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MASTER

CRYOGENIC ASPECTS OF THE EXPERIENCE IN OPERATING THE U-25 SUPERCONDUCTING MHD MAGNET IN CONJUNCTION WITH THE MHD GENERATOR

by

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INTRODUCTION

Commercial MHD generators will have to operate under conditions of strong electromagnetic interaction, high current densities, high Hall field, and high thermal stresses, in order to be economical both with regard to first investment and efficiency. Such conditions can be attained only by employing superconducting magnet systems with magnetic field strengths of 4-5 T along with sufficiently large scale facilities ($\sim$50 MW_t).[1]

In order to facilitate the rapid development of MHD technology for the generation of electrical energy, the U.S. and U.S.S.R. are jointly conducting research within the framework of the Program of Scientific and Technical Cooperation. The Institute for High Temperatures (IVTAN) of the U.S.S.R. has designed and fabricated a special MHD facility which uses as its base much of the equipment of the existing U-25 Facility. The new MHD flow train consisting of a combustor, magnet, channel, and diffuser is named U-25B. The U.S. has provided a superconducting magnet system for the U-25B MHD Facility. As a result of these joint efforts, a unique and broad range of experimental test conditions similar to those that will exist in operation of commercial MHD generators has been created.

The United States Superconducting Magnet System (U.S. SCMS) was designed, fabricated, and delivered to the U-25B Facility by the Argonne National Laboratory (ANL) under the sponsorship of the U.S. Department of Energy. The following description focuses on the cryogenic-related aspects of the magnet system commissioning and operation in the U.S.S.R. Details of the magnet design and fabrication techniques have been presented previously.[2,3,4,5]

U.S. SCMS SYSTEM

Magnet. The magnet provides a tapered on axis dipole field having a peak value of 5 T. The magnet is cryostable by design, the conductor is fabricated from copper stabilized niobium-titanium, and is cooled by pool boiling liquid helium at ~4.3 K. The magnet warm bore which contains the MHD channel has an inlet diameter of 0.40 m, an overall length of 4.20 m, and an exit diameter of 0.67 m. The major geometric parameters and the field profile for the magnet are shown in Figure 1.

Cryogenics. The cryogenic system for the U.S. SCMS has been designed with emphasis placed on component reliability and system redundancy.[6]

The basic elements of the cryogenic system are a CTI-Cryogenics Model 1400 Helium Liquefier with built-in purifier and a CTI-Cryogenics Model 1430 Helium Refrigerator/Liquefier. The two elements are used in the cooldown and steady state operation of the magnet system.

The primary cold box is the refrigerator/liquefier which is designed to operate in a closed cycle and includes dual regenerable charcoal adsorbers to continuously remove small amounts of impurities from the helium. The liquefier is used as a backup to provide liquid helium during maintenance of the refrigerator/liquefier. Both cold boxes are interconnected to the four remote compressors via common room temperature helium piping.

The system consists of the necessary support elements to provide for the transfer and storage of the cryogens. Included in the support elements are the liquid helium transfer lines and storage dewars, low pressure helium gas storage, high pressure recovery compressors, high pressure helium gas storage, intermediate pressure helium compressors, intermediate pressure helium storage, cryogenic adsorbers and freeze-out traps, liquid nitrogen supply and distribution, and an instrumentation and control system.

A schematic of the integrated cryogenic system is shown in Figure 2. The details of the configuration of the cryogenic system relative to the magnet cryostat are presented in Figure 3.

U-25B MHD FACILITY[7]

The design concept for the U-25B MHD Facility and its primary operational parameters was governed by two principal factors: 1) consideration of minimizing capital expenditures and construction time, and 2) the requirement for high performance and duplication of all of the characteristics of MHD generators. An operational performance range sufficient to support the extensive series of experiments necessary for the further development of commercial-scale MHD generator components was also required of the facility.

The principal components of the gas and air system of the U-25B MHD Facility are located on a specially-built platform and in parallel to the gas and air system of the U-25 MHD Facility. This bypass loop design made it possible to use the following components of the U-25

MHD Facility: 1) oxygen and air supply system, 2) natural gas supply systems, 3) water cooling system for test components, 4) seed injection and recovery system, 5) electrical loading and inverter system, and 6) control and measurement equipment. The physical arrangement of the U-25B MHD Facility is presented in Figure 4.

Ambient air is enriched with oxygen obtained in the U-25 air separation plant and compressed with air compressors, preheated in the high temperature air preheaters of the U-25 MHD Facility, then injected into the oxidizer pipeline of the U-25B MHD Facility.

From the oxidizer pipeline the oxidizer is directed through an electrically insulating spacer into the combustor along with natural gas and seed. The combustion products, at a temperature in the range of 2750-2800 K, are accelerated in the nozzle attached to the combustion chamber and enter the MHD channel located inside the warm bore of the U.S. SCMS. The relationship of the magnet and the channel are presented in Figure 5. The MHD generator is electrically loaded by an inverter system which transfers the electrical power produced by the MHD generator onto the ac grid. Downstream of the MHD generator the combustion products enter the diffuser where dynamic pressure is recovered and the combustion products are partially cooled by injection of aqueous solution from the seed recovery system.

Calculations show that the first U-25B channel is capable of producing high-performance characteristics with a predicted electric power output in the range of 1.2-1.4 MW.

COMMISSIONING IN THE U.S.S.R.

Record. The record of events for the U.S. SCMS commissioning activities at the U-25B MHD Facility is presented in Table I.

Installation. To facilitate the installation of the magnet system, the major elements of the cryogenic system were installed at an earlier time. Included in this installation were the refrigerator/liquefier; liquefier; three intermediate pressure compressors; one cryogenic adsorber; low, medium, and high pressure storage volumes; one high pressure recovery compressor; one 500 L helium dewar; and all necessary interconnecting lines with the exception of the transfer lines to the magnet cryostat. The installation was supervised by a representative of the manufacturer of the cryogenic equipment. System check-out included operation of both cold boxes with the refrigerator/liquefier and the liquefier producing at a rate of 18-19 liters per hour. A total of ~50 liters was liquefied into the helium storage dewar. The installation activity included training of the IVTAN personnel in system operation and maintenance.

After initial assembling and performance testing at ANL, the U.S. SCMS was shipped to Moscow, U.S.S.R. The system was installed and cooldown begun approximately two weeks after arrival.

Cooldown. The magnet system cooldown, using the refrigerator/liquefier as a refrigerator, closely paralleled the record of the initial cooldown at ANL until the magnet cold mass temperature was 15 K. The cooldown record is presented in Figure 6. At that time, the liquefier was put into operation to begin to make liquid helium from the high pressure gas storage prior to the filling of the magnet as part of the last phase of cooldown. Simultaneous with this accelerated extraction of make-up gas from the high pressure storage bank, considerable difficulty was encountered in maintaining the refrigerator/liquefier and liquefier in operation.

Increased pressure drop in the liquefier and the refrigerator indicated blockages in the heat exchangers. When the heat exchangers were warmed, it was found that the impurity was water freezing out in the warm sections of the heat exchanger. After system clean-up, the operation of the equipment was resumed and the liquefier produced at rated capacity; i.e., approximately 22 liters per hour with two compressors and liquid nitrogen pre-cooling at 50 Hz. However, continued operation resulted in a gradual degradation in performance over an 8 hour shift. After several attempts to clean the water from the system, it was decided to put the cooldown in a hold position. To verify that the operational difficulties were not related to equipment malfunctions, the refrigerator was operated using a pure helium supply and found to be meeting or exceeding all specifications.

The make-up gas is stored in a bank of 40 high pressure gas storage vessels located outside the Laboratory. Dew point readings on a selected sample of these cylinders showed an average value of 20^{o} F, symptomatic of considerable water contamination of the helium. As a result of these findings a plan was formulated to clean the high pressure gas store of the impurities. The specified level of purity was set at dew points of -60° F for the storage bank, -80° F for the intermediate pressure helium compressors, and -60° F for the system cold boxes. To provide primary protection from contaminants, two liquid nitrogen cooled water freeze-out traps were fabricated and installed, the purpose of the freeze-out traps being to remove the primary impurity, water, prior to the entry of the gas stream into the refrigeration cold boxes. In addition, it was decided that any gas coming from the high pressure storage would be channeled through the built-in purifier in the liquefier.

With the above-mentioned remedies implemented, the cooldown of the magnet was resumed after approximately a one month delay. The cooldown proceeded smoothly through its final stages and the magnet was filled to operational level.

Energization. The magnet was then energized to its design field of 5 T which completed the commissioning effort at the U-25B Facility. During the commissioning period, the various safety and magnet protection circuits were verified to be operational. IVTAN personnel were trained in the operation of the system with emphasis being placed on system reliability and safety.

During the commissioning it was observed that the helium boiloff rate significantly exceeded the design value, amounting to 27 L/hr, which required simultaneous operation of both cold boxes. It was determined that the excess heat load was caused by malfunctioning liquid helium transfer lines.

MHD OPERATING PERIODS

MHD Runs. At this time, there have been three MHD runs of the U-25B Facility.[8,9] A brief summary of the runs is as follows:

Run #1 - The initial run of the U-25B MHD Facility took place in December 1977. The purpose of this run was to verify the integration of the MHD flow train components and to determine their integrity for further operations. The magnet was energized in steps to a field of 2 T. A maximum electrical power of 5 KW was generated.

Run #2 - The second run of the U-25B Facility took place in March 1978. The purpose of this run was to generate electrical power with relatively low level of stress on the elements of the Bypass Loop. The magnet was energized in steps as outlined by the test program to a field of 5 T and de-energized in a corresponding series of steps. A maximum electrical power of 242 KW was generated.

Run #3 - The third run of the U-25B MHD Facility took place in June 1978. The purpose of this run was to generate electrical power with increased stress on the MHD flow train. The magnet was energized in steps to a maximum field of 5 T. A maximum electrical power of 575 KW was generated.

The total time of high temperature operation for the first three runs has exceeded 40 hours. Also, over 8 hours of that time have been at a magnetic field of 5 T.

Operating Personnel. The operation of the magnet system is the responsibility of IVTAN personnel. The personnel have been trained by ANL personnel in the operation of the overall system. Training has covered normal operation, fault conditions, and system safety.

Magnet/Channel Interactions. Possible interactions between the magnet system and the MHD flow train were monitored during the MHD runs. A summary of the cryogenic and/or mechanical related observations follows:

Cryogenics - During the runs, the operating conditions of the magnet were monitored and studied. No interactions between the MHD channel and the magnet have been determined as of this date that affect the cryogenic operation of the system. The liquid levels have been steady and readily maintained and no increased boiloff has been noticed due to the operation with channels. Operating data will continue to be gathered and analyzed on the cryogenic aspects of the magnet system performance. This data will be used to further establish and refine the operating parameters for the system and to determine areas of possible improvements of the system.

Vibration and Noise - During operation of the MHD flow train, the magnet platform is subject to a considerable level of vibration and a high level of acoustical noise. The primary frequency of the vibration is 250 Hertz, which corresponds to that observed in the pressure fluctuations in the MHD combustor. No detrimental coupling to the magnet cryostat was observed; however, potentially damaging coupling to some of the magnet's ancillary equipment on the magnet platform, especially power supply, was noted and corrective measures involving mechanical isolation are under study. The acoustical vibration is of a sufficient intensity to warrant the use of ear protection devices.

Fringe Field - The fringe field of the magnet at 5 T has not resulted in any problems with nearby magnet related equipment. The fringe fields existing on the magnet platform are as presented in Figure 7.

Plasma Escape - During the third MHD run, a release of plasma from the MHD channel into the warm bore of the magnet occurred and was followed by a manual shutdown of the MHD Facility. Investigation determined that the release was due to the loss of a channel pressure tap instrumentation tube as a result of either melting or being blown off. The prompt shutdown, coupled with the fact that the pressure tap was in a subatmospheric pressure region of the channel prevented damage to the warm bore of the magnet. The warm bore insulating epoxy-fiberglass liner was discolored in the area of the release. Effort is proceeding to minimize possible effects of future plasma releases. Included are improved pressure tap piping, early detection of plasma escape and shutdown, and ablative liners and shields.

NON-MHD OPERATING PERIODS

Standby. In periods between MHD runs the magnet system is maintained in a standby mode. From a cryogenic viewpoint the standby mode implies that either the magnet cryostat be maintained with a liquid level that is between one-half and full, or the magnet cold mass temperature be maintained at 20 K or less. The standby mode has been instituted since commissioning at the U-25B MHD Facility and no significant problems have been encountered in maintaining the standby conditions.

Maintenance. The refrigeration equipment has operated reliably and has been subjected to the prescribed maintenance procedures. As of this time, approximately 10,000 operating hours have been accumulated by the equipment.

IVTAN personnel have been thoroughly trained in the theory and maintenance of the equipment by personnel from both the equipment manufacturer and ANL. During the accumulated operating time span, the Facility's personnel have become both adept and confident in their ability to maintain the equipment. An adequate supply of spare parts is maintained at the Facility to perform the necessary maintenance.

OPERATING PARAMETERS

During the periods of MHD runs and during the standby mode, data has been taken on the cryogenic performance of the magnet system. The values for system operating parameters determined to date are as given by Table II.

Liquid Helium Usage. A comparison of the liquid helium use rates for the standby and MHD run modes indicates a substantial increase in the use rate when the magnet liquid level is maintained as required for magnet operation. This increase is not related to MHD channel operation but rather to the design constraints imposed on the magnet cryostat resulting in a cryostat geometry which was air transportable. The constraints imposed a severe limitation on the overall vertical height of the magnet which made necessary design compromises in the length and nature of the 300 K to 4.2 K penetration and in the resulting amount of liquid that could be stored above the coil assembly. The resulting configuration is one having a higher conduction heat flux and a small liquid ullage; i.e., 8.1 L, between fills. The configuration requires 22.1 L/hr to maintain the magnet in its operating condition as compared to 9.4 L/hr for the standby mode.

In order to reduce the frequency of liquid transfer, an operating mode in which the refrigerator/liquefier makes liquid helium directly into the magnet cryostat will be attempted. The optimum parameters for such an operating mode are being established. At present, the cryostat helium vessel is being filled by means of transfer of liquid from the cold boxes to the storage dewars to the magnet cryostat. The new operating mode will provide a more direct supply of liquid helium to the magnet cryostat and will result in an essentially closed loop system which will increase the overall system performance, reduce helium loss, and reduce the possibility of impurities being drawn into the gas stream.

Helium Loss. The initial helium loss from the system was high--20 equivalent liquid liters per day. This loss rate was a result of the extensive nature of the system piping coupled with the unavailability of sensitive portable leak detection equipment at the facility. A program for regular leak detection employing a suitable instrument has been instituted and has reduced the loss to 5 equivalent liquid liters per day. The program will be continued in order to further reduce the loss of helium from the system.

EXPERIENCE GAINED

During the installation, commissioning, and subsequent operation of the U.S. SCMS at the U-25B MHD Facility, valuable experience has been gained. A summary of the most significant elements of this experience which might apply to future such magnet systems follows:

Interfaces. To assure an efficient system design and installation, establish at the earliest practical time effective and continuing communications between the magnet design team and the MHD facility team. Employ visits to both the MHD facility and to the magnet fabricator in order to develop and to enhance mutual understanding of the personnel involved.

Address potential interface problems as they develop rather than deferring them for future consideration.

Personnel. Assume that the MHD facility operator is inexperienced in magnet system operation. As such, make the system as straightforward as possible to operate.

Select, whenever possible, MHD facility operating personnel having previous cryogenic experience.

Maximize, at an early time, the exposure and involvement of the MHD facility operating personnel with the magnet system's cryogenic system design and operation.

Devote adequate attention and effort to operator training.

Design. Incorporate into the magnet cryostat sufficient liquid helium inventory relative to the heat flux to the liquid helium that will permit filling of the cryostat at long intervals.

Employ minimum length and high efficiency helium transfer lines to maximize the effective use of liquid helium and to make possible, where appropriate, direct transfer of liquid helium to the cryostat from the system's refrigerator/liquefier.

Assume from the beginning that there will be impurities; i.e., most likely water and air, in the helium gas system. Accordingly, incorporate into the system monitors to detect and components to remove the impurities.

Provide adequate sensors to permit magnet system monitoring and diagnosis of operational problems. Sensor cost, even in the most extensive case, is a small portion of the overall system cost. Place emphasis on the measurement of system temperatures, pressures, and gas flows.

Consider equipment serviceability and the availability of manufacturer field service and training of personnel when selecting system components.

Review the spare parts requirements for the integrated magnet system and develop and maintain an adequate spare parts inventory at the facility. Include in this effort a failure mode analysis which will indicate the likelihood of component failure or wear. Place special emphasis on long lead time items.

Operations. Install and make operational the cryogenic system at an early time. Operate the equipment for a period of time which is adequate to permit the detection and remedy of cryogenic system problems. If possible, decouple cryogenic system start-up from magnet system start-up.

Develop and implement readily understandable and complete operating procedures which include theory, operations, fault conditions, and diagnosis.

Magnet system operation should not be a dominant feature of the operation of an MHD run, thus automate magnet system operation to minimize its effect on the control of overall system.

Monitor selected magnet system parameters so that effective monitoring of magnet system performance during MHD runs is realized. The selected parameters should be monitored with the appropriate transducers and signal conditioning equipment to permit on-line data acquisition and processing.

The operation of a magnet in an MHD generator facility involves a potentially hazardous environment. Included as hazards are vibration, noise, explosion, plasma escape, and fringe field effects. As such, emphasis should be placed on remote monitoring and operation.

Develop meaningful and reasonable standby criteria in order to minimize the effort required of the MHD facility operating staff.

Develop a maintenance procedure as appropriate for the system as configured.

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TABLE I

U. S. SCMS

U.S.S.R. Commissioning Event Record

Date	Event
July 4, 1976	Cryogenic equipment arrives IVTAN
February, 1977	Cryogenic equipment installation and checkout completed
June 18, 1977	System departs ANL
June 20, 1977	System arrives IVTAN Installation begins
July 4, 1977	Installation completed Cooldown begins
August 1, 1977	LHe^4 inventory accumulation begins GHe^4 impurity problems begin
August 8, 1977	Cooldown to "hold" condition GHe^4 impurity remedies begin
September 15, 1977	Cooldown resumes
September 29, 1977	Magnet energized to 5 T

TABLE II

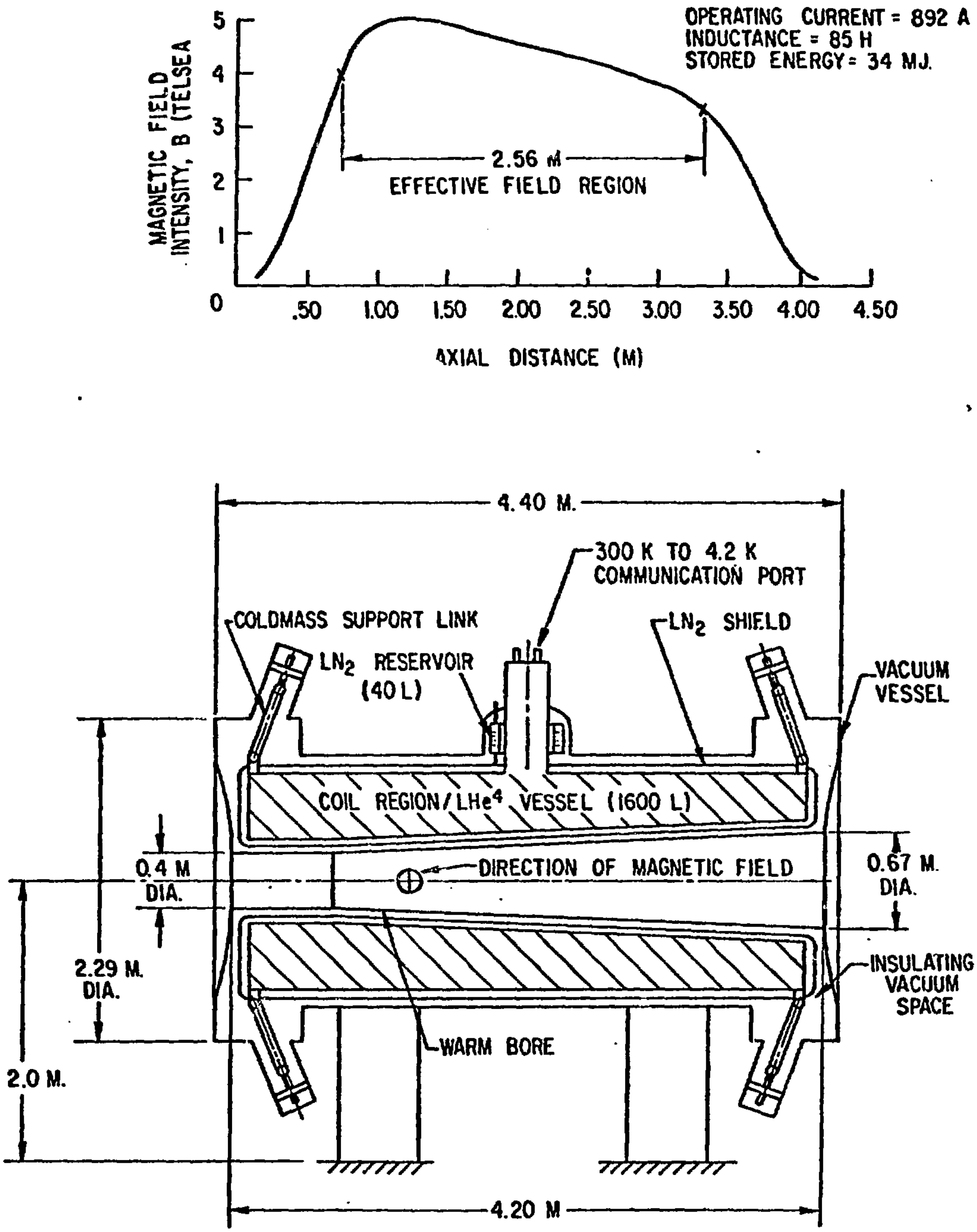
U.S. SCMS CRYOGENIC OPERATING PARAMETERS

I. Helium Inventory
   - A. Cryostat = 1600 L
   - B. System total = 2000 L (liquid equivalent)

II. Standby Mode
   - A. Cryostat pressure = 1.07 ATM (1.0 psig)
   - B. Liquid helium use rate
     1. Cryostat total (1/2 full with current leads closed) = 14.4 $\frac{L}{hr}$ (10.29 W)
     2. Cryostat total (1/2 full with current leads open) = 9.4 $\frac{L}{hr}$ (6.71 W)
     3. Current lead contribution (1/2 full) = 5.0 $\frac{L}{hr}$ (3.58 W)

III. MHD Run Mode
   - A. Cryostat pressure
     1. Start fill = 1.18 ATM (2.6 psig)
     2. Filling - 1.14 ATM (2.0 psig)
     3. Evaporation = 1.10 ATM (1.5 psig)
   - B. Fill cycle period = 22 min.
   - C. Fill levels
     1. Low = 15% of 10 cm probe
     2. Low control setpoint = 25% of 10 cm probe
     3. High control setpoint = 45% of 10 cm probe
     4. High = 65% of 10 cm probe
     5. Equivalent liquid (low to high) - 8.1 L
   - D. Liquid helium use rate
     1. Liquid delivered to cryostat = 22.1 $\frac{L}{hr}$
     2. Liquid transferred from storage dewar No. 1 = $\frac{28.3\ L}{hr}$
   - E. Transfer efficiency = 78%

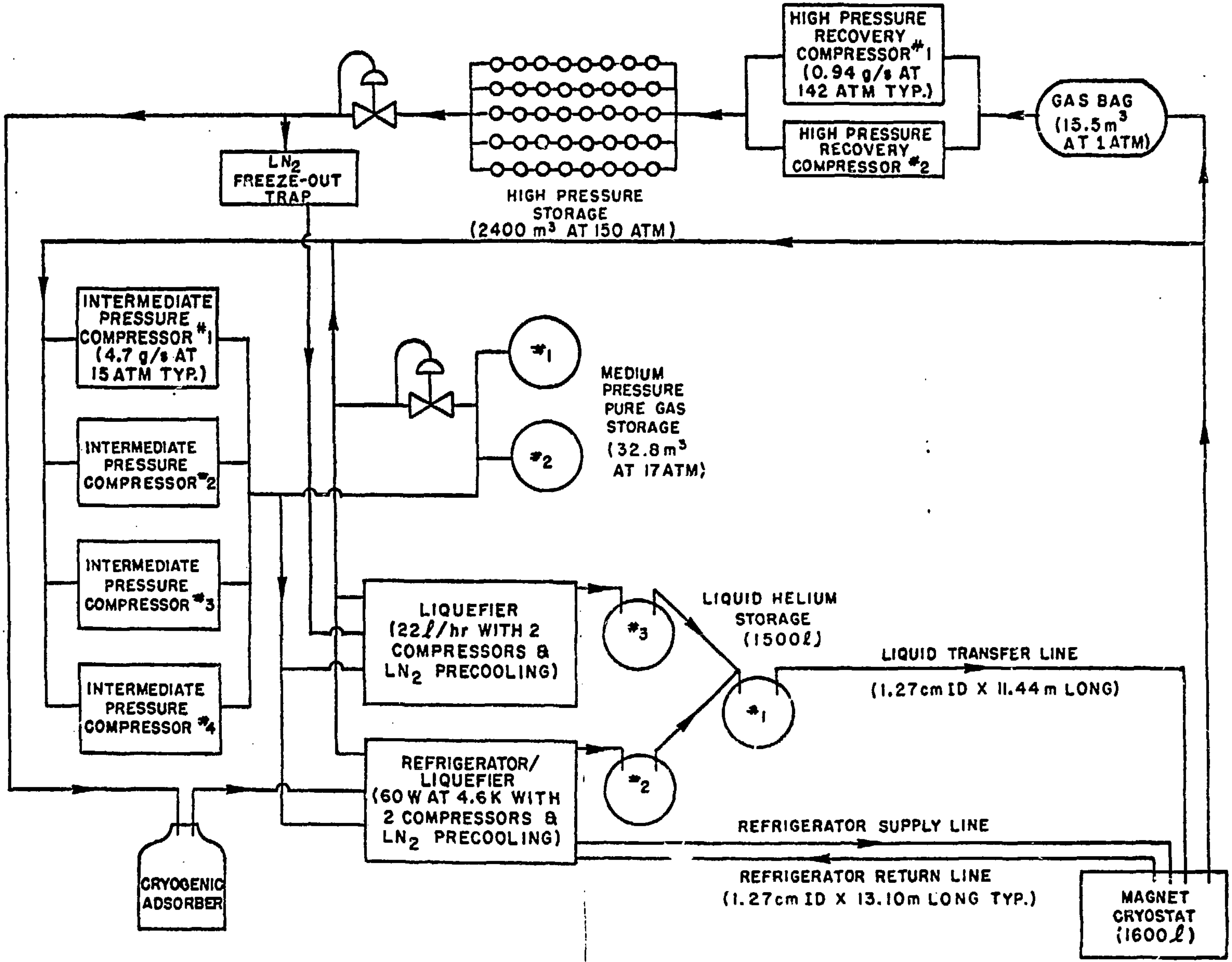
IV. Helium Loss
   - A. Initial
     1. Liquid equivalent = 20 $\frac{L}{day}$
     2. % based on total inventory = 1.00 $\frac{\%}{day}$
   - B. Present
     1. Liquid equivalent = 5 $\frac{L}{day}$
     2. % based on total inventory = 0.25 $\frac{\%}{day}$
   - C. Goal
     1. Liquid equivalent = 3 $\frac{L}{day}$
     2. % based on total inventory = 0.15 $\frac{\%}{day}$



TOTAL WEIGHT = 36,800 Kg.

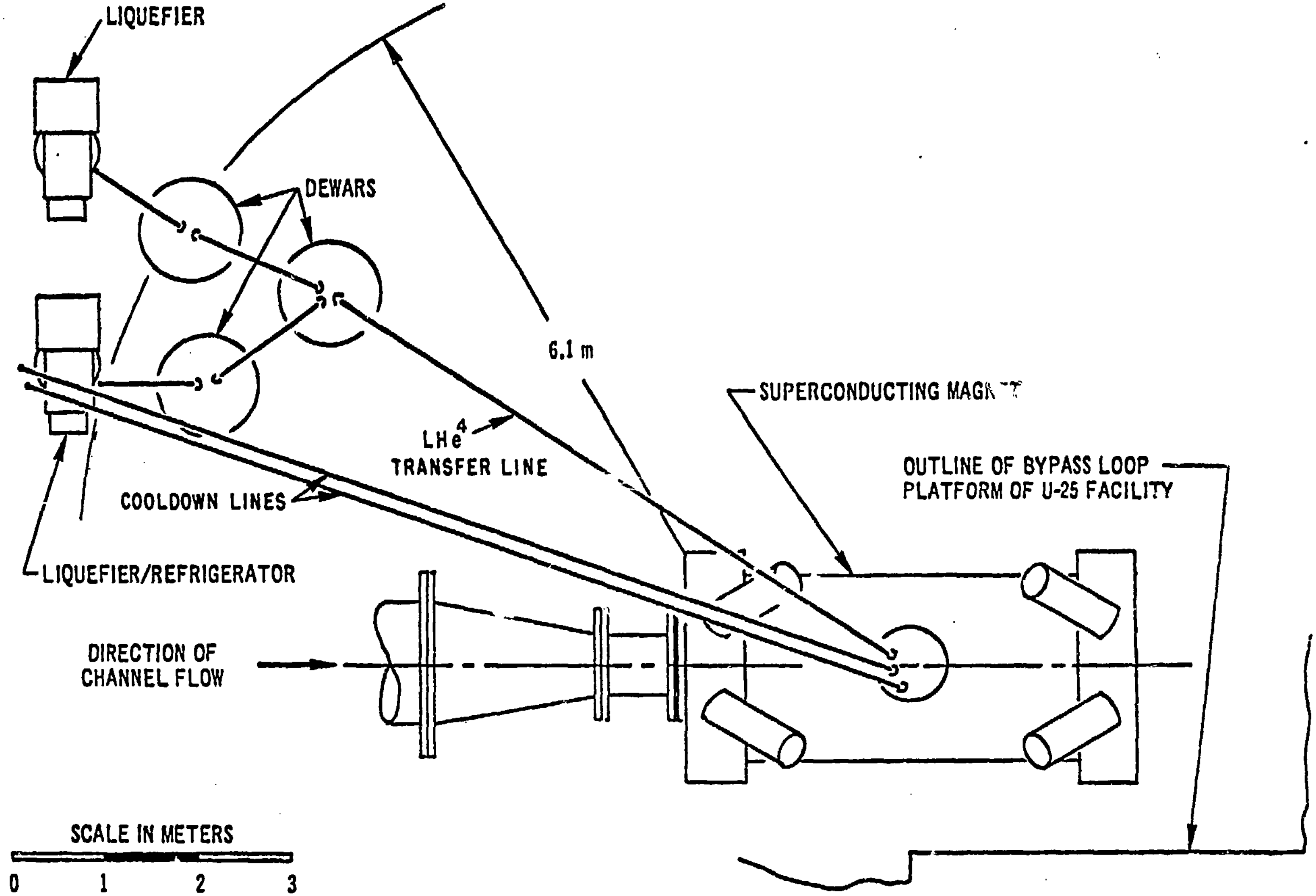
US SCMS CRYOSTAT CROSS SECTION AND ON-AXIS FIELD PLOT

FIGURE 1



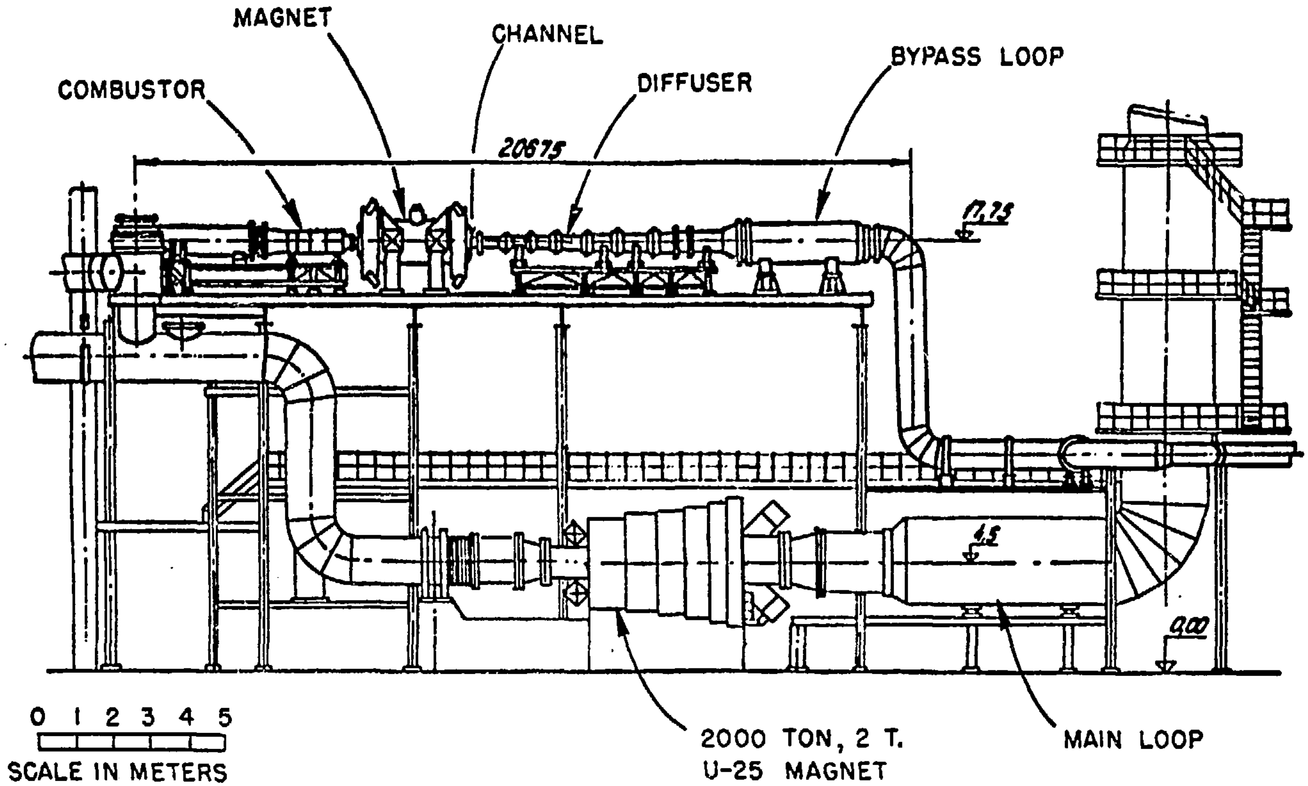
US SCMS CRYOGENIC SYSTEM CONFIGURATION AT U-25B MHD FACILITY

FIGURE 2

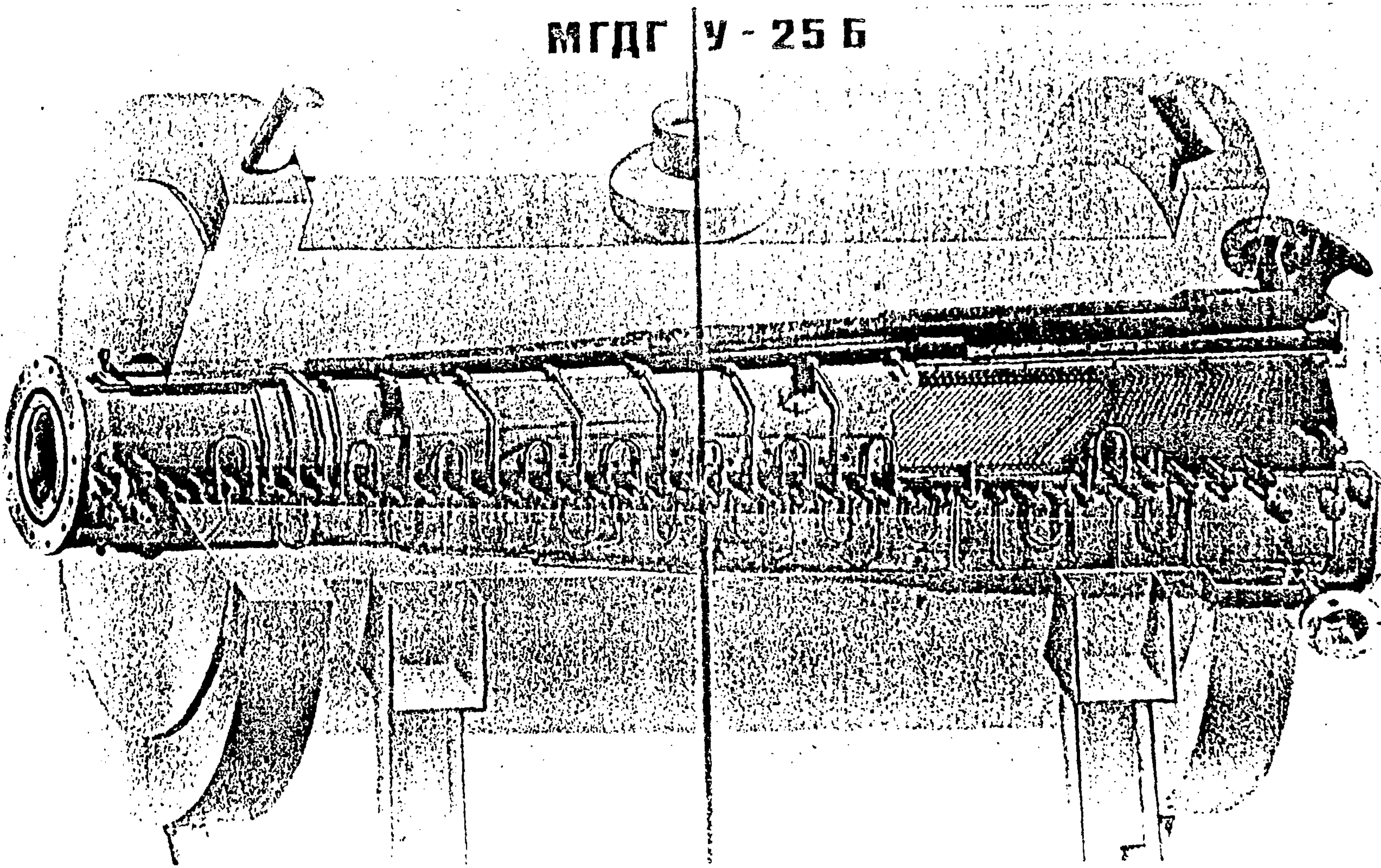


US SCMS MAGNET INSTALLATION AT U-25 B MHD FACILITY—PLAN VIEW

FIGURE 3



U-25 B MHD FACILITY ELEVATION VIEW
FIGURE 4


МГДГ У-25Б

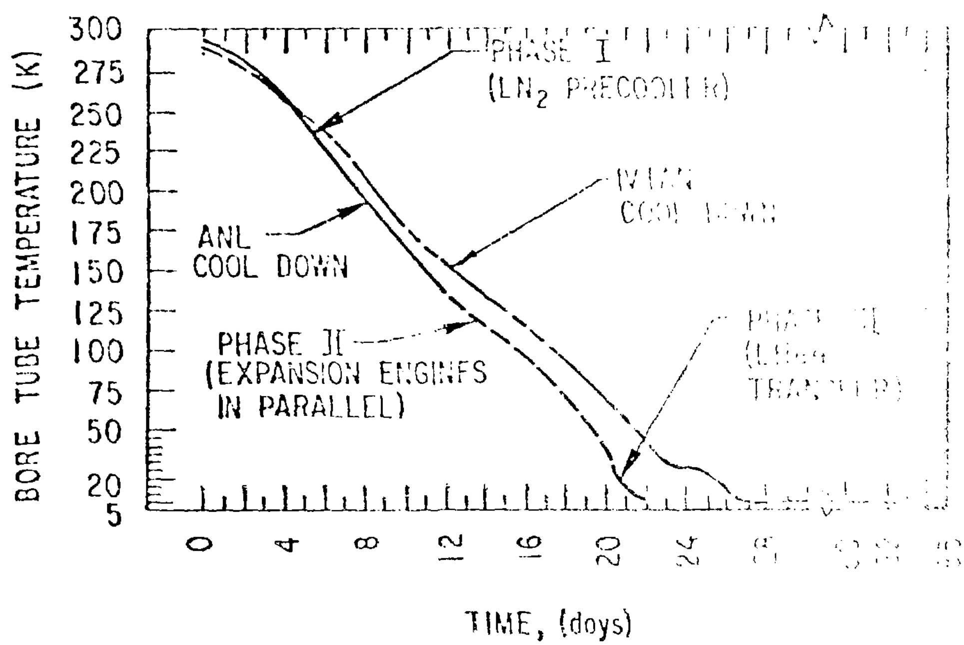
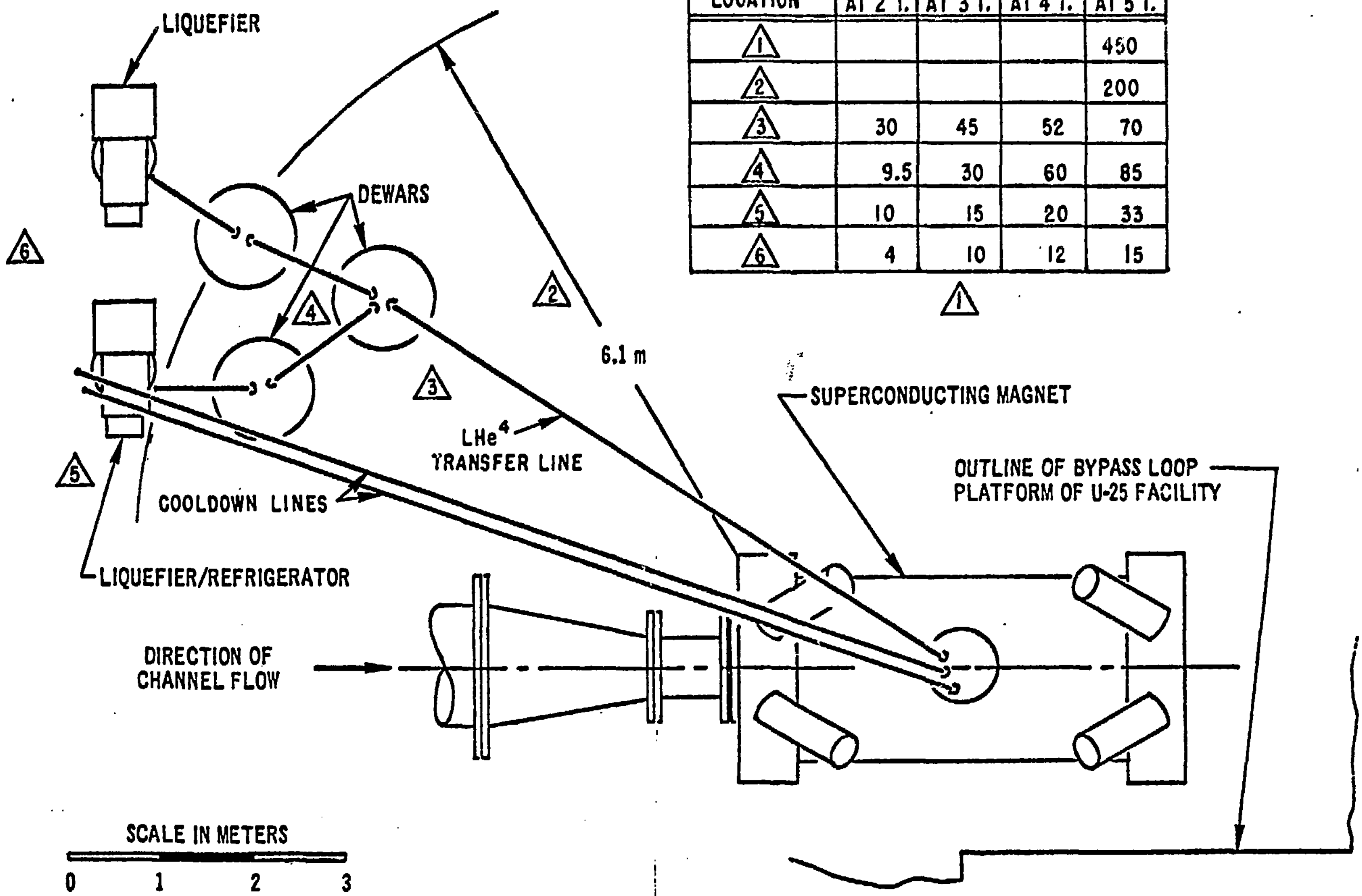


Fig. 6 US SCMS COOL DOWN



MEASUREMENT LOCATION	FRINGE FIELD (GAUSS)			
	AT 2 T.	AT 3 T.	AT 4 T.	AT 5 T.
1				450
2				200
3	30	45	52	70
4	9.5	30	60	85
5	10	15	20	33
6	4	10	12	15

US SCMS FRINGE FIELD MEASUREMENTS AT U-25 B MAGNET PLATFORM
FIGURE 7