Conductor Development For Early Commercial Superconducting MHD Magnets

Author(s): A. M. Dawson, A. M. Hatch, P. G. Marston, H. Becker, J. V. Minervini, and J. M. Tarr

Session Name: Magnets, Diffusers, and Diagnostics

SEAM: 23 (1985)

SEAM EDX URL: https://edx.netl.doe.gov/dataset/seam-23

EDX Paper ID: 1101

PAPER NO. 14

CONDUCTOR DEVELOPMENT FOR EARLY COMMERCIAL SUPERCONDUCTING MHD MAGNETS

A. M. HATCH, P. G. MARSTON, J. M. TARRH, H. BECKER, A. M. DAWSON, J. V. MINERVINI
MIT/Plasma Fusion Center, Cambridge, Massachusetts 02139

Abstract

A three-year program is underway at the MIT Plasma Fusion Center to develop and test a full-scale conductor for early commercial superconducting MHD magnets. A conceptual design for a 4.5 T magnet sized for a retrofit MHD power train of approximately 35 MWe output has been generated and used as a basis for establishing a preliminary conductor design requirements definition. The magnet design is described, together with supporting analyses. The design is based on an 18 kA internally cooled cabled superconductor (ICCS), which is the most suitable configuration for this application. Plans for future activities are outlined, including the development of conductor design requirements, supporting design and analyses, small scale and a full-scale proof-of-concept test of a prototypical ICCS conductor.

Introduction

In the existing technology for coal-fired, open-cycle MHD systems, major concerns are the constructability of a commercial-size MHD superconducting magnet at an acceptable level of risk, and the long-term structural durability of such a magnet. The development of a high-current conductor for the magnet winding, together with appropriate winding construction techniques and structural support criteria, are essential first steps in the development effort required prior to beginning the design and construction of a retrofit scale magnet. The internally cooled cabled superconductor (ICCS) concept[1,2], which has been under development at MIT for a number of years, is for many reasons the most promising candidate for this application.

A three-year program of conductor development is underway at the MIT Plasma Fusion Center (PFC) to develop and full-scale proof-of-concept test an ICCS conductor for this application. The goal of this effort is to translate and transmit the existing, fusion related, niobium tin ICCS technology base and then to further that technology through proof-of-concept testing of a 15 m length of prototypical conductor. The program includes: conceptual design of a retrofit-size MHD magnet to serve as the basis for the conductor design requirements definition; establishing conductor design requirements; analytical work to support the design effort; and, finally, small scale experimental testing and full scale proof-of-concept testing. The program was specifically defined to be in harmony with the recently realigned DOE national MHD program and represents the minimum effort required to design and verify a high current superconductor suitable for a magnet of the retrofit size contemplated. The total three year program at MIT represents approximately 10% of the development effort required prior to beginning the design and construction of an MHD retrofit-scale magnet.

The results of the initial portion of the program are described including the conceptual design of the retrofit-size magnet, the design and design requirements for the 18 kA ICCS conductor used in the retrofit-size magnet and the analytical work done to date in support of the magnet and conductor designs. Future work plans are outlined.

Magnet Conceptual Design

The conceptual design for a retrofit-size MHD magnet with a winding of ICCS conductor was developed by MIT with emphasis on manufacturability and reliability. The design incorporates a pair of 60° rectangular saddle coils of copper-stabilized NbTi cable conductor sheathed with stainless steel and insulated with fiberglass wrap. The main coil support structure and cryostat are of stainless steel. The rectangular cross-section warm bore incorporates a water-cooled liner with its inner surface coated with ablative, electrically insulating material.

The design parameters for the magnet, listed in Table I, were selected as representative for an initial retrofit MHD magnet, based on information obtained from the MHD community including the Advanced Power Train contractors.

TABLE I

Magnet Design Parameters

Conceptual Design Retrofit MHD Magnet

MHD Data		
Plant power input	(MWt)	250 to 275
Channel power output	(MWe)	35 to 40
Peak on-axis field	(T)	4.5[1]
Active length	(m)	8 to 11
Inlet dimensions	(m)	0.42 sq. to 0.45 sq.
Exit dimensions	(m)	0.85 sq. to 1.00 sq.
Magnet Data		
Peak on-axis field	(T)	4.5[1]
Active length (3 T to 3 T)	(m)	9
Bore util. factor, start act. length	(m)	0.2 to 0.25[2]
Bore util. factor, end act. length	(m)	0.35 to 0.50[2]

[1]Peak on-axis fields other than 4.5 T will be investigated later.

[2]Tentative range. Final values of bore utilization factors to be established when outside dimensions of channel assemblies are known.

An outline drawing of the magnet is shown in Figure 1, an assembly drawing of the magnet is shown in Figure 2, and a section drawing of the magnet is shown in Figure 3. A field profile and a cutaway view of the magnet are shown in Figure 4; the channel is depicted in its operating position in the warm bore. Magnet design characteristics are summarized in Table II.

The winding of the retrofit magnet is shown diagrammatically in Figure 5. Details of the winding and conductor are shown in Figure 6.

The conductor, designed for 18 kA operating current, consists of a twisted cable of copper-stabilized NbTi strands enclosed in a squared stainless steel sheath, produced by a continuous cable sheathing process as shown in Figure 7. The conductor is of the same type and outside dimensions as used in a large D-shaped experimental coil[1] constructed for the Fusion Energy Program, which contains about 5000 meters of conductor. The selection of this physical size and configuration for development as an MHD magnet conductor takes advantage of the existing manufacturing technology development. Production facilities are available and user experience exists for this particular size and configuration.

The ICCS conductor has many significant advantages over bath-cooled conductors: relatively higher stability margin, greater electrical integrity (because the conductor can be wrapped with continuous insulation), greater mechanical integrity and durability, and the elimination of a heavy-walled liquid helium containment vessel.

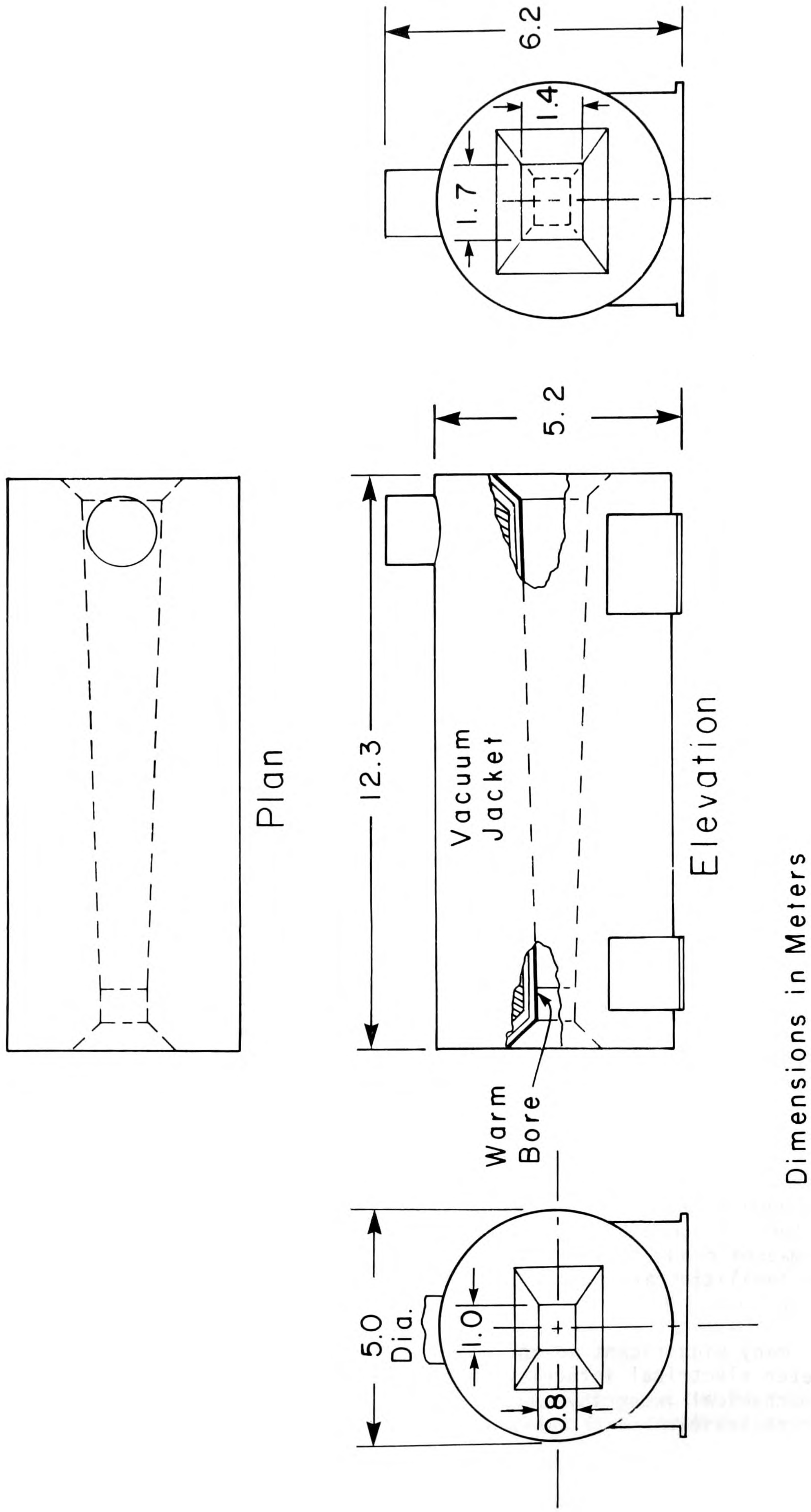


Figure 1

Outline, 4.5 T Retrofit MHD Magnet

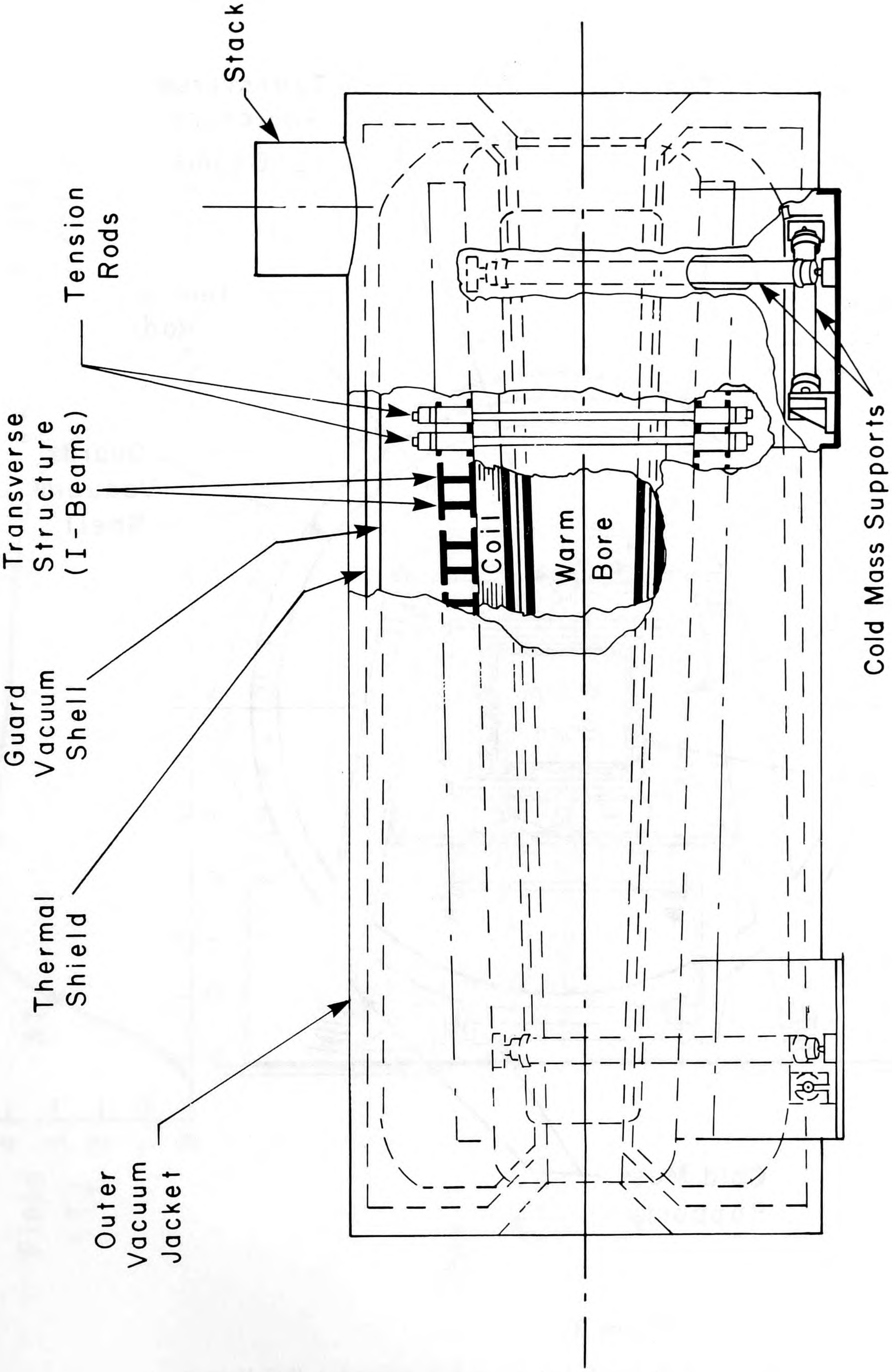


Figure 2

Assembly, Elevation, 4.5 T Retrofit MHD Magnet

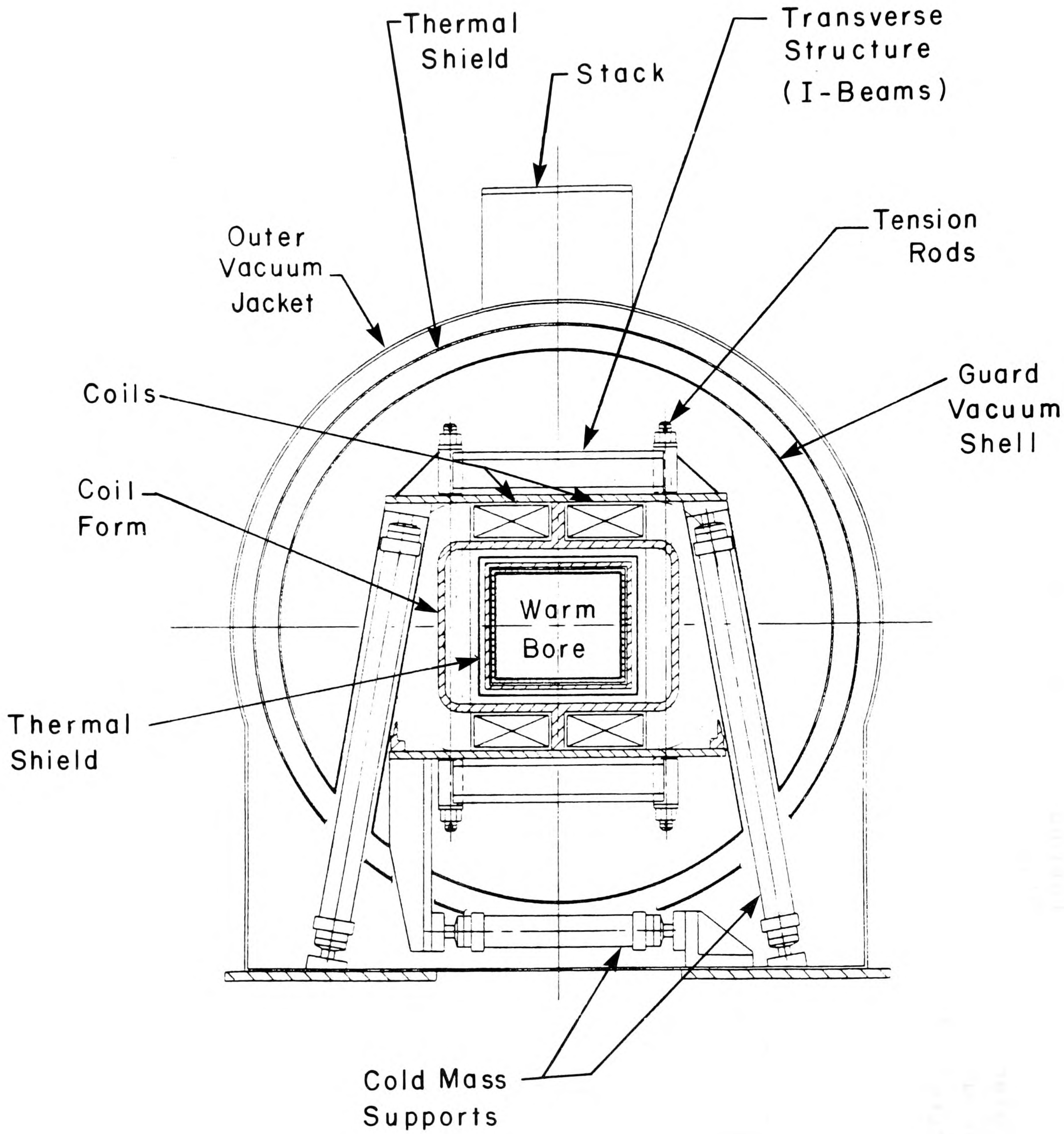


Figure 3

Assembly, Section at Plane of Channel Inlet, 4.5 T Retrofit MHD Magnet

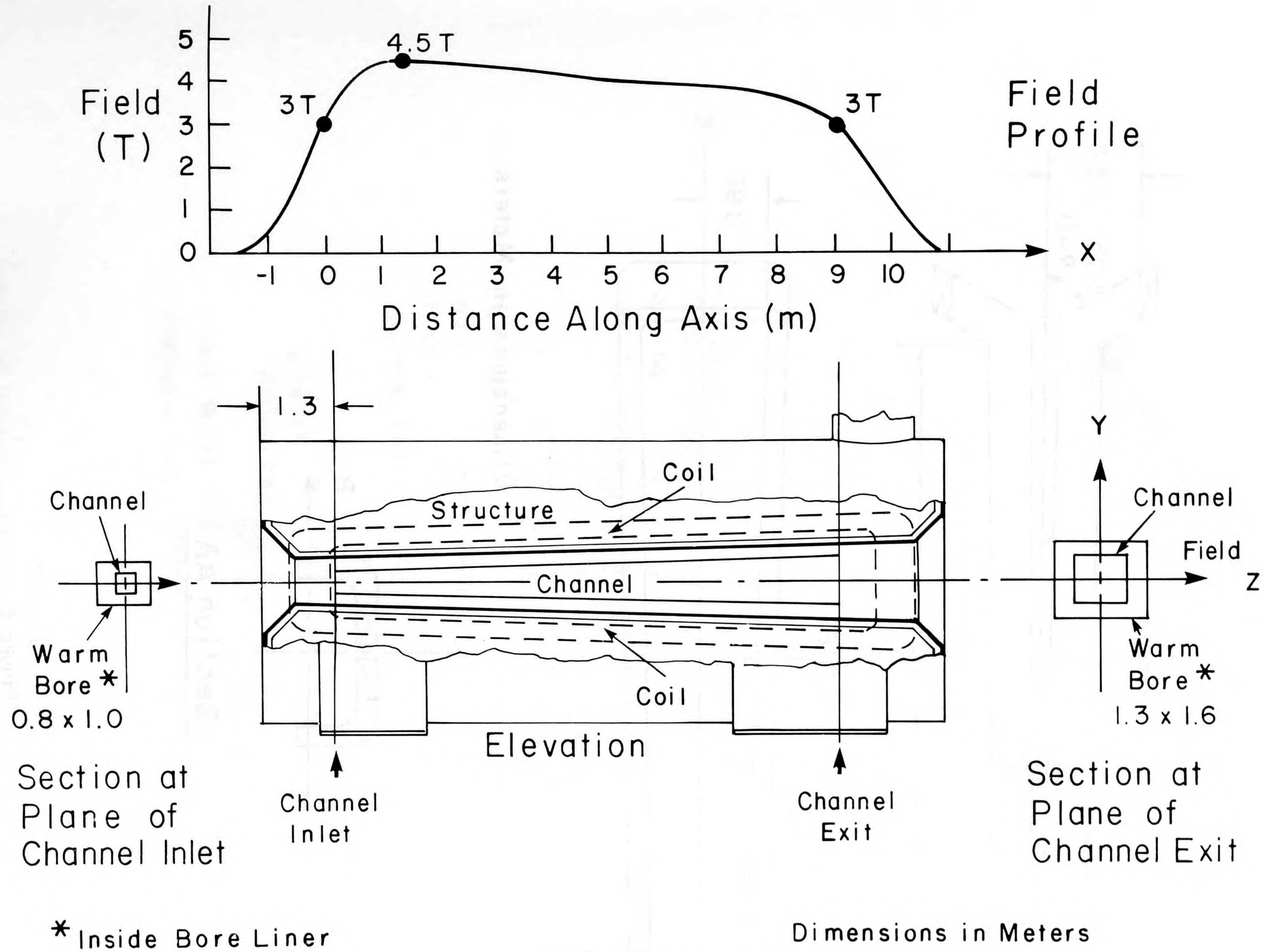


Figure 4

Magnet Field Profile and Cutaway View Showing Channel Installed in Warm Bore, 4.5 T Retrofit MHD Magnet

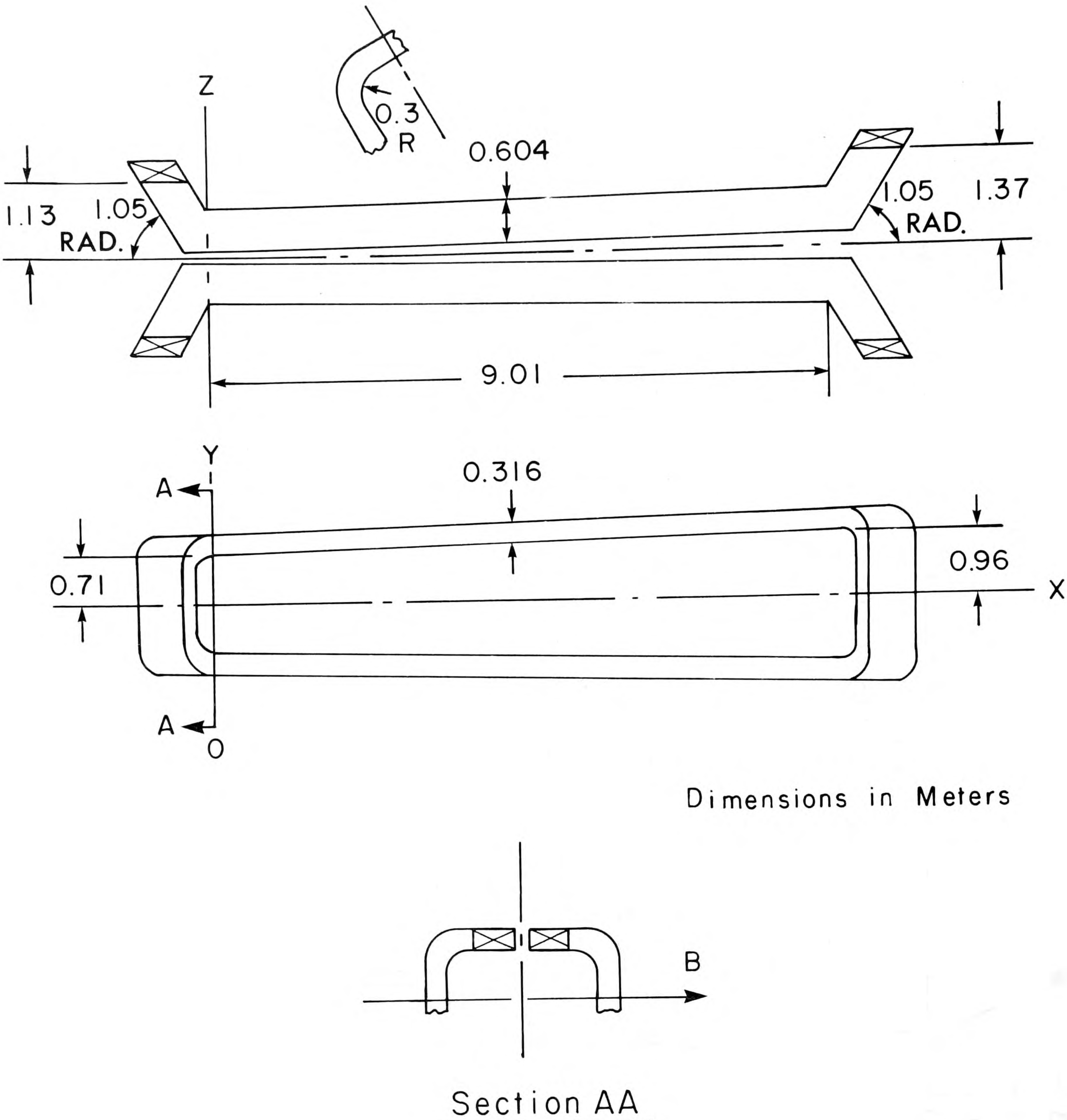


Figure 5

Diagram of Winding, 4.5 T Retrofit MHD Magnet

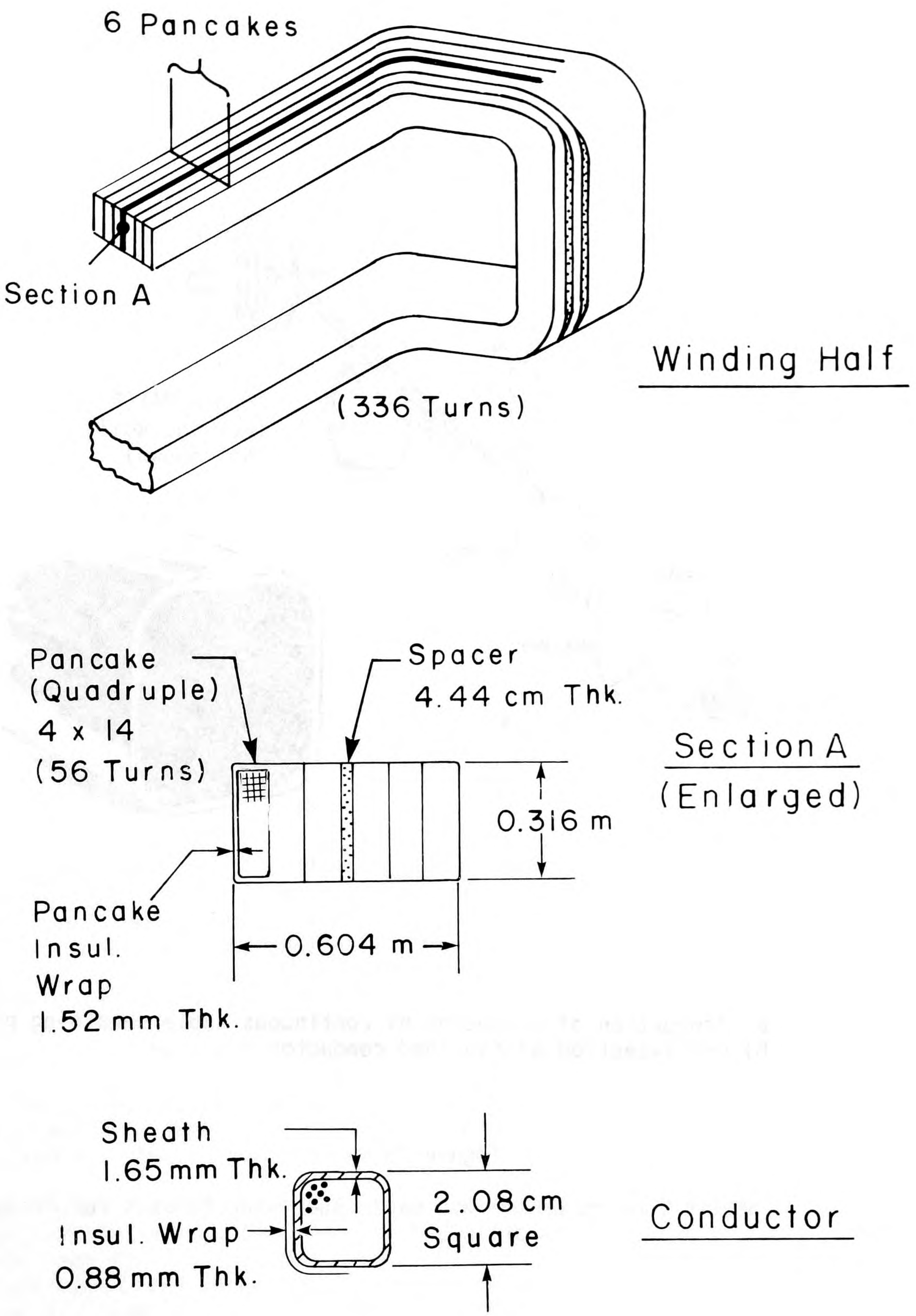
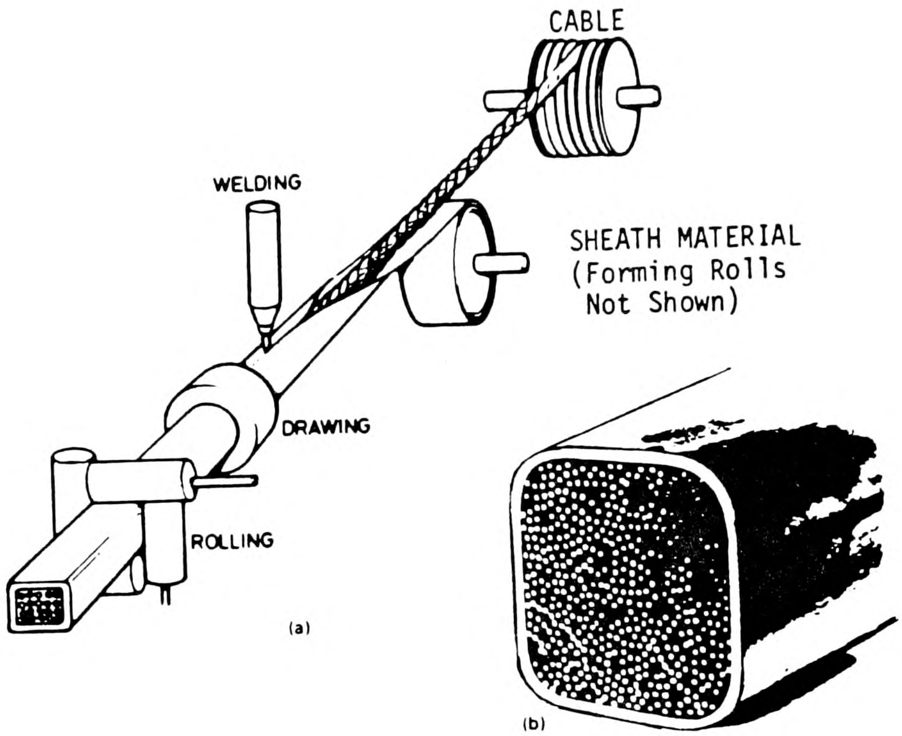


Figure 6

Details of Winding and Conductor, 4.5 T Retrofit MHD Magnet



a) Production of conductor by continuous cable sheathing process
b) Cross-section of finished conductor

Figure 7

Sketch Showing Continuous Cable Sheathing Process for Production of ICCS

TABLE II

Summary

Magnet Design Characteristics

Conceptual Design Retrofit MHD Magnet

Peak on-axis field	(T)	4.5
Active length (3 T to 3 T)	(m)	9
Maximum field in winding	(T)	6.9
Warm bore dimensions, inlet	(m)	0.8 x 1.0
Warm bore dimensions, exit	(m)	1.3 x 1.6
Magnet overall dimensions	(m)	
Width		5.0
Height		5.2
Length		12.3
Design (average) current density	($A \cdot cm^{-2}$)	3200
Design current	(kA)	18
No. of turns		672
Ampere turns	(A)	12×10^6
Total length conductor	(km)	18
Inductance	(H)	3.0
Stored energy	(MJ)	490
Magnet weight	tonnes	280

Each half of the winding consists of six saddle-shaped quadruple pancakes nested as shown in Figure 6. Each pancake, containing 56 turns, is wound from a continuous length of conductor using essentially the same winding techniques used in making the saddle coils of conventional water-cooled copper MHD magnets. The conductor is wrapped with fiberglass turn-to-turn insulation, each pancake is enclosed in an overwrap of fiberglass, and each winding half is epoxy impregnated. The complete winding (2 halves) contains 672 turns and requires about 18 km of conductor.

The main support structure for the magnet winding consists of a rectangular cross-section coil form on which the two coil halves are mounted, end plates welded to the inlet and exit ends of the coil form, and a system of beams and tie rods which clamp the coils to the coil form and provide restraint against outward-acting magnetic forces. Longitudinal forces are restrained by the end plate and coil form assembly. The entire structure is made of stainless steel.

The cryostat consists of a cylindrical stainless steel guard vacuum shell surrounding the coils and structure and operating at the same temperature as the coils, a room-temperature stainless steel outer vacuum shell with central warm bore tube and a liquid-nitrogen-cooled aluminum alloy thermal shield covered with multilayer insulation and interposed between the guard vacuum shell and the room temperature cryostat walls. The coils, coil support structure and guard vacuum shell are carried on low-heat-leak struts placed inside the outer vacuum shell. The configuration of the structure and cryostat are shown in the assembly drawing of Figure 2.

The power supply and protection system for the magnet includes vapor cooled electrical leads, a rectifier power supply package (rectifiers, transformers, controls), circuit breakers, a discharge resistor package and a quench detector system. The purposes of this system are to charge the magnet, maintain the desired field strength for long periods of time and to discharge the system under either normal shutdown or emergency (fast) shutdown conditions.

The cryogenic support equipment for the magnet includes a refrigerator/liquefier package, compressors, heat exchangers, gas storage, liquid helium storage and liquid nitrogen storage tanks. The purposes of this equipment are to cool the coils and main structure from room temperature to liquid helium temperature, to maintain the cold mass at liquid helium temperature for long periods of time with the magnet operating at full field strength and to warm the cold mass to room temperature in the event that repairs or long plant shutdowns are necessary. The equipment supplies supercritical helium (2.5 atm; 4.5 K) for circulation through the conductor and saturated liquid helium at about 1.2 atm pressure for cooling conductor joints, vapor-cooled power leads, and the guard vacuum shell and associated parts. The equipment also supplies liquid nitrogen at approximately 80 K for cooling the thermal shield and for precooling.

In developing the conceptual design, a major consideration has been to maximize predictability in magnet performance, reliability and cost. To accomplish this, the conceptual design is based primarily on the current state of the art, using concepts and techniques already proven or well advanced in development within the superconducting MHD magnet discipline[2,3,4]. Scalability to commercial size has also been a major consideration, keeping in mind that future commercial MHD/steam generators may be designed for outputs of 500 to 2000 MWe and may require magnetic fields up to 6 T.

In addition to the use of ICCS conductor, there are other features of the conceptual design presented here which are also especially advantageous. These features are:

- A rectangular saddle coil configuration which allows the warm bore at the magnet to be rectangular in cross section (instead of square or round) providing more effective use of high field volume.[5]

- An end turn configuration (60° slope of side bars) which provides maximum access to the flow train at both ends of the magnet by allowing cryostat end surfaces to slope inward toward the bore.

- Structural design (using mechanical fastenings) to minimize on-site welding during magnet assembly while maximizing inspectability.

- Elimination of winding substructure (intermediate structure within the winding), made possible by the use of ICCS rather than a bath-cooled conductor, with the result that the winding is more compact and overall cost is reduced.

- Provision of a guard vacuum enclosure around the winding so that a small leak in the conductor sheath, should it develop during service, would not degrade the main cryostat vacuum. (The guard vacuum enclosure is a simple thin-walled vessel, not required to withstand any substantial pressure differential).

- Locating all conductor joints (splices) in the service stack where they are cooled independently of the conductor forced cooling circuit, and are readily accessible.

Analysis

Field and force calculations were made for the winding shown in Figure 5. The desired peak on-axis field was obtained with 12 x 10^6 ampere turns. The curve of on-axis field as a function of distance along the axis is shown in Figure 8. Curves of field as a function of transverse distance in the magnet bore cross section at the plane of peak on-axis field are shown in Figure 9. Curves of fringe field as a function of distance from the magnet center are shown in Figure 10.

The field concentration factor for the winding (ratio of maximum field in winding to peak on-axis field) is approximately 1.5. The locations of the calculated maximum field point and other high field points are shown in Figure 11. It should be noted that the field concentration factor is substantially higher in this retrofit MHD magnet design than in earlier MHD magnet designs[2,3,4], because the retrofit magnet design has a relatively smaller winding cross section (and higher average current density) than earlier MHD magnet designs. The use of ICCS makes possible the smaller winding area, with potential savings in magnet structure and cryostat costs[6]. At the same time, the higher field concentration factor tends to increase conductor cost. Therefore, it will be necessary to make careful trade-offs in a final magnet design to assure minimum overall cost. A

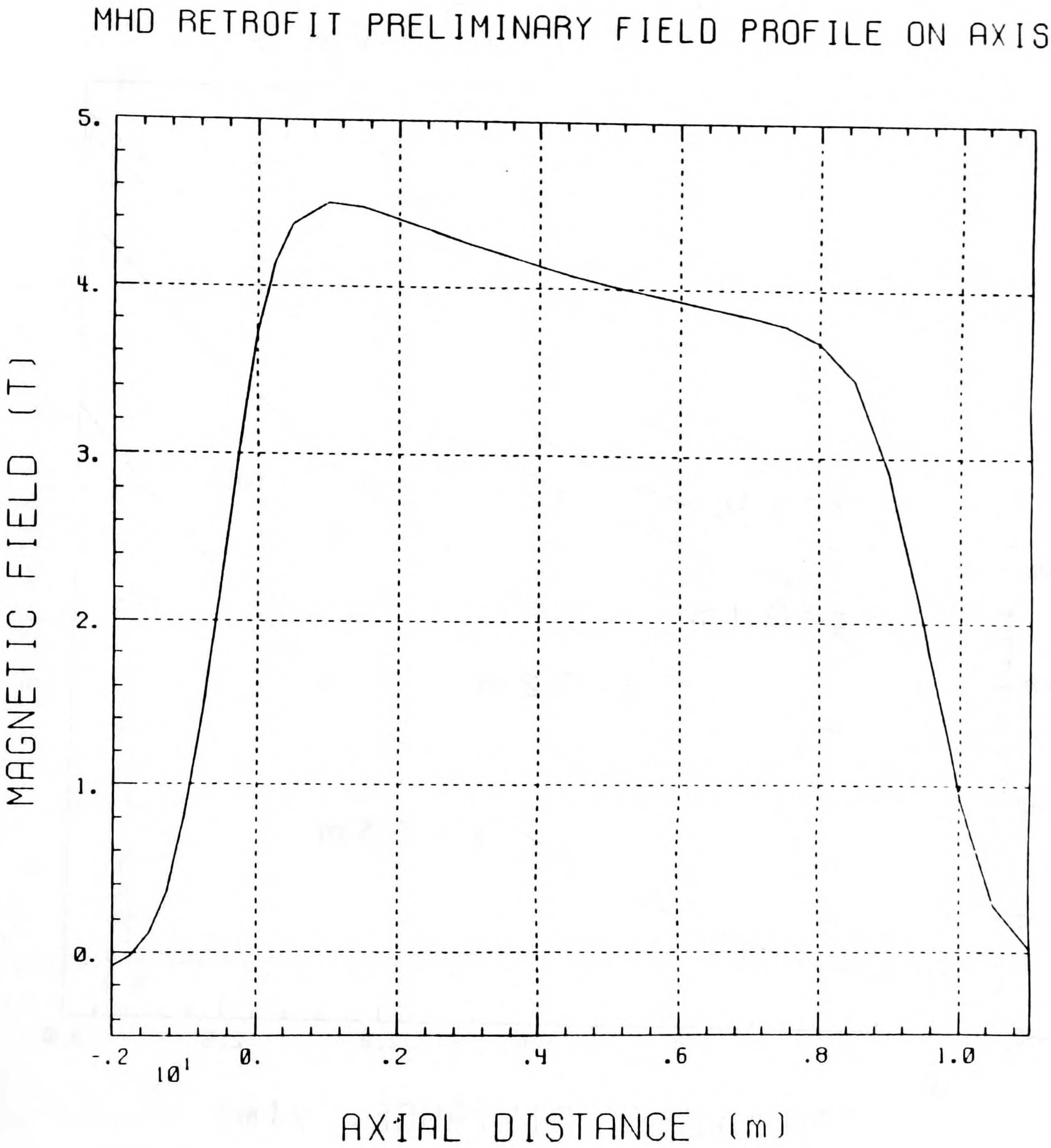


Figure 8

Curve of On-Axis Field vs Distance Along Axis, 4.5 T Retrofit MHD Magnet

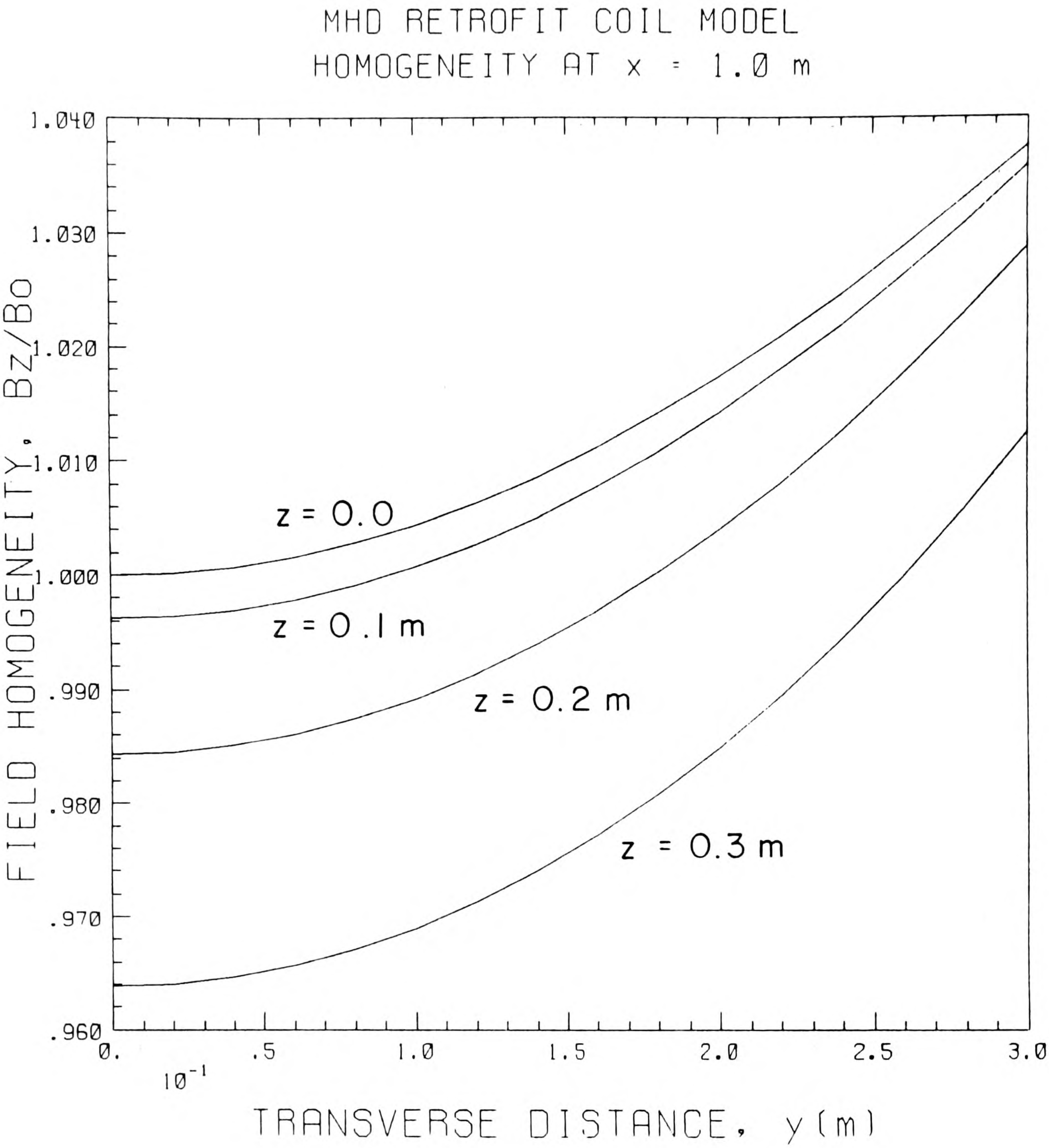


Figure 9

Curves of Field vs Transverse Distance in Magnet Bore in Plane of Peak On-Axis Field, 4.5 T Retrofit MHD Magnet

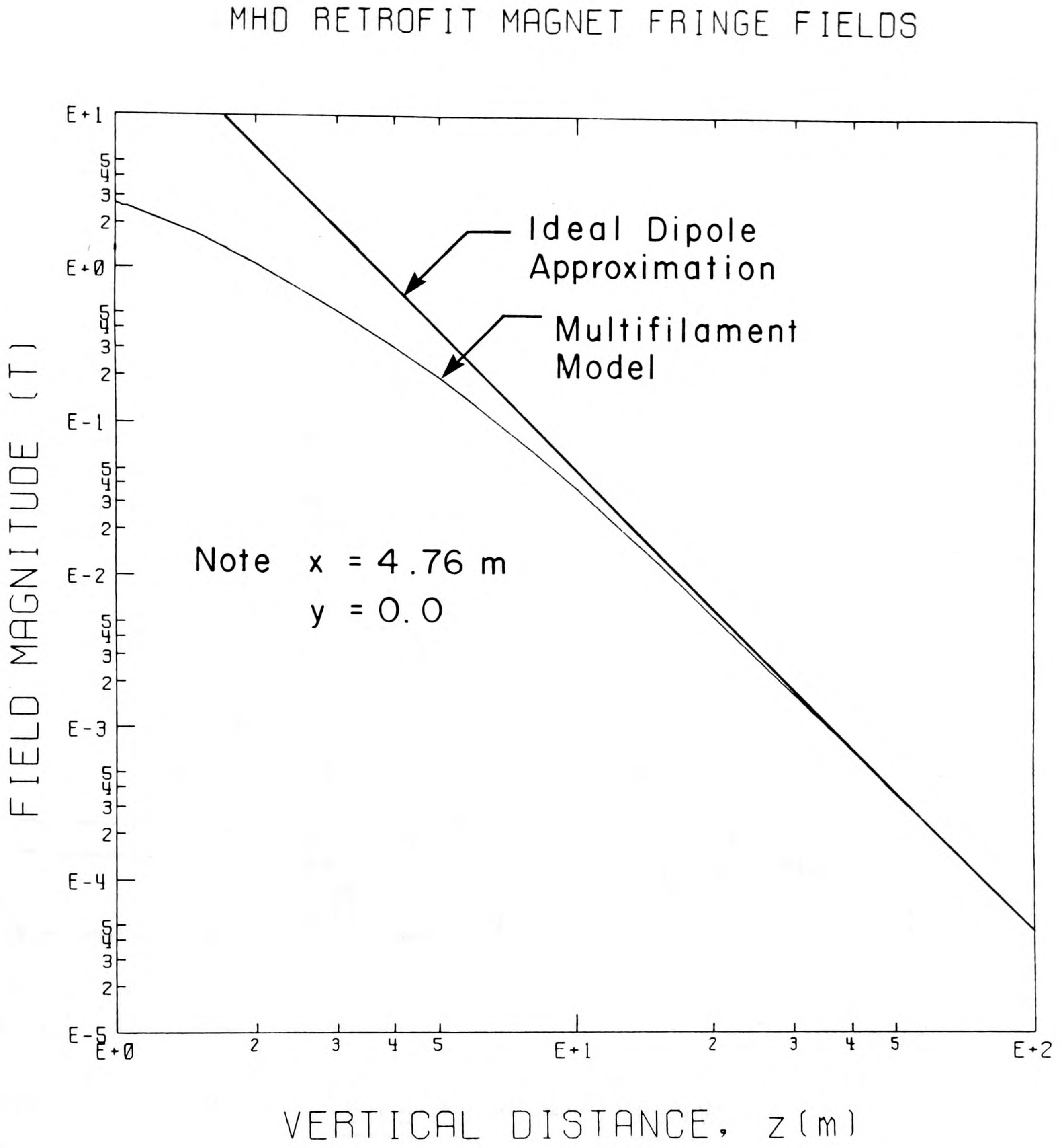
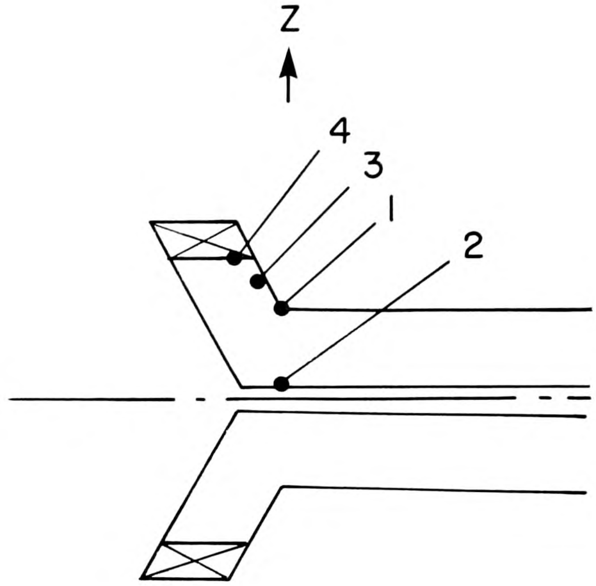
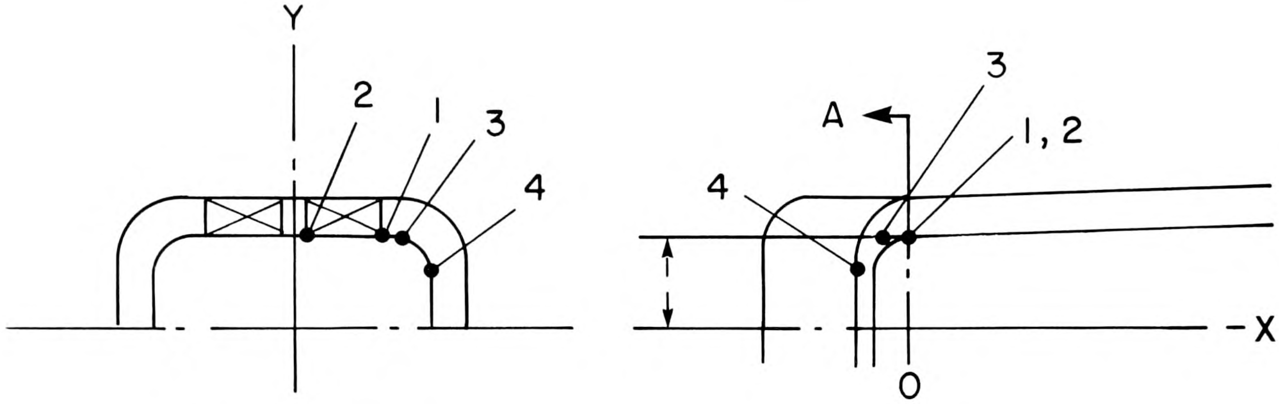


Figure 10

Curves of Fringe Field vs Distance from Magnet Center in Direction of Magnetic Field, 4.5 T Retrofit MHD Magnet

Point	Coordinates			Field
	X (m)	Y (m)	Z (m)	(T)
1	0	0.71	0.65	6.92
2	0	0.71	0.12	5.21
3	-0.24	0.71	0.87	6.55
4	-0.39	0.41	1.13	6.32





Section O-A

Winding - Inlet End

Figure 11

Diagram of Winding Showing Locations of Point of Maximum Field and Other High Field Points, 4.5 T Retrofit MHD Magnet preliminary assessment of system cost optimization, however, does suggest that the maximum field to central field ratio for ICCS magnets should be somewhat higher than the value identified in previous studies using more conventional conductors.

Force calculations show that the maximum pressure exerted by the winding bundles against the restraining I-beams is about 12 MPa and the maximum compression in the winding bundles is about 30 MPa. Structural analysis of this configuration indicates satisfactory performance for compression loading up to 50 MPa.

Calculations of conductor characteristics were made for a conductor of the dimensions shown in Figure 6, with various design current ratings and ratios of design current to critical current. Results are listed in Table III.

TABLE III

Calculated Conductor Characteristics

Alternative Conductors

Design Current	Max. Field	Length Between Vents	Magnet Inductance	Ratio cu/sc	Ratio I_{design}/I_{crit}	Stability Margin	Max. Press. (Quench)
kA	T	m	henries			mJ/cm^3	MPa
20	6.9	700	2.5	6.4	0.75	9.5	TBD
20	6.9	700	2.5	4.9	0.60	13	TBD
17.5	6.8	800	3.5	7.7	0.75	70.5	112
15	6.8	800	4.5	9.2	0.75	106	TBD

Stability margin, defined as the maximum energy that an ICCS type conductor can absorb without quenching[7], is an appropriate measure of stability of the conductor. The margin of about 40 mJ/cm^3, which has been estimated for the 18 kA conductor, is considered satisfactory for this application.

Internal pressure under quench conditions is safely within the rating of this conductor.

Conductor Design Requirements Definition

A preliminary draft of the design requirements definition for ICCS conductor for MHD superconducting magnets has been established, and is presented in Table IV, Conductor Design Parameters.

Requirements concerning conductor quality control and conductor splice design and performance will be developed at a later date.

The design requirements definition will be updated and finalized when the program of analysis and testing is completed.

Future Analysis and Testing

It is planned that conductor analysis will continue, including thermodynamics, quench propagation, pressure dynamics, structural and systems protection analysis, in conjunction with the test program and finalizing of the requirements definition.

An experimental program will be performed with subscale conductors consisting of subelements of the proposed full scale conductor. The basic elements, as well as different combinations of elements, will be configured and tested to determine an optimum design configuration. Tests will be performed to study strength fatigue under long term cyclic magnetic load conditions. The design of the full scale conductor will be finalized, a sample length will be manufactured and a test coil will be wound and tested, including long-term cyclic verification testing.

TABLE IV

Conductor Design Parameters

(Retrofit Size MHD Magnet

Performance	
Maximum field at conductor (T)	6.9
Operating temperature (K)	4.5
Operating pressure, helium (atm)	2.5
Design current at oper. press., temp. and max. field (kA)	18
Critical current at oper. press., temp. and max. field (kA)	24
Stability margin[1] (mJ/cm^2)	(TBD)
Quench heating temperature rise (K)	(TBD)
Materials	
Conductor	NbTi/Cu
Min. copper resistivity ratio at 4.5 K, 0 field	(TBD)
Sheath	Type 304 St. Steel
Copper to superconductor ratio	(TBD)
Dimensions	
Sheath outside dimensions (cm)	2.08 x 2.08
Sheath outside corner radius (cm)	0.673
Sheath thickness (cm)	0.165
No. of strands	486
Strand diameter (mm)	0.7
Void fraction	0.32
Mechanical	
Minimum bend radius (cm)	15
Maximum continuous length required (cm)	1600
Maximum internal pressure	(TBD)
Maximum compressive load (on side)	(TBD)
Maximum tensile load	(TBD)
Internal flow resistance	(TBD)
Durability (in magnet)	
Service life (years)	30
No. of cooldown/warmup cycles	60
No. of charge/discharge cycles	600

[1]As defined in Reference 7.

References

1. Heyne, C. J., et al., Westinghouse Design of a Forced Flow Nb_3Sn Test Coil for the Large Coil Program, Proceedings of the 8th Symposium on Engineering Problems of Fusion Research, Vol. III, 1979.

2. MHD Magnet Technology Development Program Summary, Plasma Fusion Center, MIT, September 1982 (PFC/RR83-6).

3. MHD Magnet Technology Development Program Summary, Plasma Fusion Center, MIT, September 1984 (PFC/RR84-18).

4. NASA/LeRC Conceptual Design Engineering Report - MHD Engineering Test Facility 200 MWe Power Plant, prepared for NASA/LeRC for DOE by Gilbert/Commonwealth, DOE/NASA/0224-1 Vol. I-V, September 1981.

5. Marston, P. G., et al., Magnet - Flow Train Interface Considerations, 19th S E A M, University of Tennessee Space Institute, June 1981.

6. Hatch, A. M., et al., Impact of Design Current Density on Cost and Reliability of Superconducting Magnet Systems for Early Commercial MHD Power Plants, 21st Symposium on Engineering Aspects of MHD, Argonne National Lab., June 1983.

7. Minervini, J. V., et al., Experimental Determination of Stability Margin in a 27 Strand Bronze Matrix Nb_3Sn Cable-in-Conduit Conductor, IEEE Transactions on Magnetics, Vol. MAG 21, No. 2, March 1985, p. 339.

8. Becker, H., et al., Structural Behavior of Internally Cooled Cabled Superconductors under Transverse Load, MIT Plasma Fusion Center Research Report (to be issued).