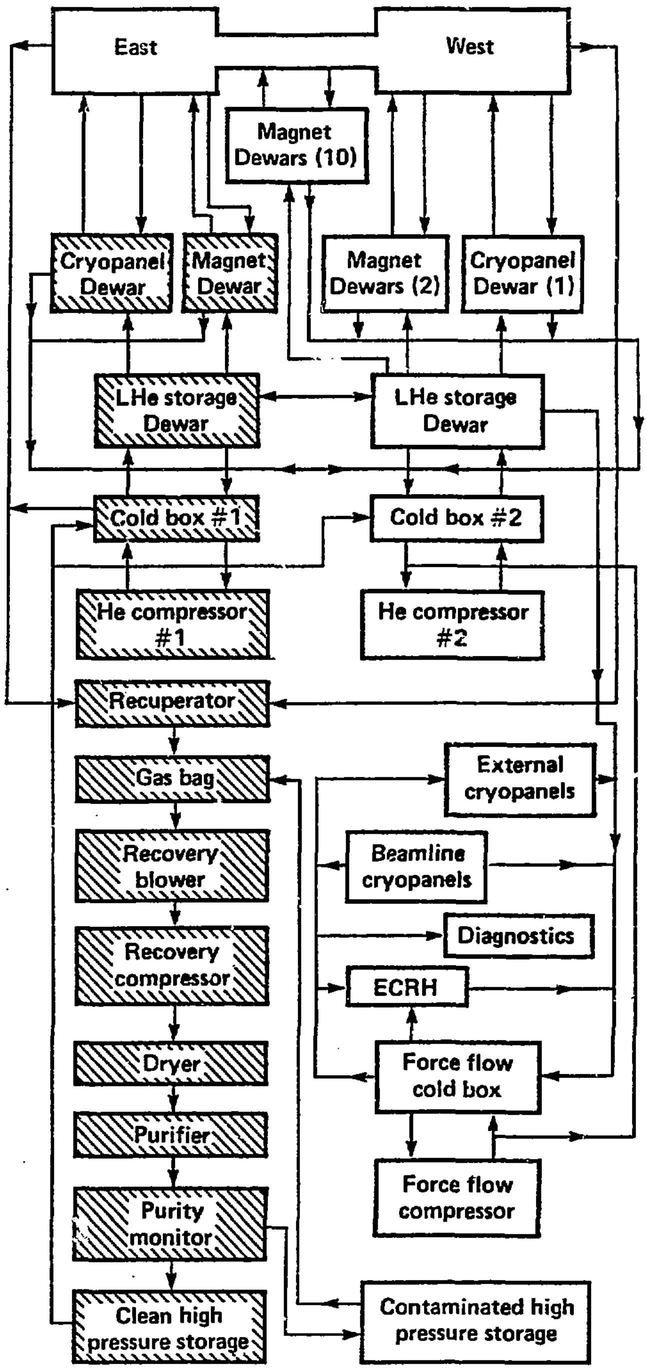

FIGURE I.

MFTF-B HELIUM CRYOGENIC SYSTEM BLOCK DIAGRAM.

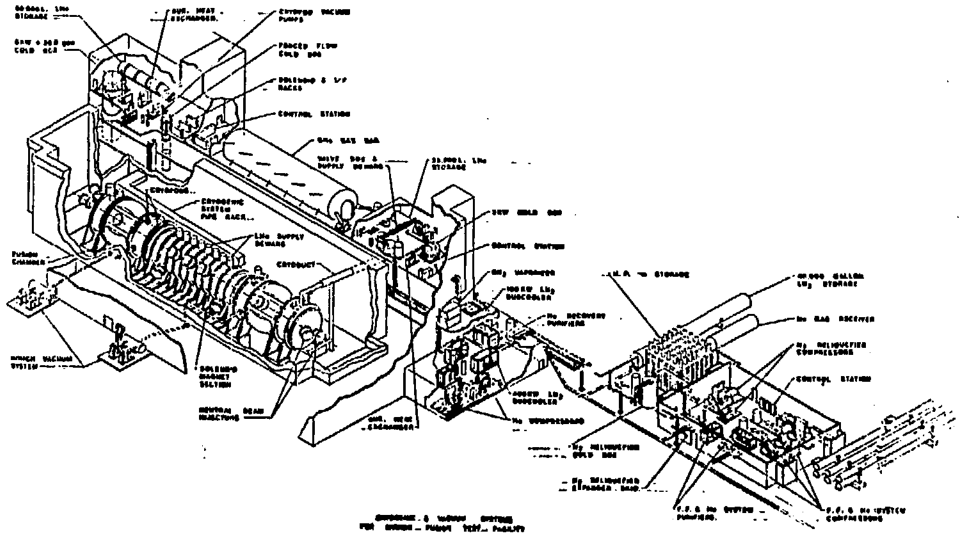

FIGURE II.
MFTF-B CRYOGENIC EQUIPMENT LAYOUT

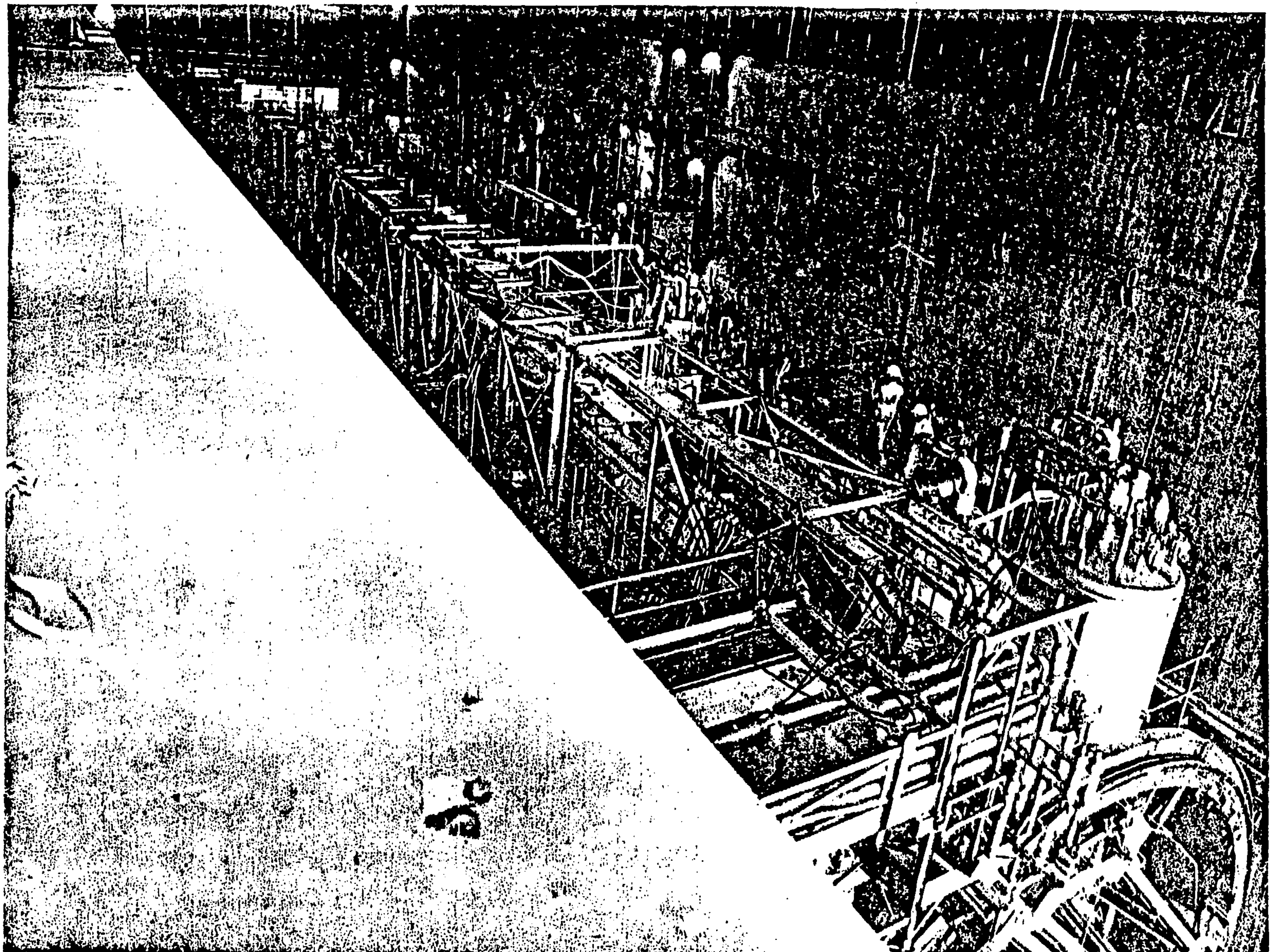

FIGURE III.

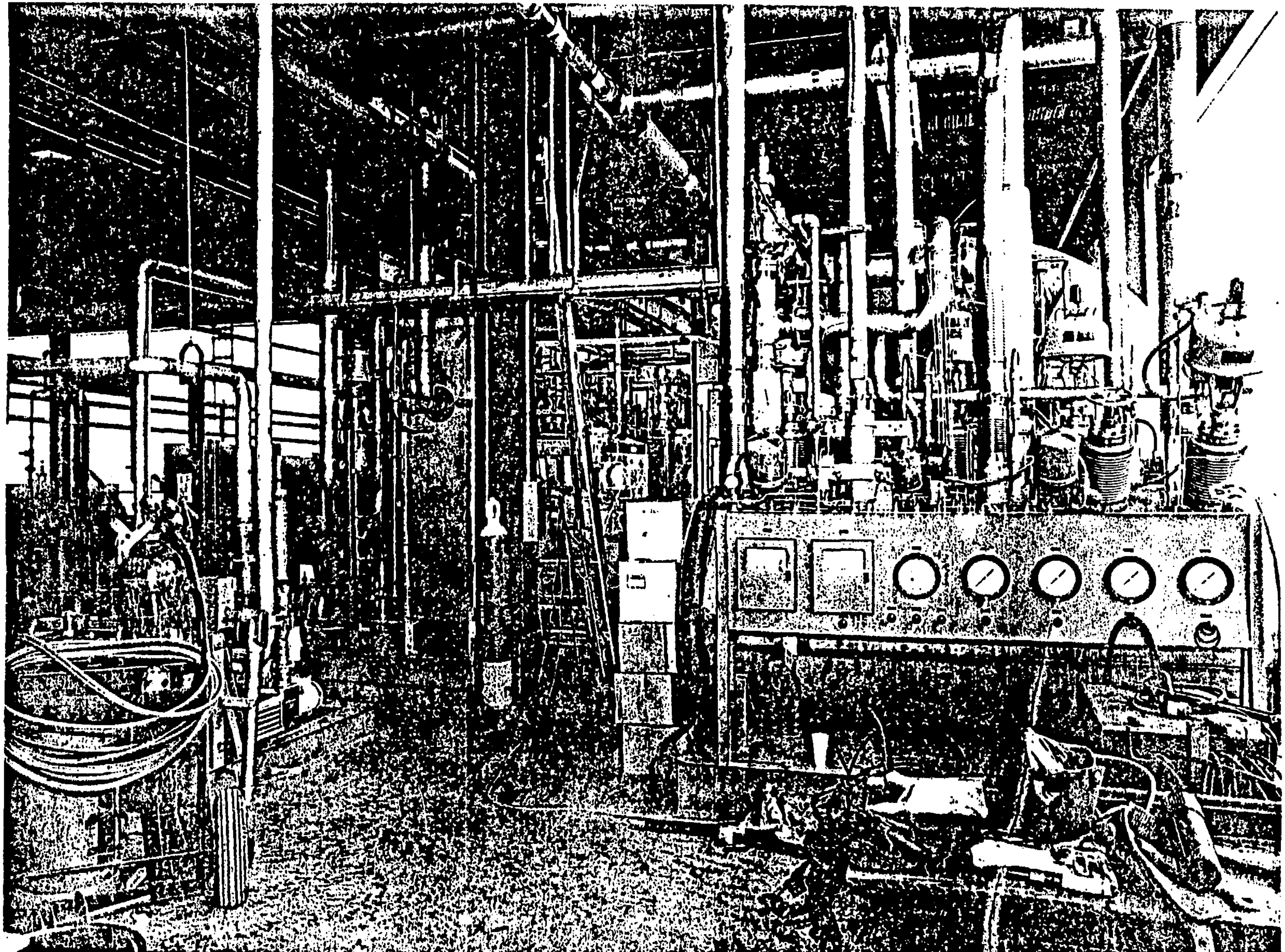

FIGURE IV.

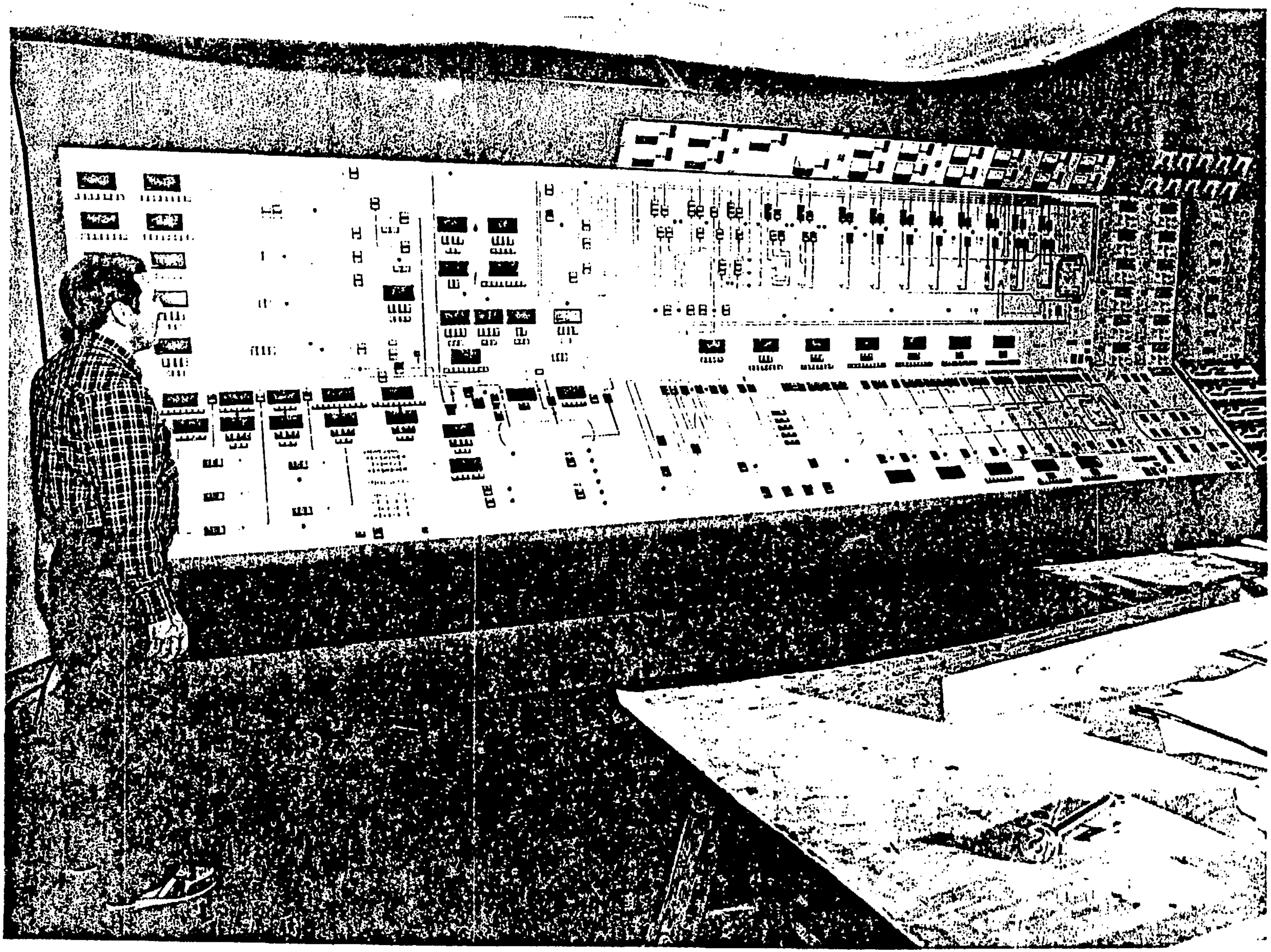

FIGURE V.

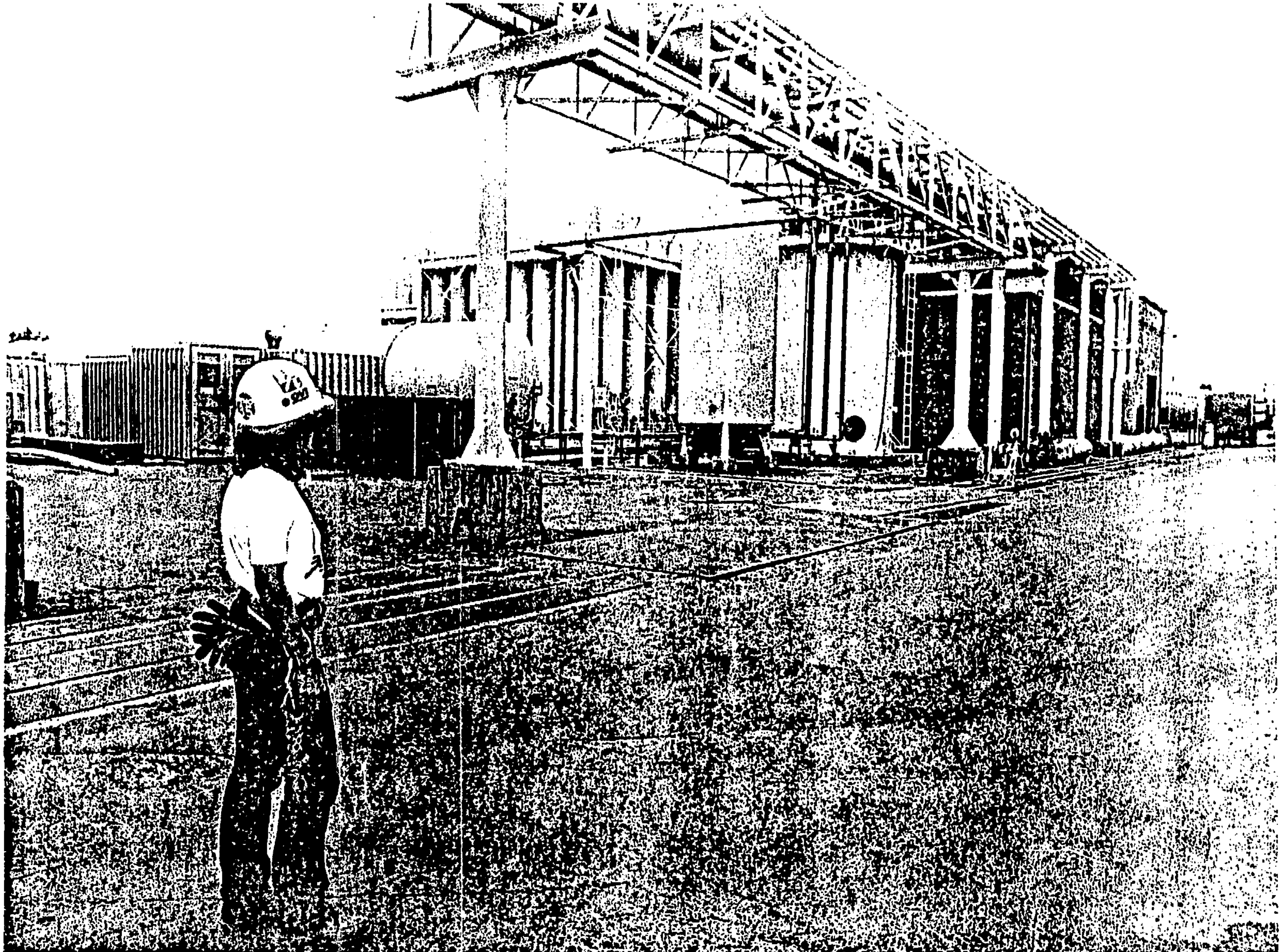

FIGURE VI.

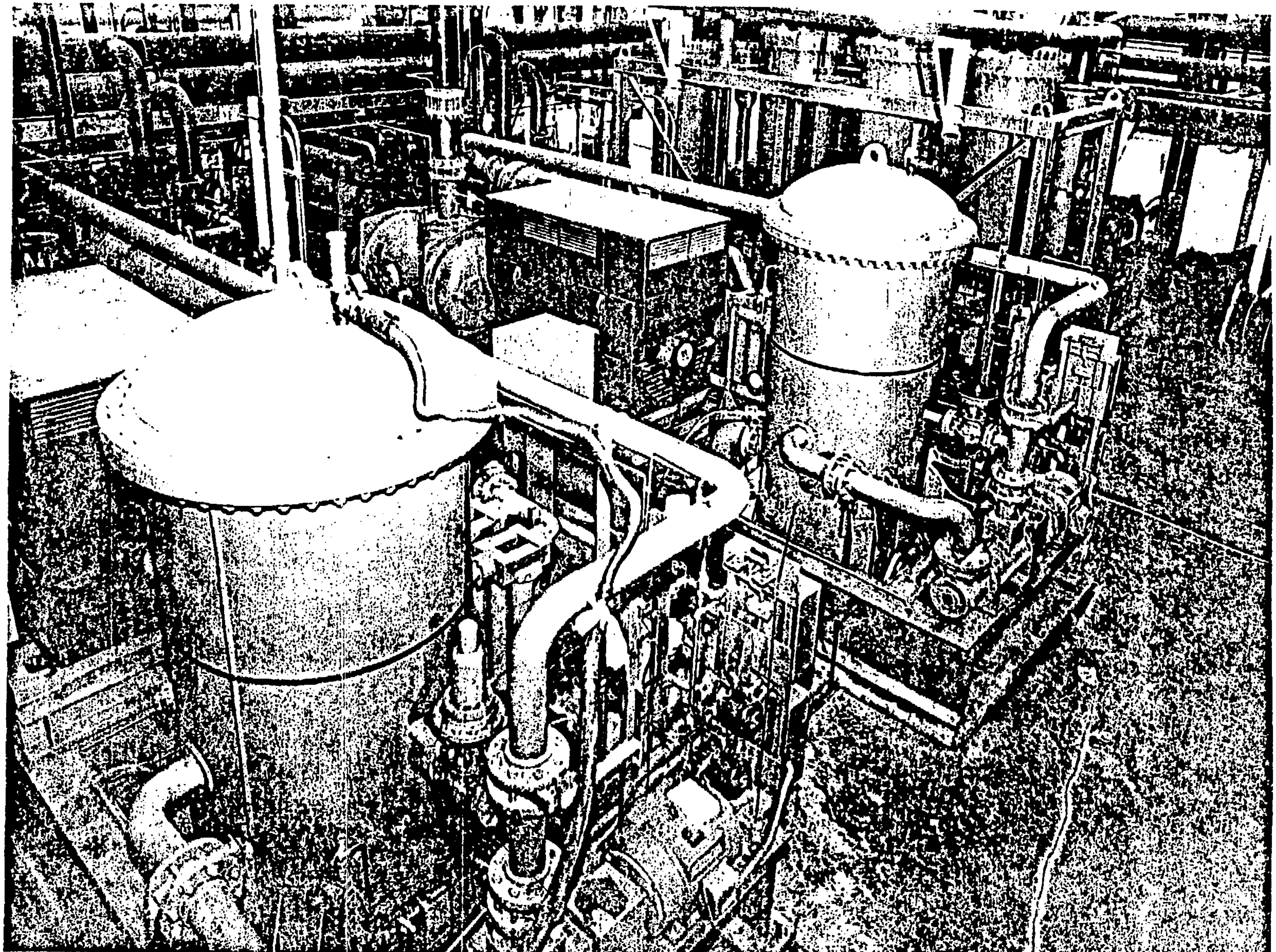

FIGURE VII.

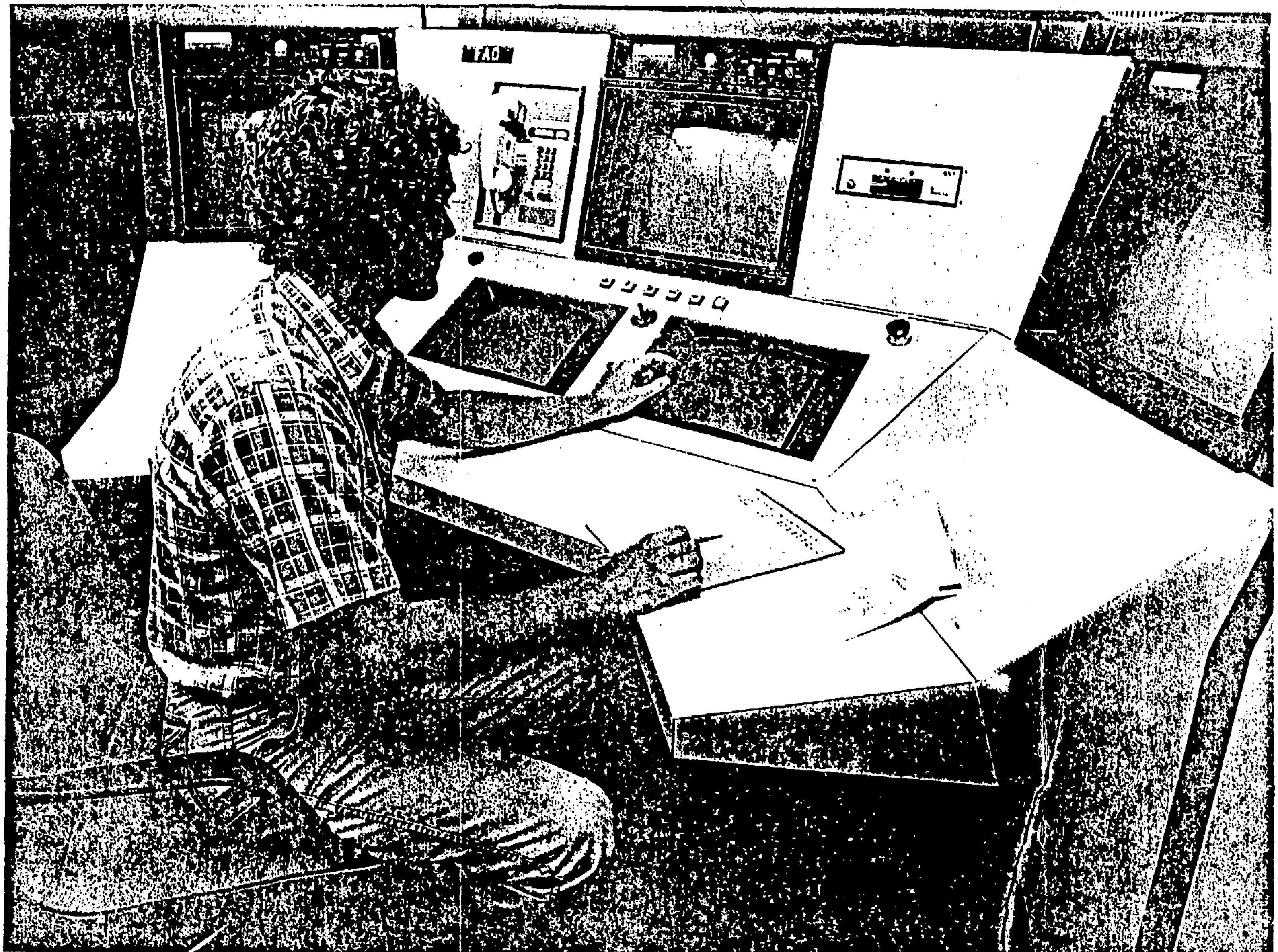

FIGURE VIII.

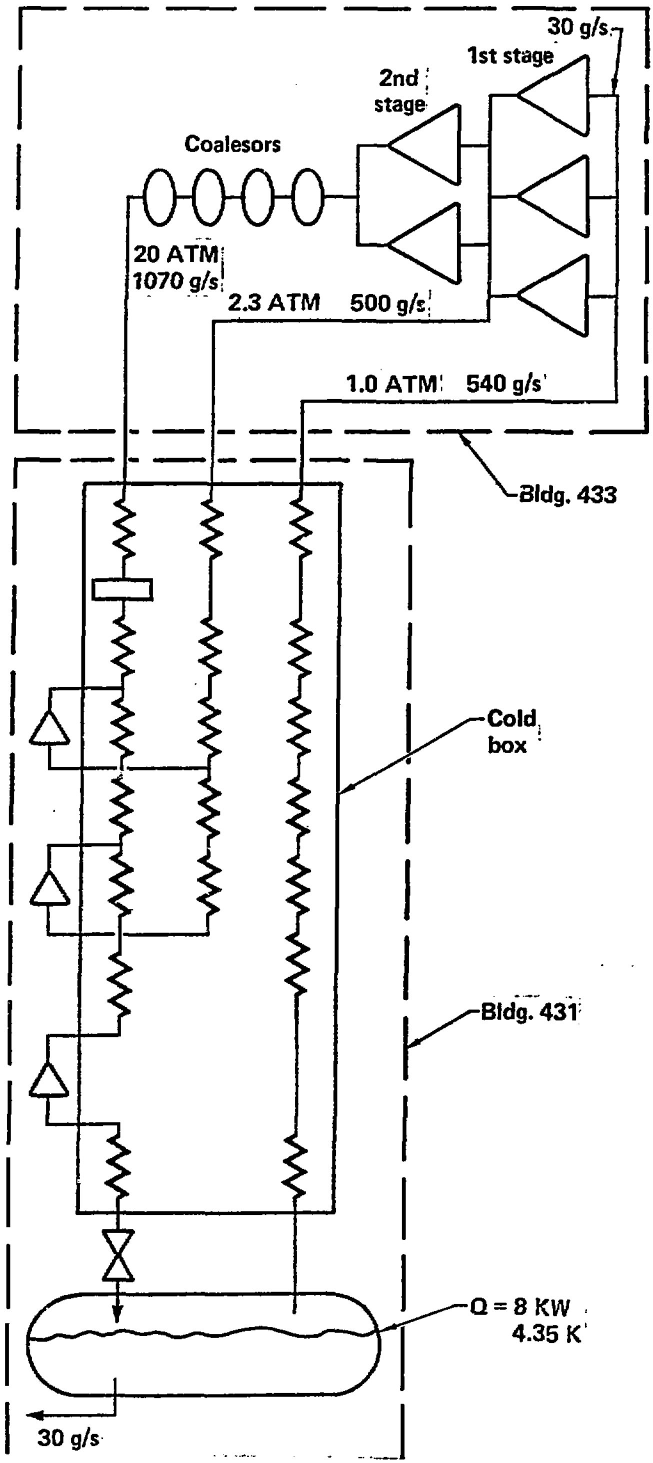

FIGURE IX.

8kW REFRIGERATION SYSTEM

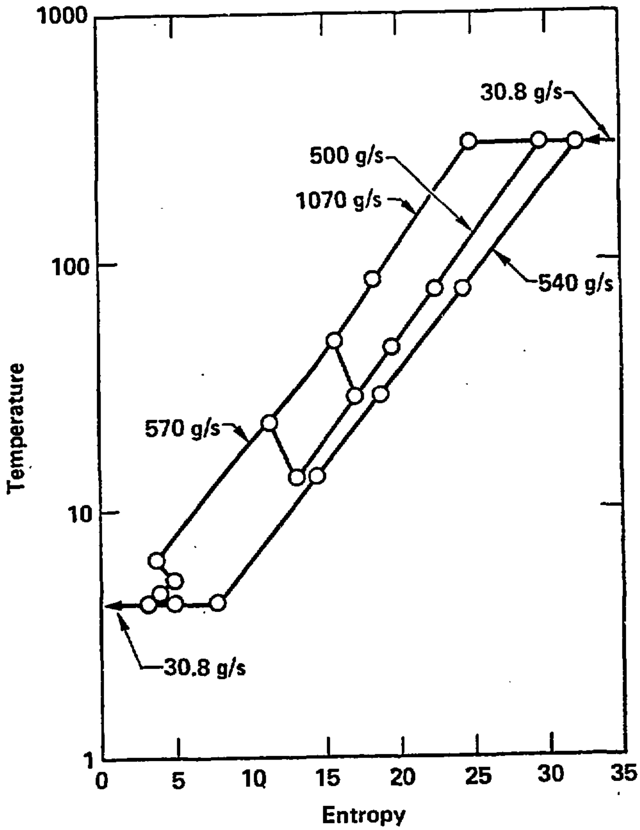

FIGURE X.

T-S DIAGRAM 8kW REFRIGERATOR

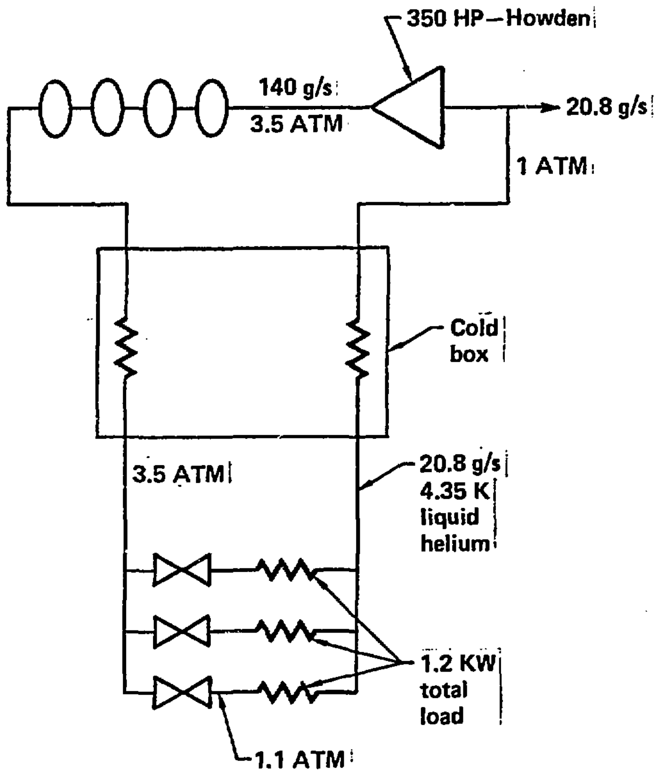

FIGURE XI.

1.2kW FORCED-FLOW HELIUM REFRIGERATOR SYSTEM

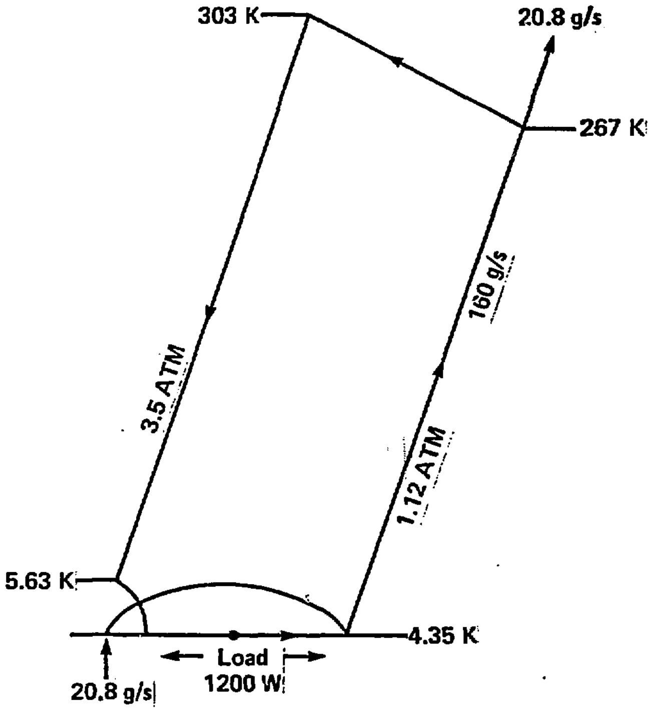

FIGURE XII.

T-S DIAGRAM 1.2kW FORCED-FLOW REFRIGERATOR

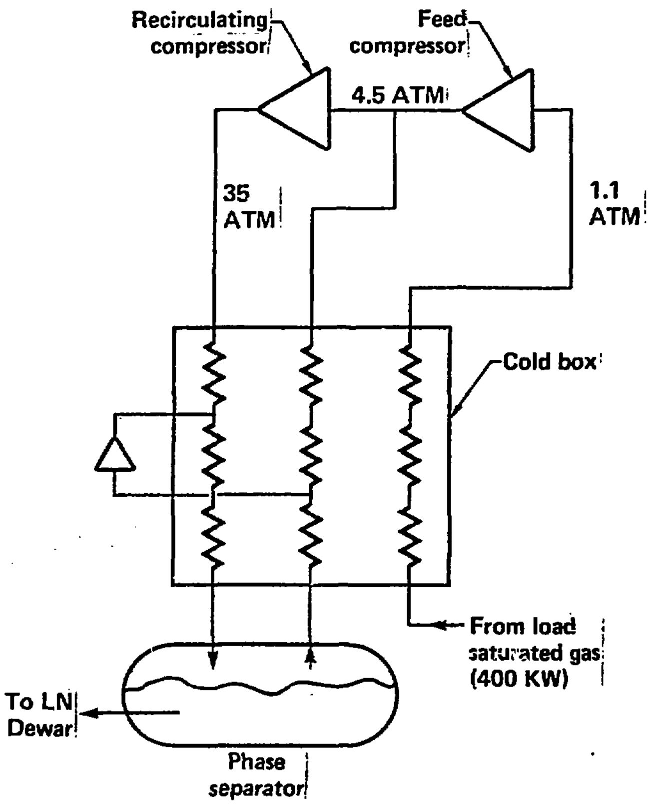

FIGURE XIII.

NITROGEN RELIQUEFIER SCHEMATIC

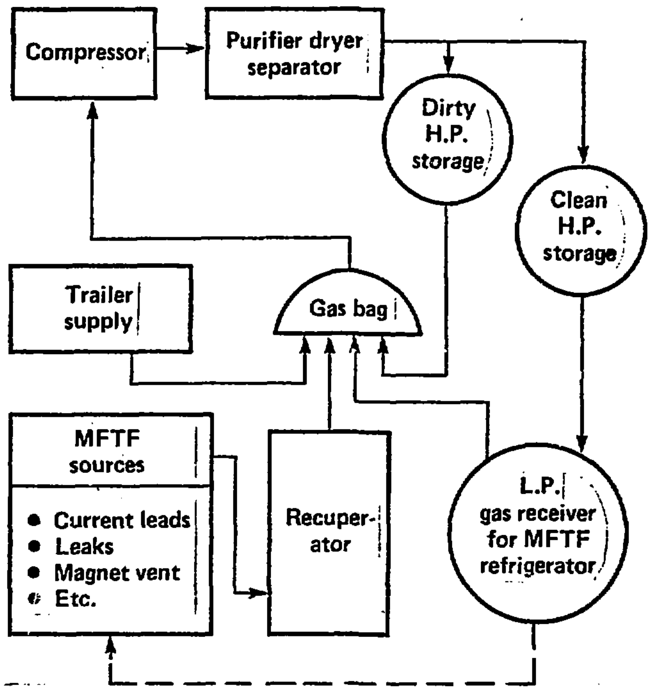

FIGURE XIV.

HELIUM RECOVERY SYSTEM BLOCK DIAGRAM