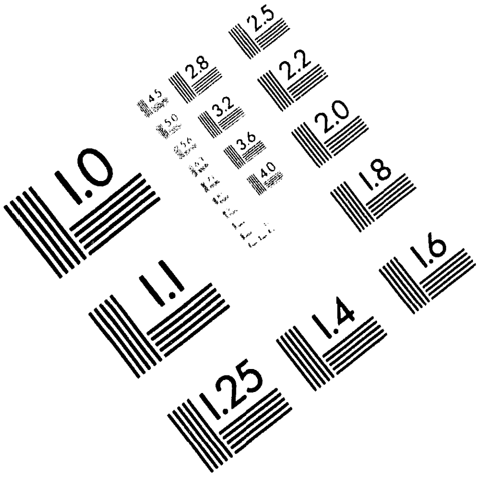
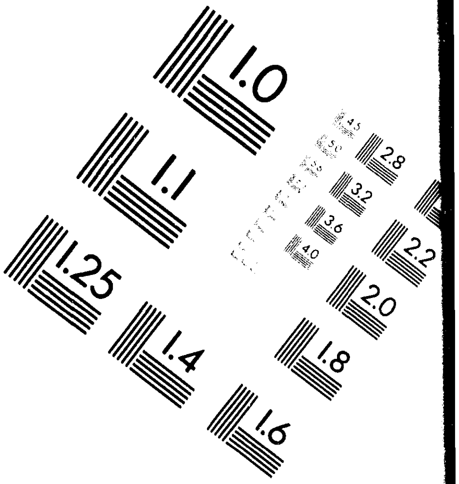


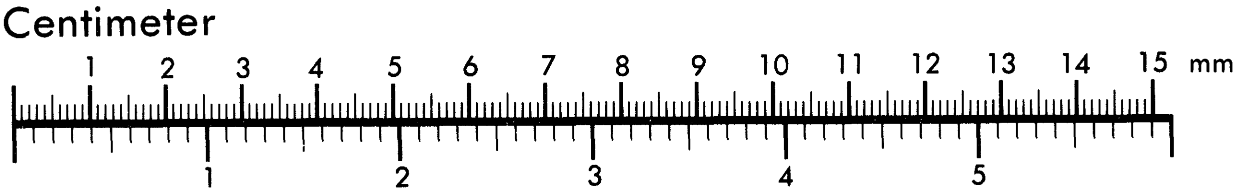
AIIM

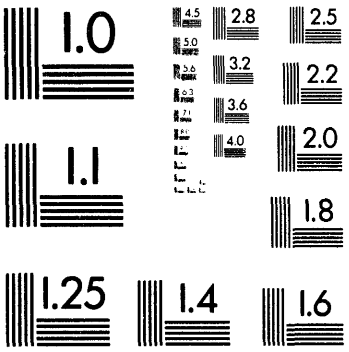
Association for Information and Image Management

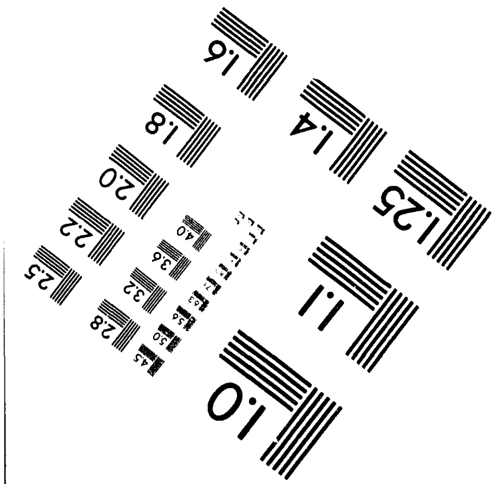
1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910

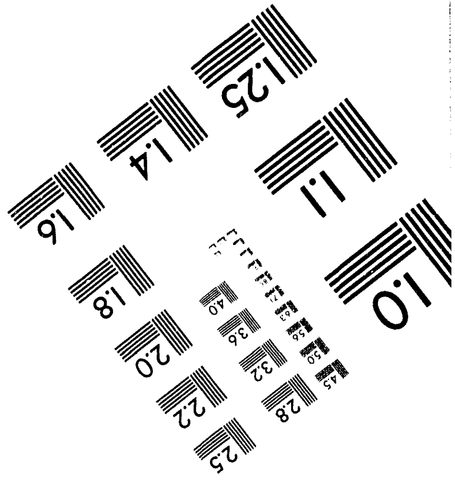
301/587-8202











MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 1

J-2
1

Final Report
Contract No. DE-FG22-90PC90350

DC CICC Retrofit Magnet Preliminary Design, Protection Analysis, and Software Development

Peter G. Marston

April 28 1994

Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02139

Final Report, Contract No. DE-FG22-90PC90350

DC CICC Retrofit Magnet Preliminary Design, Protection Analysis and Software Development

Peter G. Marston
MIT Plasma Fusion Center
Cambridge MA 02139

INTRODUCTION

The MIT Plasma Fusion Center magnet technology development effort, in support of the DOE/PETC MHD program, has culminated in two recent innovations which, when combined, will not only improve the reliability of commercial scale MHD magnets but will also reduce their cost by a factor of two. The first of these is a new form of Cable In Conduit Conductor (CICC) designed specifically for large scale DC superconducting magnets and the second is a highly efficient, quasi-momentless force containment structure which is made possible by the new conductor.

BACKGROUND

During the period from the mid-1970^{S} to the early 1980^{S} MIT created, implemented and managed a national program of magnet technology development for the US Dept. of Energy, MHD Division. The intent of the program was not only to develop and demonstrate superconducting technology but also to transfer that technology and the understanding of its large scale applications from the National Laboratories and Universities into the mainstream of US industry.

Encouraged by the federal promise to support the large scale demonstration of MHD as a commercial source of clean energy from coal, a number of major corporations invested in the creation of first class facilities and technical teams to enter these promising new markets. The university / industry collaboration provided the best of both in the marriage of advanced technology and large scale manufacturing. A number of interesting and useful concepts for structural designs, manufacturing and on site assembly techniques emerged and preliminary codes and standards for cryogenic materials and structures were developed. Three large SC magnet construction contracts were issued under the aegis of the DOE program to General Dynamics, General Electric and Argonne National Laboratory. Only the ANL magnet was funded through completion. Accomplishment of our own programmatic goals is best demonstrated by the fact that during this period the superconducting magnet, for a magnetohydrodynamic power plant, moved from consideration as the highest risk component to one of little concern. In addition the MIT / DOE program, together with the Fusion Energy sponsored Large Coil Program (LCP), very successfully developed a strong and capable national industrial capacity for the design and manufacture of superconducting magnets.

Federal support for energy technology was severely curtailed in the early 80'^{S} and all that survived of the MHD superconductivity R&D was a small conductor and magnet design study. This focused on an advanced "momentless" structural support concept identified as having significant potential for cost reduction. Cost effective implementation of this concept , however, required development of a new form of Cable in Conduit Conductor (CICC) capable of operating at high tensile and compressive stress.

TECHNOLOGY-DESIGN STATUS

Introduction

The generic shape and direction of the electromagnetic forces for a typical MHD magnet coil winding is shown in Fig. 1. Figure 2 shows a section of the coil with its support structure at the mid-axial, Y-Z plane.

The fundamental problems of design and manufacture, common to all magnets, include winding, insulation, cooling and structural support. Unique to superconducting magnets are problems of thermodynamic "stabilization", "quench" protection, behavior of materials at very low temperatures and the structural support of the very large electromagnetic forces associated with the high magnetic flux densities enabled by the technology. Considerations for commercial systems of the size and weight required for MHD must include cost, reliability, shipping, on site manufacturing and installation, development of design codes and standards and systems issues of flow train integration, channel change out etc.

The "prior art" magnets (including that completed and successfully tested at ANL) were based on conservative assumptions appropriate to the level of understanding and experience at the time of their design but not so with respect to the "present state of the art". This creates a situation wherein the only fully proven technology is obsolete! Manufacturers of large superconducting magnets may thus consider it conservative and expedient to use the obsolete (expensive but proven) technology if required to provide such devices for commercial use. In view of the fact that the magnet is the "cost driver" for the topping components this obviously has a negative impact on the commercial acceptance of MHD power generation.

The status of the new technology and the means by which it can affect a factor of two cost reduction for large scale MHD magnets are summarized below.

The Conductor and Coil Winding

The winding design must include consideration of the conductor, electrical insulation, cooling method, thermodynamic "stability", "quench" protection, structural support and the manufacturing, shipping and site assembly techniques.

The basic SC wire, an alloy of Niobium and Titanium coextruded (and twisted) as micron sized filaments in a copper matrix, has been readily available in a variety of forms and from a variety of worldwide vendors for several decades.

All of the early designs are wound from monolithic conductors supported by massive external girder structures and "pool cooled" in a bath of liquid helium. In these designs the conductor-to-conductor electrical insulation is such that approximately 50% of the conductor surface is directly exposed to the bath of liquid helium coolant in which the total coil winding is immersed. The result is excellent cooling and therefore a magnet that will recover (to a superconducting state) from virtually any thermal disturbance. This superior "stability" was considered of prime importance to reliability prior to the present understanding of the nature of the sources and sizes of thermal perturbations which might temporarily drive the superconductor into a "normal state". Inherent in these designs, however, is an insulation system having rather poor mechanical integrity and a "mushy" (having a low compressive modulus and exhibiting visco-elastic behavior) winding composite which is structurally difficult to support. These well cooled insulation configurations are also unable to support the large compressive stresses which accumulate at the winding median plane of large MHD magnets. The coil windings thus require mechanical regionalization to limit cumulative compressive stresses. The General Dynamics "Cask" Design proposed for the Corette Retrofit and the General Electric "Grooved Plate" design used in the magnet intended for the CDIF are typical examples of such regionalization.

The Support Structure

The prior art designs also relied on a massive system of girders and support links to contain both the large transverse loads in the central region and the complex end loads in the saddle regions of the windings. Large bending stresses in materials made brittle by their operation at very low temperatures require particular (and conservative) attention to issues of fatigue and crack propagation. These concerns relate to not only the support structure but also to the heavy walled helium pressure vessel required for the pool-cooled designs. The low temperature integrity of the heavy section welds in these structures is of particular concern. The result is a large, heavy and costly coil and force containment structure and consequently an overall magnet cryostat envelope which is almost ridiculously large with respect to the size of the warm aperture available for the MHD flow train.

Cable in Conduit Conductors / Momentless Support

Originally named Internally Cooled, Cabled Superconductors (ICCS) this configuration was invented at MIT twenty years ago and has since become the conductor of choice for virtually all large scale applications. Early in the MHD magnet technology development program it was recognized that this configuration, by virtue of its excellent mechanical properties, could enable the use of an advanced force containment structure in which bending moments could be eliminated allowing structural materials to be used in either pure compression or pure tension (their most efficient state). The cabled strands of these conductors and their helium coolant are contained inside the conduit. This allows full coverage of individual conductors with high mechanical strength electrical insulation and thus a winding composite having excellent mechanical strength and integrity. It also eliminates the need for the massive, heavy walled helium containment vessel.

Initially the focus of the CICC development for MHD was (more or less) the simple translation of the enormous Fusion funded effort on this technology from the Niobium Tin based conductors required for high field Tokamaks to the Niobium Titanium based conductors adequate for the more modest field strength requirements of MHD. It was, however, soon realized that the dynamic behavior and response requirements for magnets operating in the almost purely DC mode (such as MHD) are very different from those which must survive rapidly changing magnetic fields (such as in Tokamaks).

This recognition led to the development of a fundamentally new and different form of CICC as follows;

The conductor design for any superconducting magnet must satisfy requirements for thermodynamic stability and protection. "Stability" requires that, in the event of a thermal transient of adequate magnitude to drive some portion of the superconductor above its transition temperature (and into a "normal" state), local cooling will overcome heating and the conductor will recover to its superconducting state temperature. "Protection" requires that in the event that the normal region of the conductor does not recover and instead "quenches" (the normal region propagates throughout the winding), no portion of the conductor will be heated (via joule heating) above a "safe" temperature. For large magnets, which store large amounts of energy, a large fraction of normal "protection" metal (usually copper) is required in the composite conductor to reduce resistive heating (in the quenched region) and provide thermal mass to absorb the stored energy. In magnets subject to rapidly changing fields (and related AC heating) the most appropriate location for the protection material is in the strands of the cable located inside the conduit. This results is copper to superconductor ratios in the range of ten to twenty to one and the need for high purity, high process cost material. Good mechanical properties are furthermore inconsistent with the required electrical properties of this internal protection metal. For DC magnets, however, it is possible (and less costly) to put the normal, "protection" material outside of the conduit. The advantages of this are; it allows optimization of the conductor in the cable for stability (typically 3 to 4 : 1, Cu : SC ratio) and it allows the use of materials having comparatively poor electrical properties but good mechanical properties for the protection thermal mass. These combine to permit the design of a lower cost and extremely robust conductor which is particularly well suited for the rigors of on-site fabrication.

Comparative cross sections of the new and the old CICC are shown in Fig. 3. Instead of high purity copper, the new conductor will use high strength aluminum for its "protection" thermal mass. It is obvious by inspection that the new configuration has the good compressive and tensile properties required for effective implementation of the efficient "momentless" support concept.

In the conceptual design shown in Fig. 2 both bending and shear stresses in the support band and in the winding, though non-zero, have been reduced to very low values. The design is thus referred to as "quasi-momentless". This stress state is achieved via careful design of the outer contour of the coil winding such that the band which reacts the outward, transverse electromagnetic forces has the shape of a funicular curve (implying that, at all positions, the product of the local radial pressure and the local radius of curvature is constant). If these conditions are satisfied the support band will be in pure tension. They are very closely satisfied in the design shown. The radial pressure (from the band) is reacted by the coil winding. This has the effect of (approximately) doubling the total compressive stress at the median plane of the winding. Under these conditions he structural integrity of the original CICC (Fig. 2-b) was marginal even at retrofit scale. The new configuration (Fig. 2-a) is conservative at all anticipated commercial MHD magnet sizes. The aluminum sheath of the new conductor is adequately strong to support the axial (X directed) forces on the saddles. All that is required at the ends are simple gusseted plates to hold the saddle cross over regions apart.

The new concept has been analyzed in adequate detail to have a high degree of confidence in its predicted impact on weight and cost which, at retrofit scale, is as follows;

	Weight (tonnes)	Cost (k$)
Cask Design (Corrette Study)	320	45,500
Quasi-momentless (w/DC-CICC)	133	19,625

Potential for fail safe operation

In most designs, there is adequate thermal mass in the magnet winding to absorb the total stored energy in the magnetic field without overheating as long as that energy is reasonably uniformly distributed through the winding. The danger, in most designs, is that only a relatively small region of conductor becomes resistive, absorbs all the energy and overheats (quite possibly melts). Superconducting magnets thus require a dynamic protection system which can detect a small normal region in the conductor and activate switchgear which connects the coil to an outside resistor into which the stored energy is "dumped".

Insertion of an electrically insulating barrier between the cable and the surrounding conduit and/or the "protection" sheath has the effect of forcing very rapid propagation of the "normal front" in the event of a magnet quench. This rapidly induced, global quench effectively distributes the stored energy deposition and, although the magnet will require re-cooling, it will survive failure of the quench detection and energy dumping system. This performance has verified at POC scale in short length tests and analytically for full scale, long lengths.

SUMMARY

The MIT/PFC development, design and test effort has proven, to a high degree of confidence, the reality of a factor of (at least) two cost reduction for reliable, manufacturable, commercial scale, superconducting magnets for MHD power generation.

With a modest amount of additional analysis, test and large scale verification the "state of the art" of this new technology can be equivalent to that of the "prior (expensive) art". The new concepts will produce inherently robust and reliable magnets and the risks associated with their use are thus inherently reduced.

EPILOGUE

The collapse of the MHD program (and support for technology in general) is a tragedy of leadership which has committed to the trash heap billions of dollars of the efforts of many of this nations top scientific and technical talent. This MHD supported, conductor development, however, has applications in a broad variety of technologies including Fusion, SMES, High Energy and Nuclear Physics, MagLev and Ship Propulsion. It, at least, will survive as a commercially beneficial technology.

REFERENCES

Detailed descriptions and results of all analyses, designs and tests have been previously submitted. A list of the principal references and a detailed description of a retrofit scale magnet incorporating the above described advanced design concepts are attached hereto.

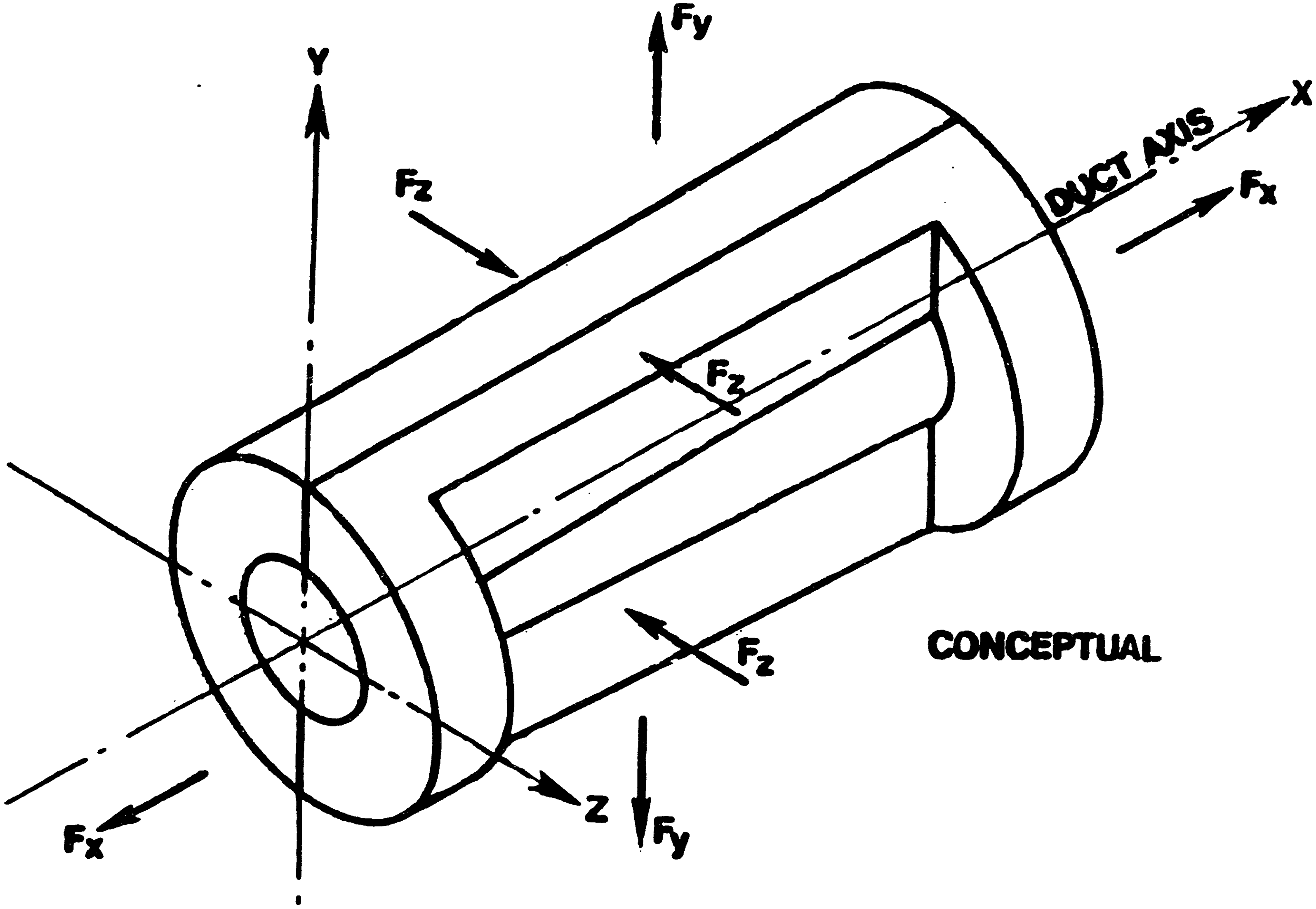
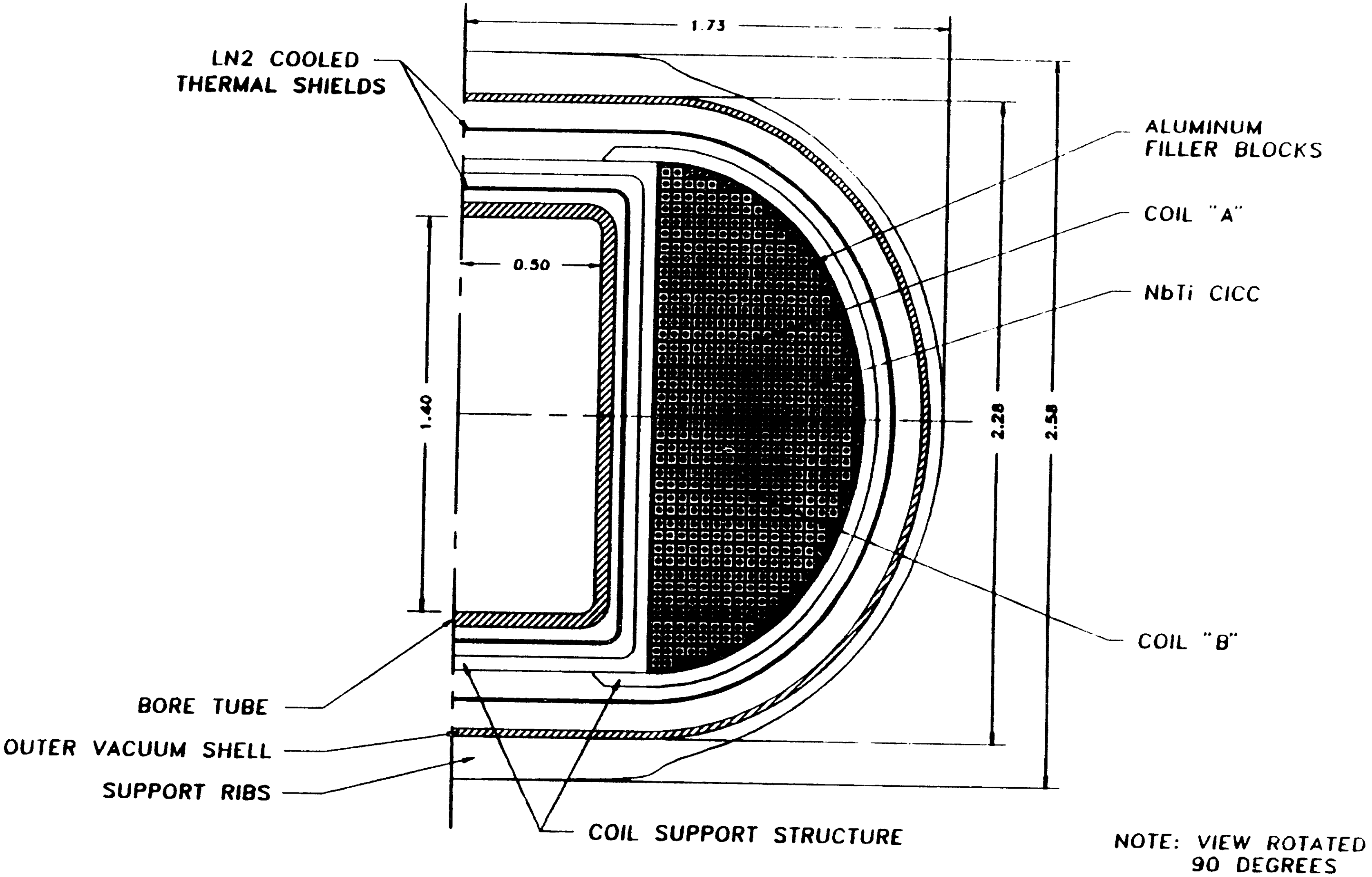


Figure 1. Forces on a circular saddle winding



HALF SECTION VIEW THRU AXIAL MID-PLANE

Figure 2

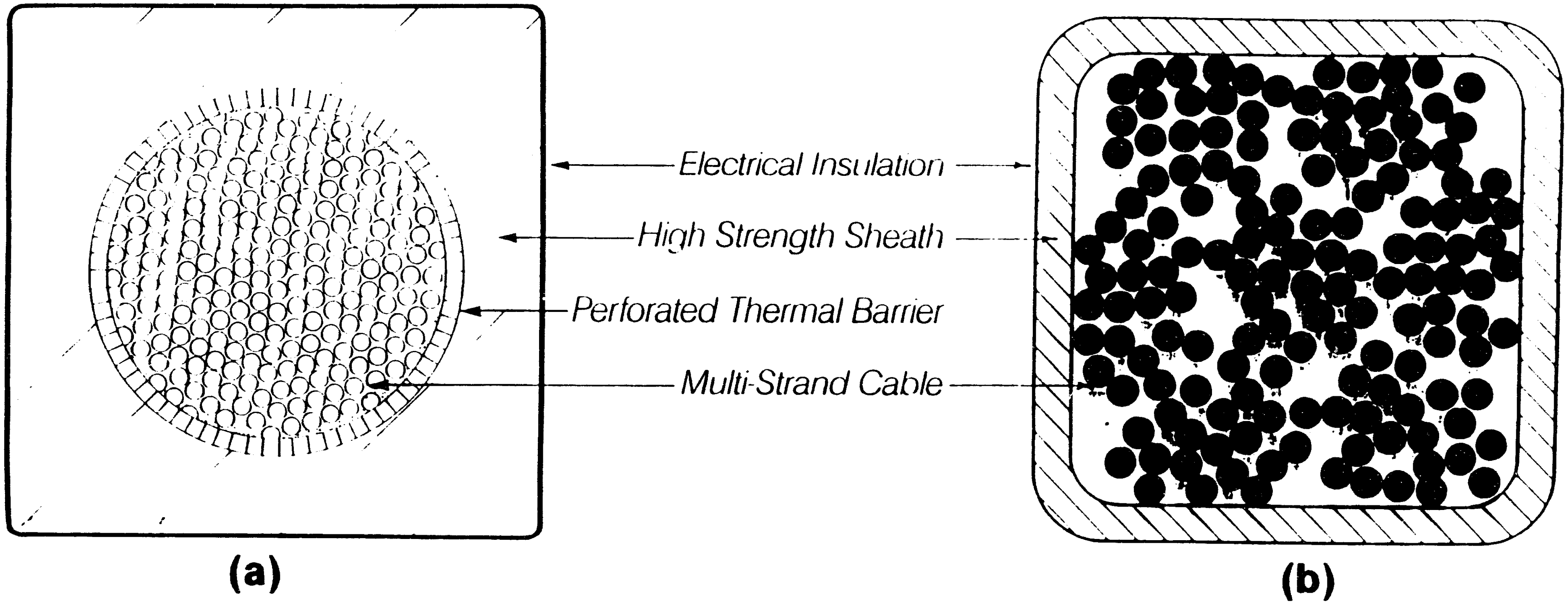


Figure 3. Cable-in-conduit conductors

Reports Prepared Under Contract No. DE-FG22-90PC90350
DC CICC Retrofit Magnet Preliminary Design, Protection Analysis and Software Development

1) PFC/RR-91-7, DC CICC Retrofit Magnet Preliminary Design, Protection Analysis and Software Development, P. G. Marston, J. Chen, J.R. Hale, A, M. Dawson, Feb. 1991.

2) PFC/RR-91-8, DC CICC Retrofit Magnet Preliminary Design, Protection Analysis and Software Development, J. H. Schultz, P.G. Marston, A.M. Dawson, April, 1991.

3) PFC/RR-91-10, DC CICC Retrofit Magnet Preliminary Design, Protection Analysis and Software Development, J. Chen, P. G. Marston, J. R. Hale, A. M. Dawson, May, 1991.

4) PFC/RR-91-17, DC CICC Retrofit Magnet Preliminary Design, Protection Analysis and Software Development, J. H. Schultz, P. G. Marston, J. R. Hale, A. M. Dawson, November 1991.

5) PFC/RR-91-18, DC CICC Retrofit Magnet Preliminary Design, Protection Analysis and Software Development,, P.G. Marston, J. R. Hale, A.M. Dawson, November 1991.

6) PFC/RR-92-2, DC CICC Retrofit Magnet Preliminary Design, Protection Analysis and Software Development, R. L. Myatt and P. G. Marston, February, 1992.

7) PFC/RR-92-8, DC CICC Retrofit Magnet Preliminary Design, Protection Analysis and Software Development, R. L. Myatt and P. G. Marston, May 1992.

8) PFC/RR-92-14, DC CICC Retrofit Magnet Preliminary Design, Protection Analysis and Software Development,, Final Progress Report, R. L. Myatt and P. G. Marston, October 1992.

9) P. G. Marston, J. R. Hale, A. M. Dawson, A. Zhukovsky, J. Chen, Design of a Retrofit Magnet Using Advanced Cable-in-conduit Conductor, *IEEE Trans. Mag.*, **28**:971, 1992.

10) P.G. Marston, J. Chen, A. M. Dawson, J. R. Hale, MHD "Retrofit" Magnet Using Quasi-Momentless Support, VIII.5.1, Proc. SEAM 29, 1991.

11) P. G. Marston, J. R. Hale, R. L. Myatt, A. M. Dawson, J. Chen, A Retrofit MHD Magnet Using CICC and a Quasimomentless Force Containment Structure, Abstract only, VII.1.1, Proc. SEAM 30, 1992.

reprint
removed
ds

DATE

FILMED

9/9/94

END