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ABSTRACT

The design features and accumulated operating experience, from a cryogenics point of view, of the United States Superconducting Magnet System (U.S. SCMS) are presented. The principal cryogenic system design parameters are enumerated. Details of the cryogenic aspects of magnet system commissioning, standby mode, and operation with MHD generators are discussed. Included are system operation, problems encountered and corrective actions taken, and measured operating parameters which include liquid helium boiloff, cryostat pressure and level versus time, etc. The aspects of the transition between operation in the laboratory and in an MHD plant are elaborated.

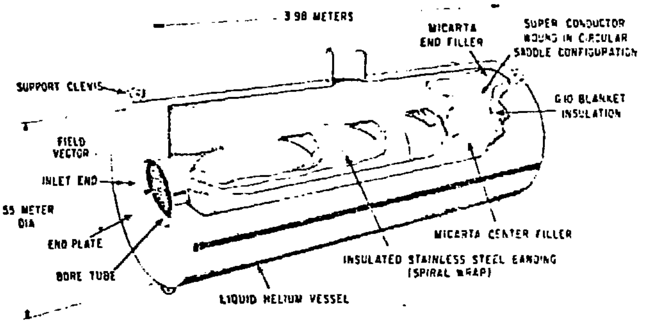
INTRODUCTION

As part of the U.S./U.S.S.R. cooperative agreement on magnetohydrodynamic (MHD) information exchange, Argonne National Laboratory (ANL), under the sponsorship of the U. S. Department of Energy, has designed and built a large superconducting magnet system for use in MHD research. The magnet provides a 5 T dipole field over a warm bore having a minimum aperture of 40 cm. The magnet has been shipped to the U-25 facility of the Institute for High Temperatures (IVTAN) in Moscow, U.S.S.R., and has been installed, commissioned, and is now an operating element of the U-25B MHD research facility.

The magnetic aspects of the design and operation of the system have been described extensively in the literature and will not be considered here.[1,2,3,4,5] The purpose of this paper is to describe the cryogenic aspects of the U.S. SCMS. Included are details of the cryostat design, the cryogenic system design and experiences of magnet system cooldown, commissioning, operation and standby modes as installed in the U.S.S.R.

CRYOSTAT

The superconducting coils of the U.S. SCMS are contained in a liquid helium vessel having cylindrical configuration as shown in Fig. 1. The cold bore of the vessel functions as the coil assembly substructure. The liquid helium vessel is fabricated as a weldment from 316 SST. The cold mass is supported relative to the 300 K environment by a tension member support system consisting of epoxy fiberglass support links, heat intercepted to liquid nitrogen at a point intermediate along their length.[6] The entire surface of the liquid helium vessel is covered with ten layers of aluminized multilayer insulation with paper separators. Surrounding the insulated liquid helium vessel is a liquid nitrogen shield fabricated from 304 SST, the material being selected to reduce the eddy currents and associated forces during magnet charging and during rapid magnet discharge. The shield is trace cooled with liquid nitrogen in free convection to provide a uniform temperature; i.e., $\Delta T = 2.5$ K, shield surface. The entire surface of the liquid nitrogen shield is insulated with 50 layers of the same composition multilayer insulation as used on the helium vessel. The cryostat outer vacuum jacket is fabricated as a weldment from 304 SST and provides, in addition to the necessary insulating vacuum, the connection of the cold mass to the 300 K environment.



US SCMS COLD MASS

Fig. 1.

The design parameters of the magnet cryostat are presented by Table I.

CRYOGENIC SYSTEM

The cryogenic system for the U. S. SCMS has been designed with stress being placed on component reliability and system redundancy.

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 remote compressors via common room temperature helium piping.

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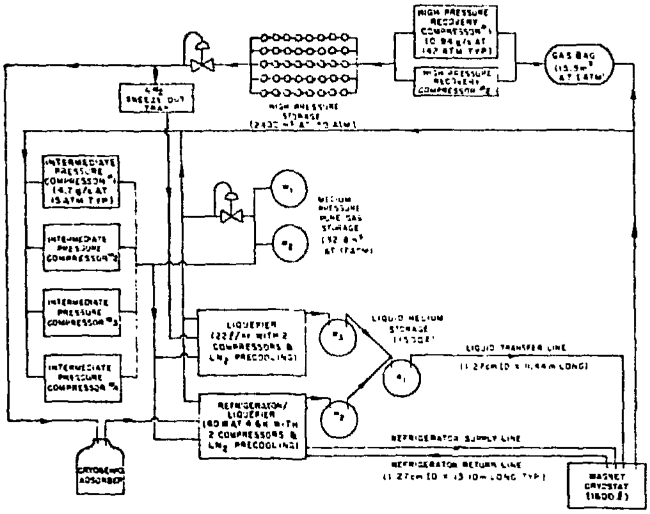
The system consists of the necessary support elements to provide for the transfer and storage of the cryogens. Included in the support elements are the liquid helium transfer lines and storage dewars, low pressure helium gas storage, high pressure recovery compressors, high pressure helium gas storage,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

The details of the configuration of the cryogenic system are as presented in Fig. 2.



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

Fig. 2.

COOLDOWN AND COMMISSIONING

After initial assembling and performance testing at ANL,[7] the U. S. SCMS was shipped to Moscow, U.S.S.R. The system arrived in Moscow in mid-June 1977, was installed and cooldown begun approximately two weeks after arrival.

The magnet system cooldown closely paralleled the record of the initial cooldown and operation at ANL up until the point where the cold mass temperature was 15 K. At that time, the cryogenic system was being operated to both cool down the cold mass using the refrigerator/liquefier in the refrigeration mode and to begin to make liquid helium from the high pressure gas storage to fill the magnet as part of the last phase of cooldown. At this point, 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 exchanger. Indications on warm-up were that the impurity was water freezing out in the warm sections of the heat exchanger. The make-up gas is stored in 40 high pressure gas cylinders located outside the Laboratory. Dew point readings on a selected sample of these cylinders showed an average value of 20° F systematic of considerable water contamination of the helium. After system clean-up, the operation of the equipment was resumed, the liquefier produced at rated capacity, i.e., approximately 22 liters per hour with two compressors and liquid nitrogen pre-cooling at 50 Hz. Continuous operations resulted in a gradual degradation in performance over an 8 hour shift. After several concerted 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.

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. In addition, it was decided to fabricate two liquid nitrogen cooled water freeze-out traps, 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 of the system's 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. 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.

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.

OPERATIONS WITH MHD CHANNELS

Following commissioning, the magnet system was integrated into the U-25B Facility. Included in the activity was the installation of the MHD channel, the combustor, the diffuser section and the balance of the flow loop, and necessary instrumentation and control elements.

As of this time, there have been three MHD runs of the U-25B Facility. 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.[8] The purpose of this run was to verify the integration of the system components and to determine their integrity for further operations. The magnet was energized in steps to a field of 2 T. During the run a maximum electrical power of 5 kW was generated.

Run #2 - The second run of the U-25B MHD Facility took place in March 1978.[9] The purpose of this run was to generate electrical power with relatively low level of stress on the elements of MHD flow train. 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. During the run, 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. During the run, a maximum electrical power of 5/5 kW was generated.

A typical period for each of the three runs is approximately two days of magnet energized time.

During each of the three runs, the operating parameters 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.

After the second run, a replacement set of improved liquid helium transfer lines to the magnet was installed in the system. The reason for replacement of the lines was low efficiency of the lines originally installed. After installation of the replacement lines, the cryogenic system performance was again evaluated. The system performance was determined to be noticeably improved, a significant aspect of these tests being that the refrigerator/liquefier was able to make liquid helium directly into the magnet cryostat. The optimum parameters for such an operating mode are being established for future implementation. 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 leakage, and reduce the possibility of impurities being drawn into the gas stream.

STANDBY MODE

In periods between MHD runs, the magnet system is maintained in the specified 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 conditions. The refrigeration equipment has operated reliably and has been subjected to the prescribed maintenance procedures.

MEASURED 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.

CONCLUSIONS

The U. S. SCMS is a purposeful operating element of the U-25B MHD Facility. The system has been installed, commissioned, and operated successfully for three MHD runs. The operation of the magnet system has been routine in nature and in accord with the experimental plans for the individual MHD runs. The operators have been trained in the system operation, both in MHD run mode and standby mode, and have become proficient in the regular maintenance of the system components.

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.

Two areas of major improvement exist. One is the reduction of the helium gas loss rate from the system to a more acceptable value. This will be done by regular leak checking of the entire system piping, followed by repairs of the affected areas. Another area of improvement is to establish and institute the parameters of the operating mode in which the refrigerator/liquefier delivers liquid helium directly to the magnet cryostat.

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9. Ibid.

TABLE 1

U.S. SCMS CRYOSTAT DESIGN PARAMETERS

- I. **Liquid Helium Vessel**
  - A. Material - 316 SST
  - B. Dimensions
    - 1. Inside diameter = 0.53 m (minimum)
    - 2. Outside diameter = 1.55 m
    - 3. Length = 3.66 m
  - C. Mass = 25,832 kg
  - D. Liquid helium inventory = 1500 L
  - E. Heat flux to liquid helium
    - 1. Radiation from 90 K = 30.6 m^2 x 0.043 $\frac{W}{m^2}$ = 1.3 W
    - 2. Cold mass support conduction = 6 supports x 0.8 $\frac{W}{support}$ = 0.5 W
    - 3. Neck conduction and radiation = 1.8 W
    - 4. Instrumentation lead and piping conduction = 0.7 W
    - 5. Conductor joint ohmic heating = 0.5 W
    - 6. Current lead cooling = 2 leads x 1500 $\frac{A}{lead}$ x $\frac{1 W}{1000 A}$ = 3.0 W
    - 7. Net heat flux = greater of Σ("1" through "5") or "6" = 4.8 W or 3.0 W = 4.8 W
  - F. Liquid Helium Usage
    - 1. For steady state heat flux = 4.8 W x 1.4 $\frac{L}{hr. watt}$ = 7.2 $\frac{L}{hr}$
    - 2. Transfer efficiency = 50%
    - 3. Helium use rate = 7.2 $\frac{L}{hr}$ x $\frac{1}{0.5}$ = 14.4 $\frac{L}{hr}$
- II. **Liquid Nitrogen Shield**
  - A. Material - 304 SST with copper LN_2 trace tubes
  - B. Dimensions
    - 1. Inside diameter = 0.54 m (min.)
    - 2. Outside diameter = 1.60 m
    - 3. Length = 3.73 m
    - 4. Thickness = 0.20 cm
  - C. Mass = 525 kg
  - D. Liquid nitrogen inventory = 40 L
  - E. Heat flux to liquid nitrogen
    - 1. Radiation from 300 K = 32.7 m^2 x 0.645 $\frac{W}{m^2}$ = 21 W
    - 2. Liquid helium vessel support heat intercepts = 6 supports x 0.57 $\frac{W}{support}$ = 3.4 W
    - 3. Liquid helium vessel neck heat intercept = 9.5 W

      Total 33.9 W
  - F. Liquid nitrogen usage
    - 1. Steady state = 0.8 $\frac{L}{hr}$
    - 2. Transfer efficiency = 50%
    - 3. Nitrogen use rate = 0.8 $\frac{L}{hr}$ x $\frac{1}{0.5}$ = 1.6 $\frac{L}{hr}$
- III. **Vacuum Vessel**
  - A. Material - 304 SST
  - B. Dimensions
    - 1. Inside diameter = 0.40 m (min.)
    - 2. Outside diameter = 1.78 m
    - 3. Length = 4.20 m
    - 4. Maximum width = 2.29 m
    - 5. Maximum height = 3.35 m
  - C. Mass = 10,385 kg

Table II

U.S. SCMS OPERATING PARAMETERS

- I. **Standby Mode**
  - A. Cryostat pressure = 1.07 ATM
  - B. Liquid helium use rate
    - 1. Cryostat total (1/2 full) = 9.4 $\frac{L}{hr}$ (6.71 W)
    - 2. Current lead contribution (1/2 full) = 5.0 $\frac{L}{hr}$ (3.58 W)
- II. **MHD Run Mode**
  - A. Cryostat pressure
    - 1. Start fill = 1.18 ATM
    - 2. Filling = 1.14 ATM
    - 3. Evaporation = 1.10 ATM
  - 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%
- III. **Helium Inventory**
  - A. Cryostat proper = 1600 L
  - B. System total = 2000 L (liquid equivalent)
- 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 $\frac{\%}{day}$
- V. **LN_2 Shield**
  - A. Temperature
    - 1. Average = 82 K
    - 2. ΔT maximum = 1/K
  - B. Liquid nitrogen use rate = 40 $\frac{L}{day}$