PFC/RR-86-4 DOE/PC-70512-4

Develop and Test an ICCS for Large Scale MHD Magnets

Technical Progress Report
Period from January 1, 1985 to June 30, 1985

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1.0 Introduction

A three-year program to develop and test an internally-cooled cabled superconductor (ICCS) for large scale MHD magnets is being conducted by MIT for the Pittsburgh Energy Technology Center (PETC) under Contract DE-AC22-84PC70512. The program consists of the following four tasks:

I. Design Requirements Definition
II. Analysis
III. Experiment
IV. Full Scale Test

This report describes the technical progress on Tasks I and II during the period from January 1, 1985 to June 30, 1985. Progress in the period from October 1, 1984 to December 31, 1984 is described in the Quarterly Progress Report dated March 1985[1].

The objective of Task I is to establish the design requirements definition for full-scale conductors for use in early commercial MHD magnets. Since the focus of MHD power train development is fixed now on relatively small systems such as may be used in retrofit applications, the work concerns conductors suitable for systems of that size and type.

The objective of Task II is to accomplish the analysis required to substantiate the design for the full-scale conductor, and to provide the background for defining an experimental test program (Tasks III and IV).

The program is directed specifically toward the development of ICCS because this type of conductor has many significant advantages over bath-cooled conductors for the MHD application: 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. The concept offers great promise in resolving the issues of constructability and long-term durability for commercial MHD magnets while minimizing the overall costs and risks of such systems.

In order to establish a conductor Design Requirements Definition, it is necessary to know the design characteristics of the magnet in which the conductor is intended to operate. Since a suitable reference design for a retrofit-size MHD magnet did not exist when the program was started, the development of a preconceptual design for such a magnet has been a major part of the Task I effort.

2.0 Review of Technical Progress Prior to January 1, 1985

A brief review of technical progress from the start of the program through December 31, 1984 is provided below as a background for the report of progress contained in Sections 3.0 and 4.0.

As a starting point for preconceptual magnet design, it was assumed that the typical retrofit-size MHD magnet will:

a) accommodate a supersonic MHD channel of about 35 MWe output, requiring a peak on-axis field of 4.5 T.
b) operate at a design current in the neighborhood of 25 kA.

As a baseline for conductor design, it was assumed that the dimensions and construction of the conductor would be the same as those of the ICCS conductor used in the large D-shaped magnet designed and built by Westinghouse for the fusion Large Coil Program (LCP), described in Reference 2. This was done to take advantage of the manufacturing technology that had been developed for that project. The MHD conductor will, however, use niobium titanium (NbTi) superconductor rather than niobium tin (Nb_3Sn).

The selection of magnet size and field strength is supported by information obtained from the MHD community as reported previously[1]. The selection of a relatively high design current is in the interest of minimum overall system cost, based on information provided in Reference 3. The selection of the particular ICCS overall dimensions and construction is aimed at minimizing conductor development time and cost by using a conductor size and construction for which production and tooling experience already exist.

An initial preconceptual design for a retrofit-size magnet was generated, incorporating a 60° rectangular saddle-coil winding of ICCS, without substructure, surrounded by a stainless-steel force containment structure and cryostat. Preliminary calculations of fields, forces, and cryostat heat leaks were made in support of this design. The characteristics of the initial design are recorded in Reference 1.

Tentative conductor design requirements were established and a conductor design was developed based on the Westinghouse LCP conductor dimensions. Preliminary calculations were made of stability margin, quench temperature rise, and quench pressure

The ability of the conductor to withstand structurally the Lorentz force loading existing in the fully wound saddle coil (without substructure) has been verified by structural testing and analysis (including finite element computations) of similar ICCS as reported in Reference 4.

Tentative conductor design requirements and design characteristics were developed in the initial phase of the program and are listed in Reference 1.

3.0 Summary of Technical Progress, January 1, 1985 to June 30, 1985

Based on the initial magnet design and conductor requirements developed in the preceding period, a design review and more detailed analyses were made. A detailed computer analysis of the winding showed maximum fields to be substantially higher than originally estimated (approaching 7.2 T instead of the estimated 6 T). Original estimates of current margin and stability were therefore no longer valid and redesign was required in order to achieve acceptable safety margins.

Several winding design modifications, aimed at reducing the maximum field, were then analyzed. Modifications included changing the shape of the end turns, changing the aspect ratio of the winding cross section, and decreasing the winding average current density. A reduction of maximum field to below 6.9 T was found to be possible. A revised winding design having an increased thickness, an increased bend radius in the end turns, and a lower current density was established as most suitable for the application. A comparison of the revised design with the original design as follows:

	Original	Revised
Coil thickness (m)	0.24	0.305
Minimum end turn bend radius (m)	0.15	0.30
Winding average current density (A/cm^2)	3900	3200
Design current in conductor (kA)	24	18
Maximum field in winding (T)	7.2 (Orig. est. 6.0)	6.9

Preliminary analysis of the conductor shows that the stability margin and quench pressure at the new (lower) design current level are acceptable. Adiabatic temperature rise during emergency discharge is within reasonable limits.

The revised magnet design was analyzed, including further computer calculations of fields and forces, as well as inductance and stored energy. Preliminary stress calculations were made to determine the integrity in critical areas. Cryogenic analysis was accomplished, including calculation of heat leaks and heat loads to be handled by the refrigeration system. These studies show that the overall preconceptual design is satisfactory.

Conductor design requirements were updated to be consistent with the revised magnet preconceptual design.

The end product of the work is an improved magnet preconceptual design which compares favorably with earlier magnet designs in reliability, manufacturability, and cost-effectiveness, together with a draft Design Requirements Definition for the conductor that represents a sound basis for continued development and proof-testing of subscale conductor elements as well as a full-scale conductor prototype.

4.0 Results of Design and Analysis Effort (Tasks I and II)

The results of the technical effort, including the preconceptual design for a retrofit-size MHD magnet and the draft Conductor Design Requirements Definition, are described in detail in this section.

4.1 Magnet Preconceptual Design

The preconceptual design for the retrofit-size MHD magnet described herein is an upgraded version incorporating modifications and improvements developed during the period ending June 30, 1985. MHD system requirements used as a basis for the magnet preconceptual design are listed in Table I.

Table I

System and Magnet Requirements Used as Basis for Preconceptual Design of Retrofit-Size MHD Magnet

Plant thermal input	(MWt)	250-275
Channel power output	(MWe)	35-40
Channel type		supersonic
Peak on-axis field	(T)	4.5
Warm bore dim., channel inlet	(m)	0.8×1.0
Warm bore dim., channel exit	(m)	1.3×1.6
Channel active length	(m)	9

The magnet incorporates a 60° rectangular saddle-coil winding which is supported in a stainless-steel force containment structure and enclosed in a stainless-steel cryostat. The rectangular-cross-section warm bore, diverging from inlet to exit, is fitted with a water-cooled protective liner having the inner surface coated with an ablative, electrically insulating material.

The winding consists of a copper-stabilized-NbTi twisted-cable conductor sheathed with an appropriate stainless-steel (or equivalent) material formed to a square cross section with rounded corners. The conductor, insulated with fiberglass wrap, is of the same type and outside dimensions as the ICCS used in the large D-shaped experimental coil constructed for the Large Coil Program[2]. An outline of the magnet preconceptual design is shown in Figure 1. Figure 2 is an assembly elevation drawing and Figure 3 is a section drawing of the magnet. A field profile and a cutaway view of the magnet are shown in Figure 4, with the channel depicted in an 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. Figure 6 displays details of the winding and conductor.

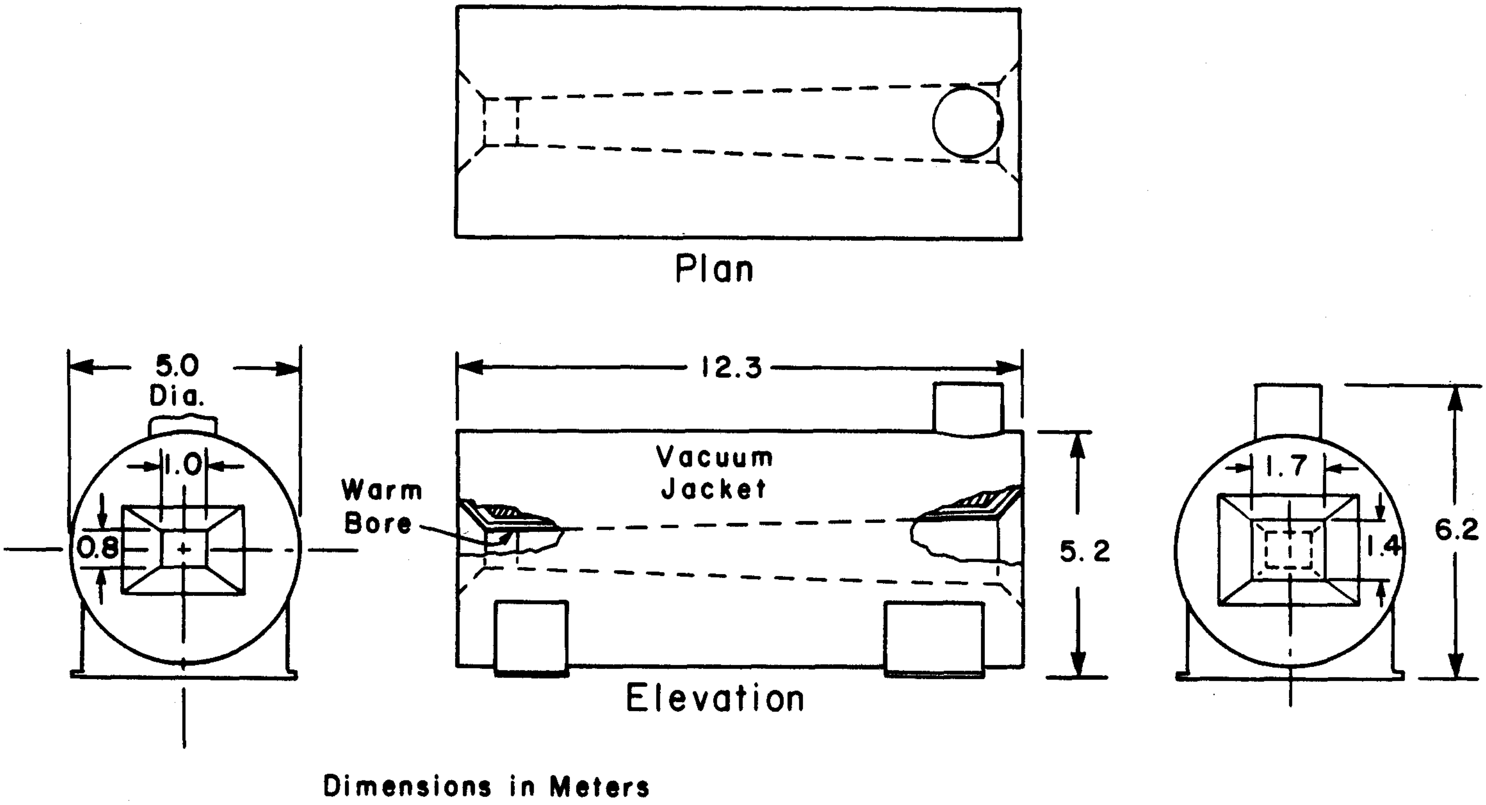


Fig. 1. Outline, 4.5 T Retrofit MHD Magnet Preconceptual Design

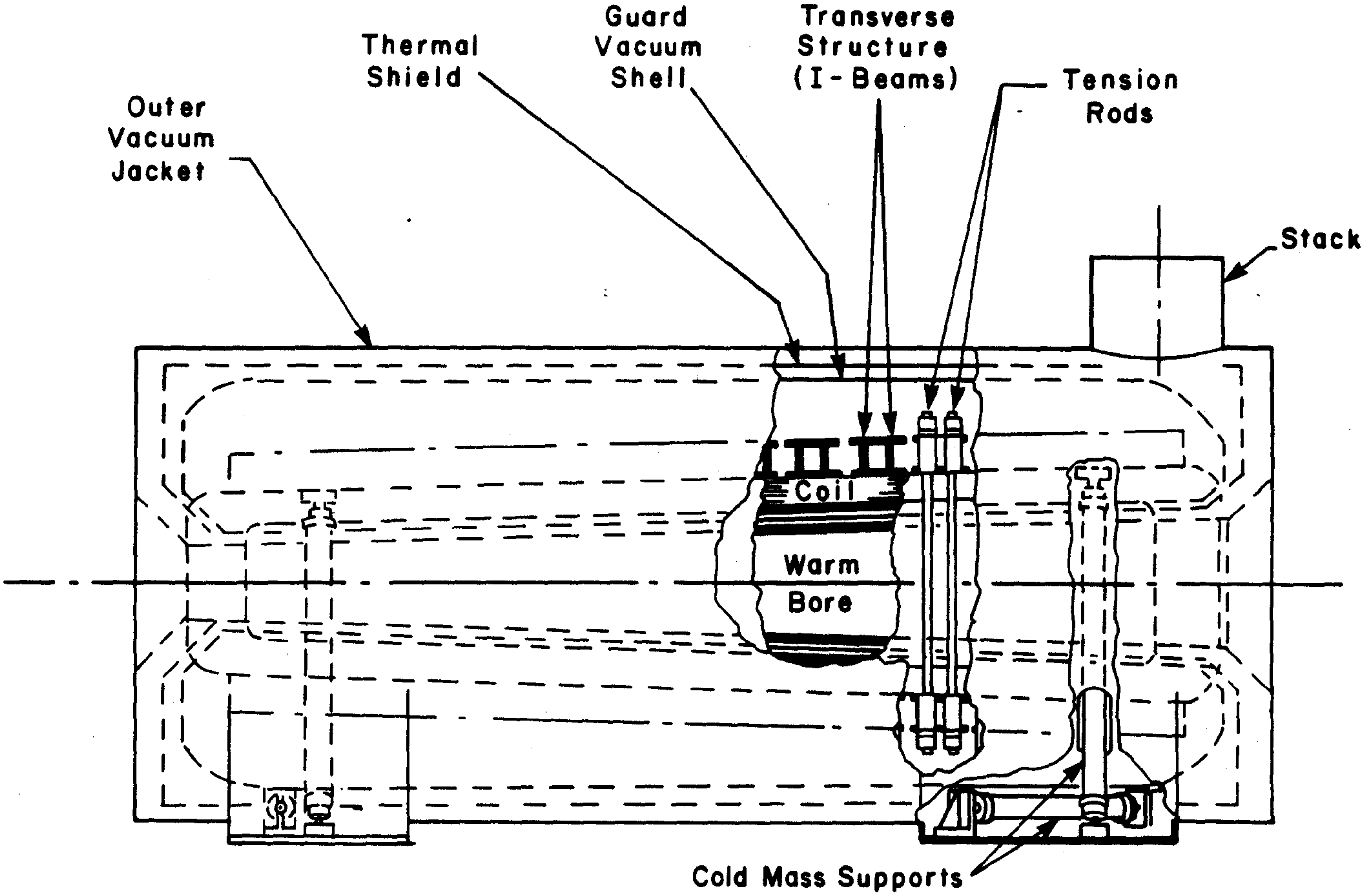


Fig. 2. Assembly Elevation, 4.5 T Retrofit MHD Magnet Preconceptual Design

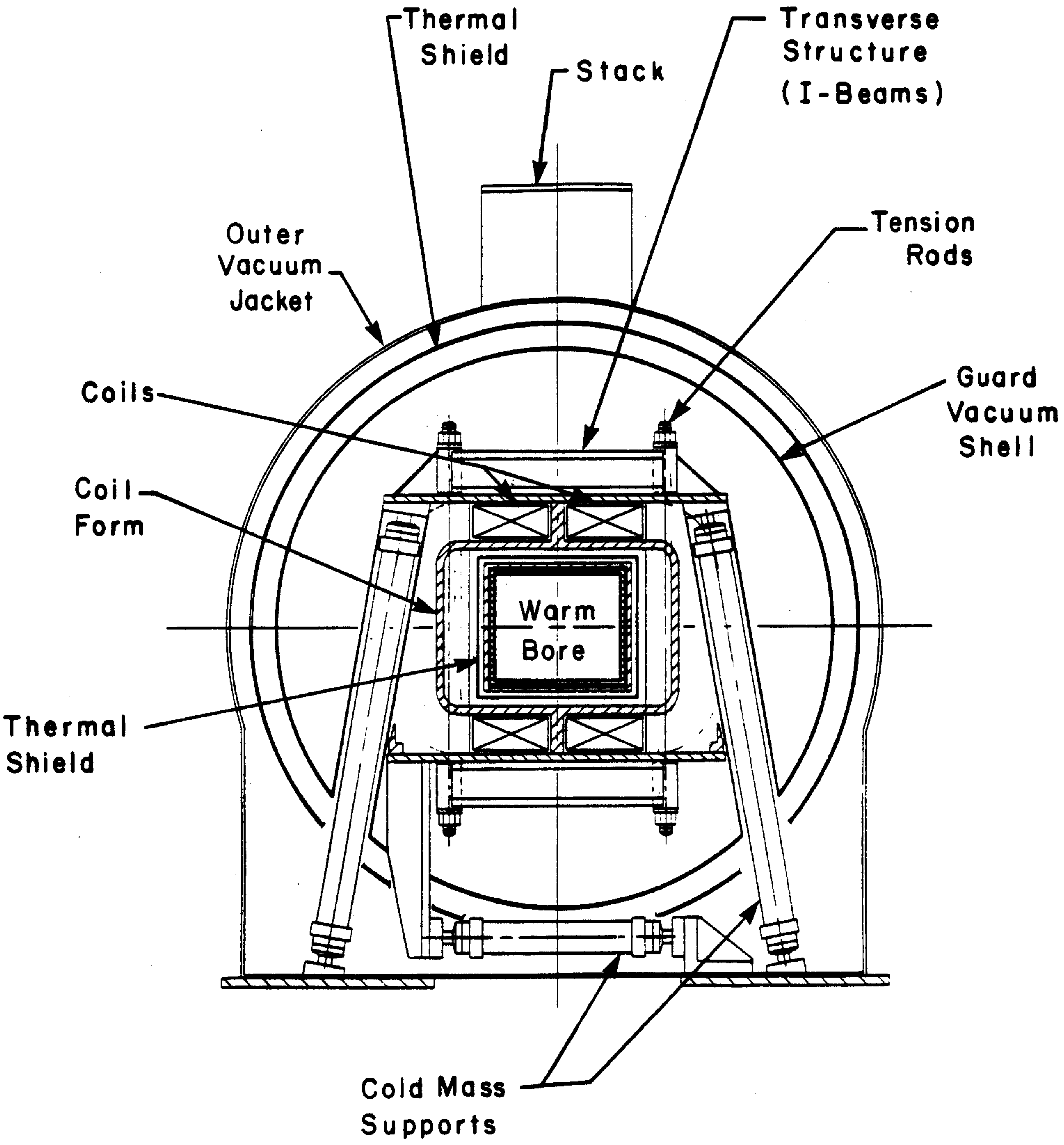


Fig. 3. Assembly, Section at Plane of Channel Inlet, 4.5 T Retrofit MHD Magnet Preconceptual Design

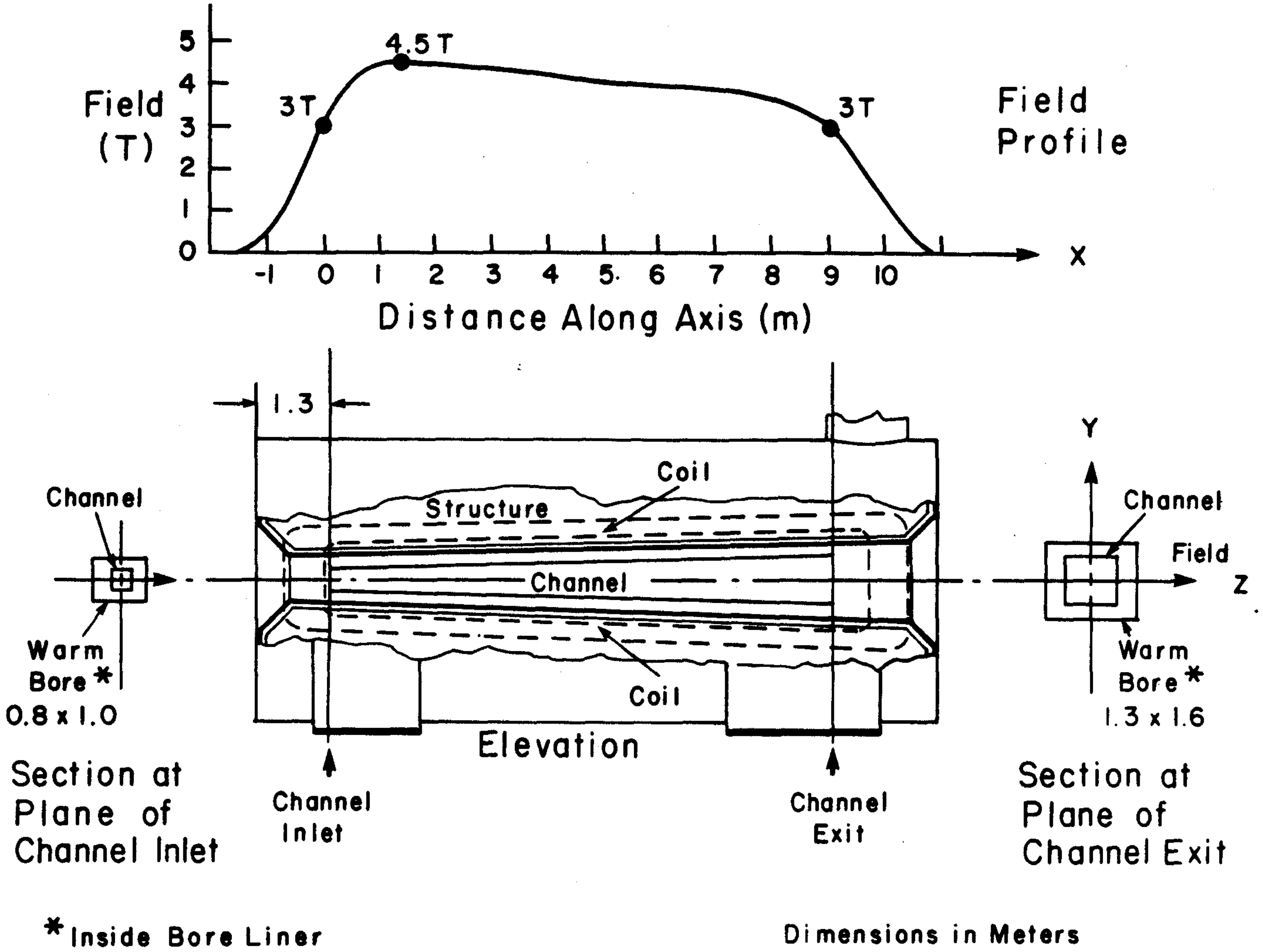


Fig. 4. Magnet Field Profile and Cutaway View Showing Channel Installed in Warm Bore, 4.5 T Retrofit MHD Magnet Preconceptual Design

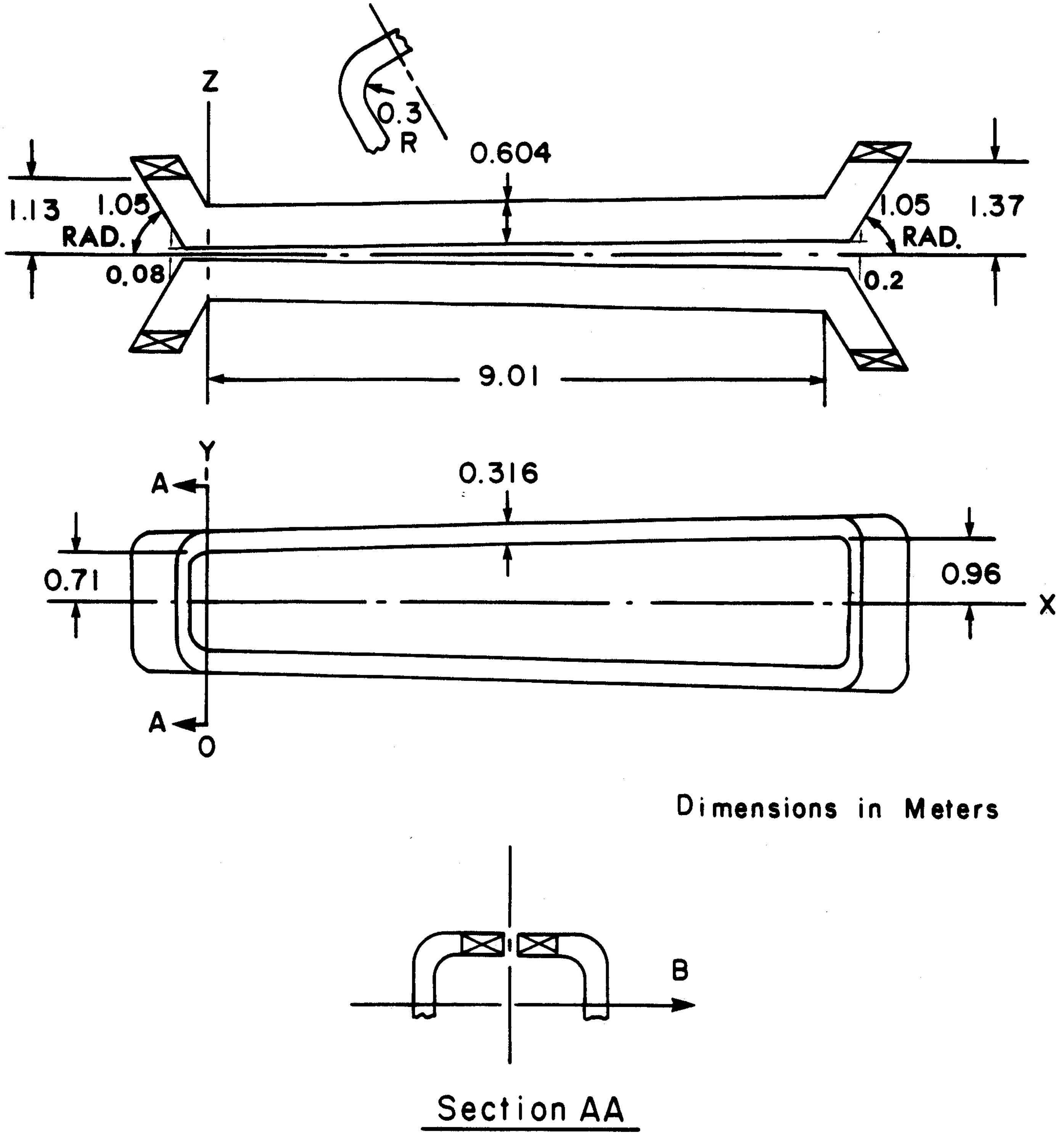


Fig. 5. Diagram of Winding, 4.5 T Retrofit MHD Magnet Preconceptual Design

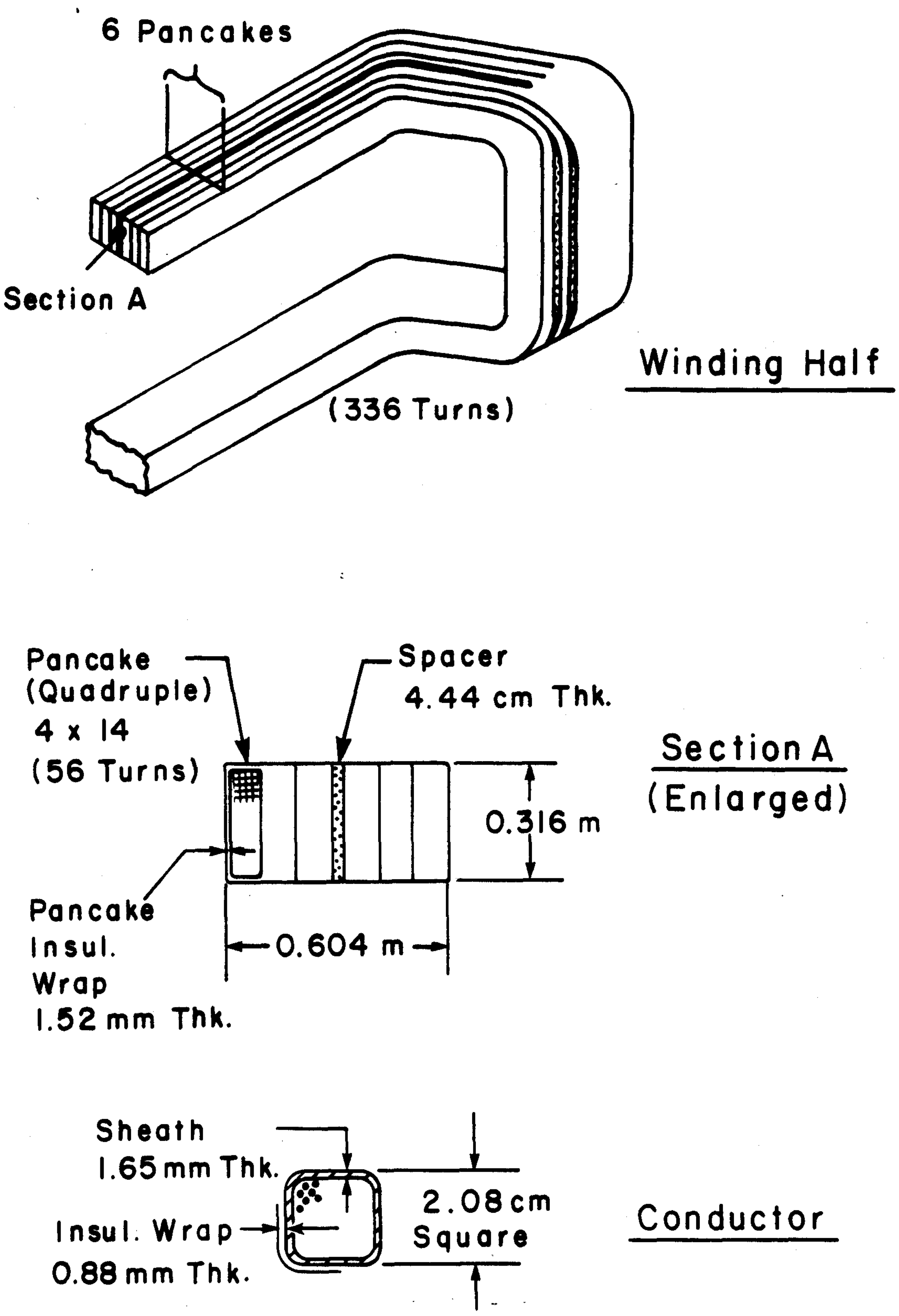


Fig. 6. Details of Winding and Conductor, 4.5 T Retrofit MHD Magnet Preconceptual Design

Table II

Summary
Magnet Design Characteristics
Preconceptual Design Retrofit-Size 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 × 1.0
Warm bore dimensions, end active length	(m)	1.3 × 1.6
Warm bore dimensions, exit end	(m)	1.4 × 1.7
Magnet overall dimensions	(m)	
Width		5.0
Height (not incl. stack)		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	(tonne)	320

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 is epoxy impregnated. The complete winding (2 halves) contains 672 turns and requires about 18 km of conductor.

The main stainless-steel support structure for the magnet winding consists of a rectangular-cross-section coil form on which the two coil halves are mounted. End plates are welded to the inlet and exit ends of the coil form. Beams and tie rods 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 and by the guard vacuum shell which is attached to the outer edges of the end plates.

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 a 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 preconceptual 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[6,7,8]. 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:

- A rectangular saddle-coil configuration which allows the warm bore of the magnet to be rectangular in cross section (instead of square or round) providing more effective use of high field volume[9].

- 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, average current density is high, 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).

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

The magnet preconceptual design is substantiated by calculations and analyses including the following:

Field Calculations

Field calculations show the desired peak on-axis field of 4.5 T to be obtainable with 12×10^6 ampere turns in the winding. The curve of on-axis field as a function of distance along the axis is shown in Figure 7. 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 8. Curves of fringe field as a function of distance from the magnet center are shown in Figure 9.

The field concentration factor for the winding (ratio of maximum field in winding to peak on-axis field) is approximately 1.53. The locations of the calculated maximum field point and other high field points are shown in Figure 10. It should be noted that the field concentration factor is substantially higher in this retrofit MHD magnet design than in earlier MHD magnet designs 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. 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 the magnet design process to assure minimum overall cost.

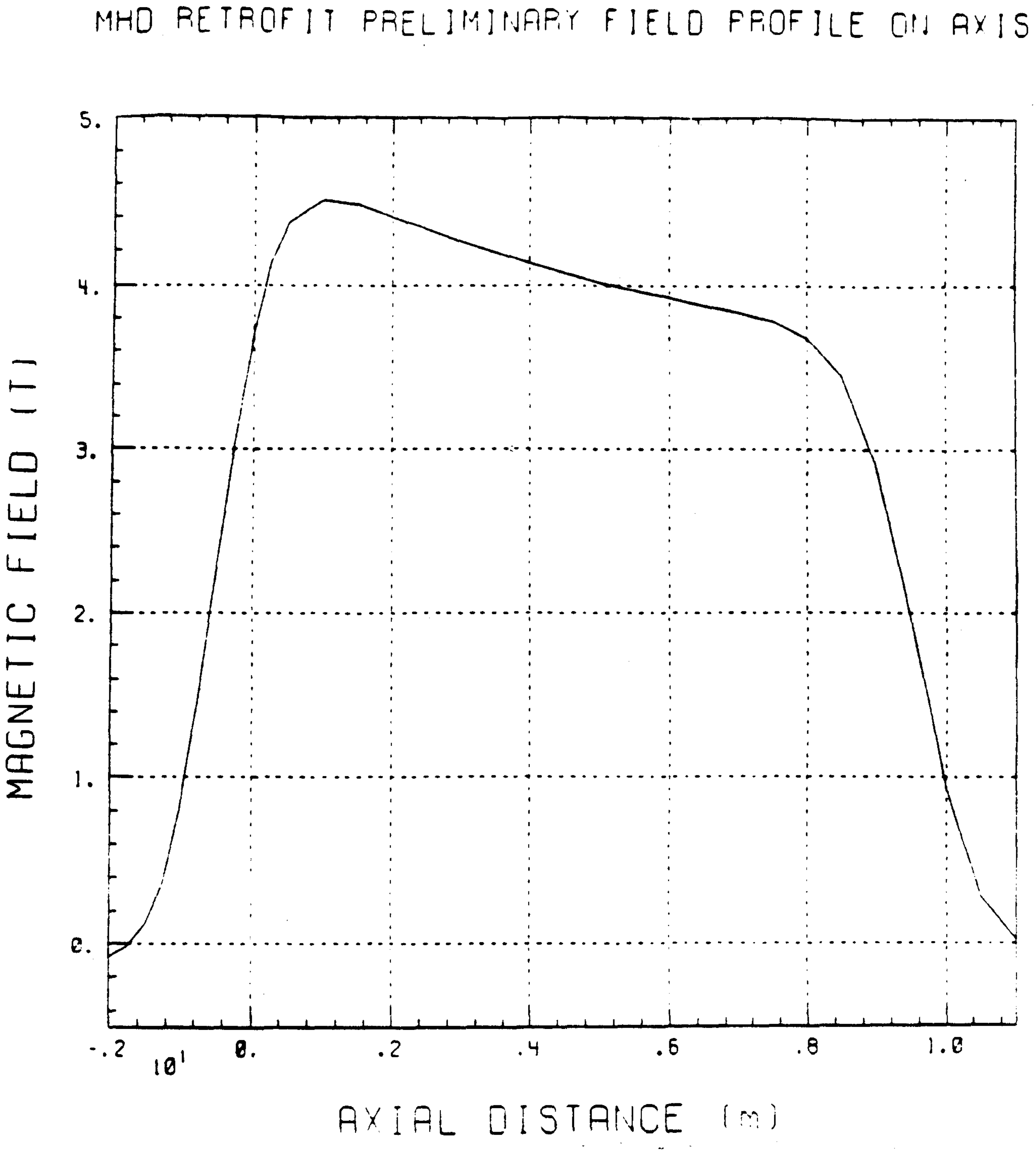


Fig. 7. On-Axis Field vs. Distance Along Axis, 4.5 T Retrofit MHD Magnet Preconceptual Design

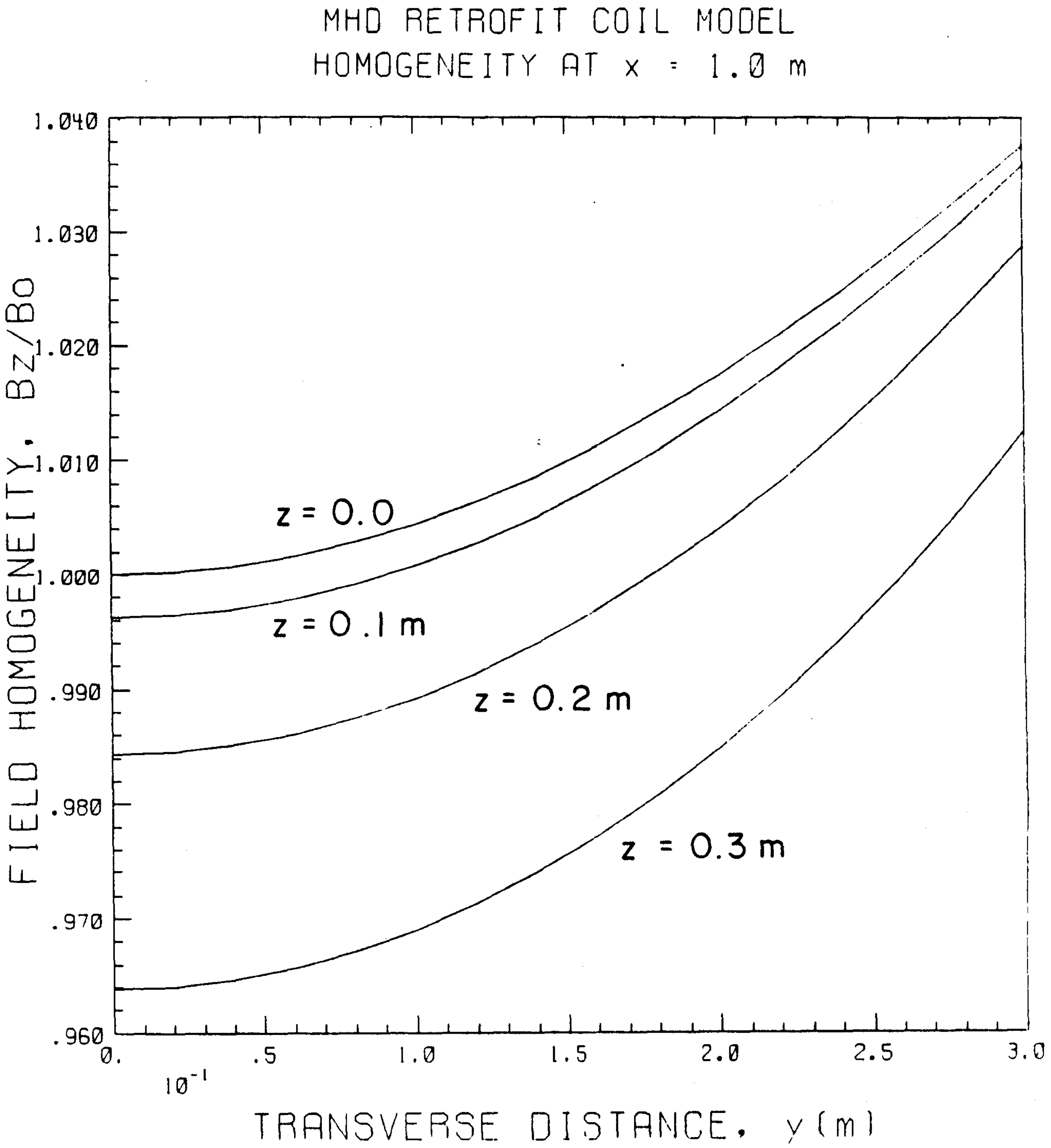


Fig. 8. Field vs. Transverse Distance in Magnet Bore in Plane of Peak On-Axis Field, 4.5 T Retrofit MHD Magnet Preconceptual Design

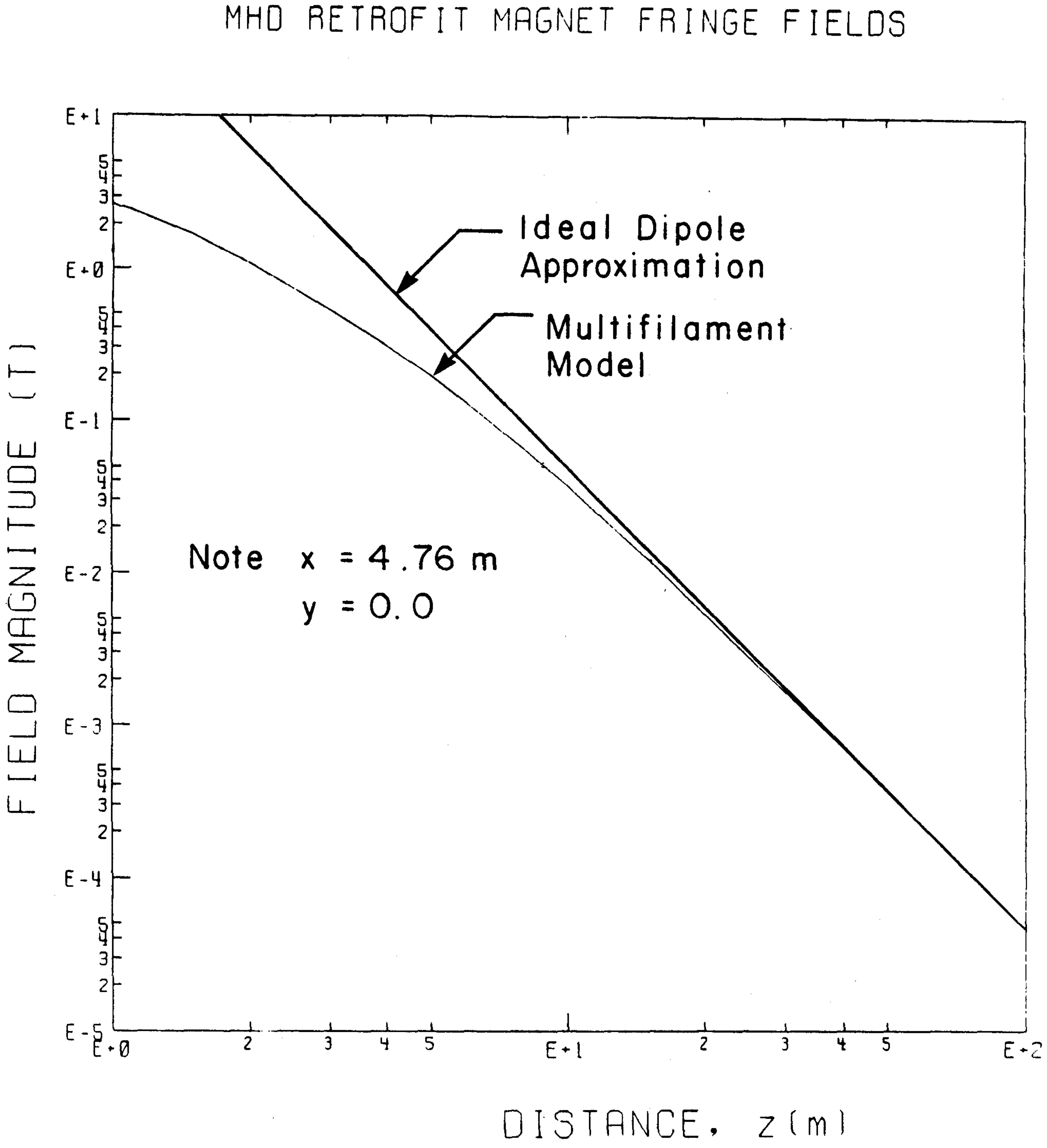
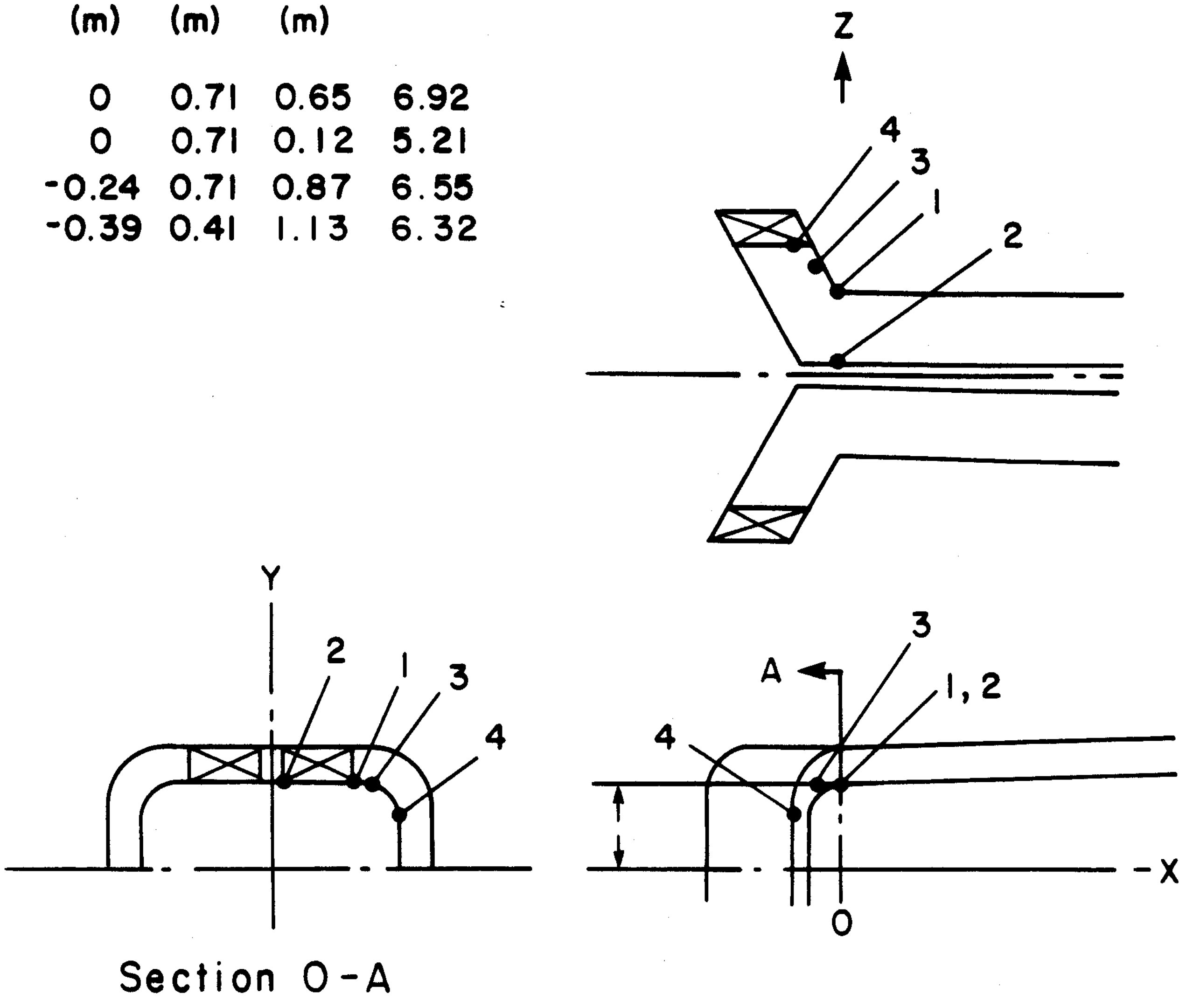


Fig. 9. Fringe Field vs. Distance from Magnet Center in Direction of Magnetic Field, 4.5 T Retrofit MHD Magnet Preconceptual Design

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



Winding - Inlet End

Fig. 10. Diagram of Winding Showing Locations of Point of Maximum Field and Other High Field Points, 4.5 T Retrofit MHD Magnet Preconceptual Design

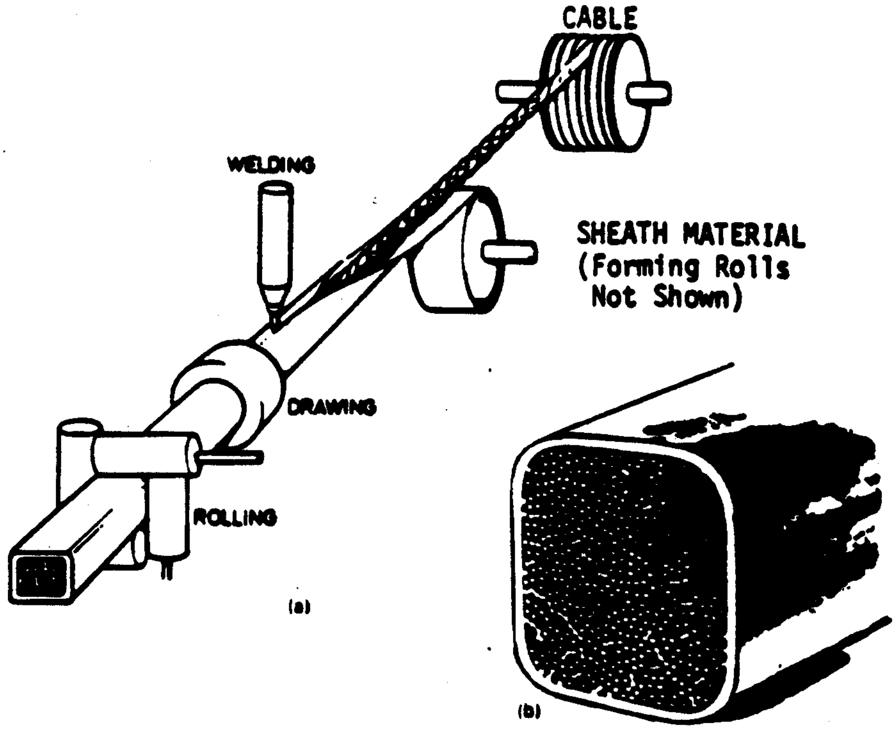
Force Calculations

Force calculations show that the maximum pressure exerted by the winding bundles against the restraining I-beams is about 12 MPa (1 Pa = 1 N/m^2) 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[4].

4.2 Conductor Design

The conductor used in the preconceptual design retrofit-size MHD magnet is a square-cross-section ICCS consisting of a twisted copper-stabilized NbTi cable enclosed in a stainless-steel sheath. Figure 11 contains a sketch showing the continuous cable sheathing process used for production of ICCS. The outside dimensions, sheath thickness, number of strands, and void ratio are the same as those of the conductor used in the Westinghouse LCP coil[2]. The major design characteristics of the conductor are listed in Table III.

Stability margin, defined as the maximum energy that an ICCS type conductor can absorb without quenching, 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.



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

Fig. 11. Continuous Cable Sheathing Process for Production of ICCS Illustrated Schematically

Table III

Summary
Design Characteristics of Conductor for Preconceptual Design 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 operating pressure, temperature, and maximum field (kA)	18
Critical current at operating pressure, temperature, and maximum field (kA)	24
Stability margin (mJ/cm^3)	40*
Quench heating temperature rise (K)	
Maximum pressure under quench conditions (MPa)	120*
Materials	
Conductor	NbTi/Cu
Sheath	Type 304 St. Steel
Copper to superconductor ratio	7.5*
Dimensions	
Sheath outside dimensions (cm)	2.08×2.08
Sheath outside corner radius (cm)	0.673
Sheath thickness (cm)	0.165
Strands (#)	486
Strand diameter (mm)	0.7
Void fraction	0.32

* Estimated. Subject to change when detailed analysis and tests are performed. Stability margin is as defined in Reference 5.

4.3 Conductor Design Requirements Definition

A draft of the Design Requirements Definition for ICCS for large-scale MHD magnets is being prepared, covering the following categories:

Functional Requirements
System Interfaces
Design Criteria
Design Parameters (typical)

The completed draft Design Requirements Definition and related data will be issued as a separate report.

4.4 Analysis

Analysis has been accomplished in support of the magnet preconceptual design, the conductor design, and the conductor Design Requirements Definition. Subtasks include the following:

a. Electromagnetic Analysis

> Determination of fields and forces in the preconceptual design magnet, including maximum fields in winding, field profile along axis, and field variation across magnet bore. Determination of inductance and stored energy.

b. Thermodynamic Analysis

> Determination of requirements for conductor stability. Determination of thermal loads, refrigeration requirements, and temperature variations in magnet windings.

c. Quench Propagation Analysis

> Determination of conductor stability margin (minimum propagating zone) and quench temperature rise.

d. Pressure Dynamics Analysis

> Determination of maximum quench pressure.

e. Structural Analysis

> Verification of the conductor structural design with respect to sheath material and thickness, considering both the behavior of the conductor under magnetic forces and the interaction of the conductor, insulation, and supporting structure in the magnet.

f. Protection and System Analysis

> Determination of the ability of the conductor to withstand emergency discharge conditions typical of the magnet for which it is intended.

A separate report will be issued describing in more detail the analyses performed in support of magnet and conductor preconceptual design.

5.0 Future Technical Effort (Tasks I and II)

Future technical work planned includes the following items:

- Completion of detail design of conductor, including identification of means for providing extra copper required (separate copper strands vs. high-copper composite strands), final filament size, twist pitch, etc. (Task I)
- Update of conductor Design Requirements Definition as needed. (Task I)
- Development of experimental test plan (Task II).
- Continuing analysis in support of conductor design and test programs (Task II).

6.0 References

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