A Survey Of Magnet Experience Relevant To MHD

Author(s): J. M. Tarrh and P. G. Marston

Session Name: Magnets, Diffusers, and Diagnostics

SEAM: 23 (1985)

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

EDX Paper ID: 1100

Paper #15

A SURVEY OF MAGNET EXPERIENCE RELEVANT TO MHD

J. M. Tarrh and P. G. Marston

Massachusetts Institute of Technology
Plasma Fusion Center
Cambridge, Massachusetts 02139

INTRODUCTION

In the late 1960s and early 1970s, superconductivity on a large scale was first applied to bubble chamber magnets for high energy physics, with enormous success. The Argonne 12-foot bubble chamber magnet, shown in the photograph of Figure 1, was the first. Completed in 1968, it was an historic device. It "...demonstrated the feasibility of large stable magnets and of the associated cryogenic techniques and led the way to all other large scale applications."[1] These large bubble chamber magnets were not without their initial problems.[1,2] However, the initial problems were solved and, since then, they have provided well over a decade of reliable service. They therefore represent a very real "proof of principle" of the large scale application of superconductivity.

Since the mid-1970s, there have been several magnificent successes with large superconducting magnets. These demonstrate that the technology of superconductivity is basically well understood and that it therefore has the potential for being applied successfully to the MHD retrofit and beyond. However, over the same period there have been a larger number of serious failures that have had disastrous consequences. If a significant magnet failure were to occur in the MHD retrofit project, it would have the potential for seriously jeopardizing not only the retrofit itself, but the entire commercialization of MHD as well. This is true because the superconducting magnet will be not only the most costly single component in an MHD plant, it will also be the most time consuming and costly to repair.

In order to minimize the overall costs and risks associated with the retrofit, it is therefore necessary to critically examine the experience with large superconducting magnets and to evaluate carefully the relevance of that experience to MHD. This paper contains a brief survey of large magnet experience over the past decade, including the successes as well as the failures. For each case, the magnet system is briefly described, the specific experience is analyzed, and the direct relevance of that experience to the MHD program is presented. Magnets for MHD are considered first, followed by experience with magnets for fusion and high energy physics.

MAGNETS FOR MHD

Three MHD magnet systems are considered. The first is the superconducting magnet system (SCMS-2) which was designed and built at Argonne National Laboratory (ANL) and originally intended to be used in the Coal-Fired Flow Facility (CFFF) at the University of Tennessee Space Institute. The second is the superconducting magnet for the Component Development and Integration Facility (the CDIF/SM) which was designed by General Electric Company (GE) under subcontract to MIT. The third is the magnet for the High Performance Demonstration Experiment (HPDE) at the Arnold Engineering Development Center.

SCMS-2

The SCMS-2, shown in the drawing of Figure 2, is a 173 tonne circular saddle magnet without iron which is capable of generating a peak on-axis magnetic field of 6.0 T within a circular warm bore.[3] Over an effective field length of 3.0 m, the warm bore diverges from 0.85 m diameter at the inlet end to 1.0 m diameter at the outlet. At an operating current of 3.6 kA, the winding current density is 2.0 kA/cm^2, the peak magnetic field at the winding is 6.9 T, and the stored energy is 210 MJ. A photograph of the completed magnet is shown in Figure 3.

The SCMS-2 was completed and successfully tested to full field at ANL in 1981.[3] This magnet must therefore be considered an enormous success. However, this success must be substantially qualified, for many reasons.

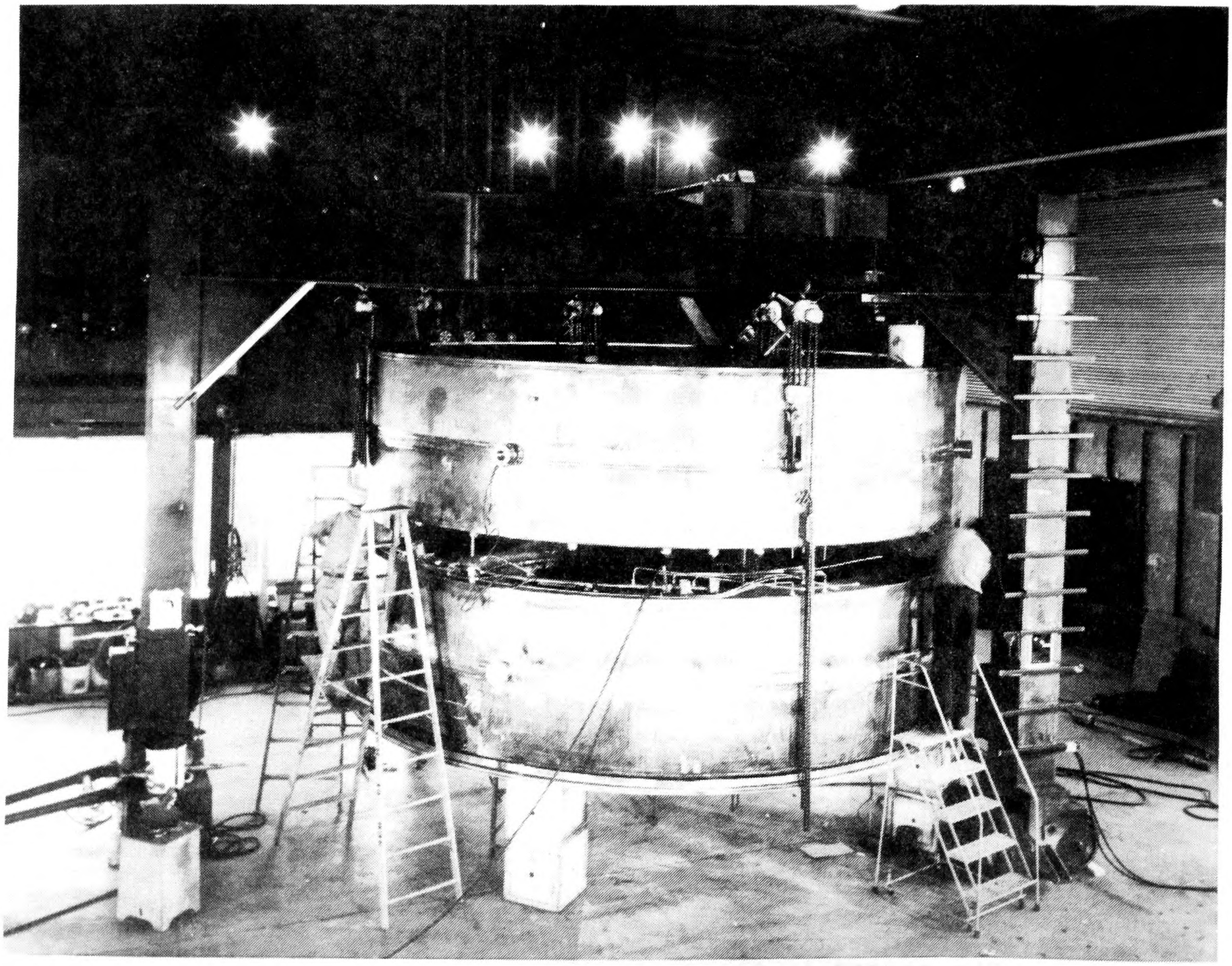


Figure 1 Final assembly of the coils and cryostat for the Argonne 12-foot bubble chamber magnet. With an inner diameter of 4.8 m, this assembly was installed in a 1500 tonne iron return frame to generate a central magnetic field of 1.8 T.

Most importantly, the magnet has undergone only very limited testing. There is essentially no operational experience with the magnet and the reliability of this particular design therefore remains unproven. As with many large superconducting magnets, large movements of the coil windings can occur relative to their supporting structures when the magnet is cycled. This design, which has no substructure to accumulate the local magnetic forces on the conductors, and then transmit these accumulated forces to the superstructure, may therefore be particularly susceptible to wear and subsequent damage of the electrical insulation.

Although many design aspects of the SCMS-2 were scaled from the very successful U-25B magnet, which was also built by ANL and installed in the Soviet Institute for High Temperatures in 1977, the basic structural support scheme for the windings is quite different and thus does not have the same long duration proof.[3,4] Neither design is readily extrapolable to retrofit scale, nor would field construction of such designs be feasible. The design also benefited from the use of readily available low current conductor, which was a practical choice for a magnet of that scale but would be unsuitable for the retrofit and larger scale systems. These factors further qualify the success of the SCMS-2. In addition, it must be noted that this magnet was designed, built, and tested within a very large and experienced national laboratory rather than in an industrial environment, where a retrofit magnet would be built. The success of the project was also strongly dependent on the experience, talent, and dedicated effort of a very few key individuals within that laboratory.

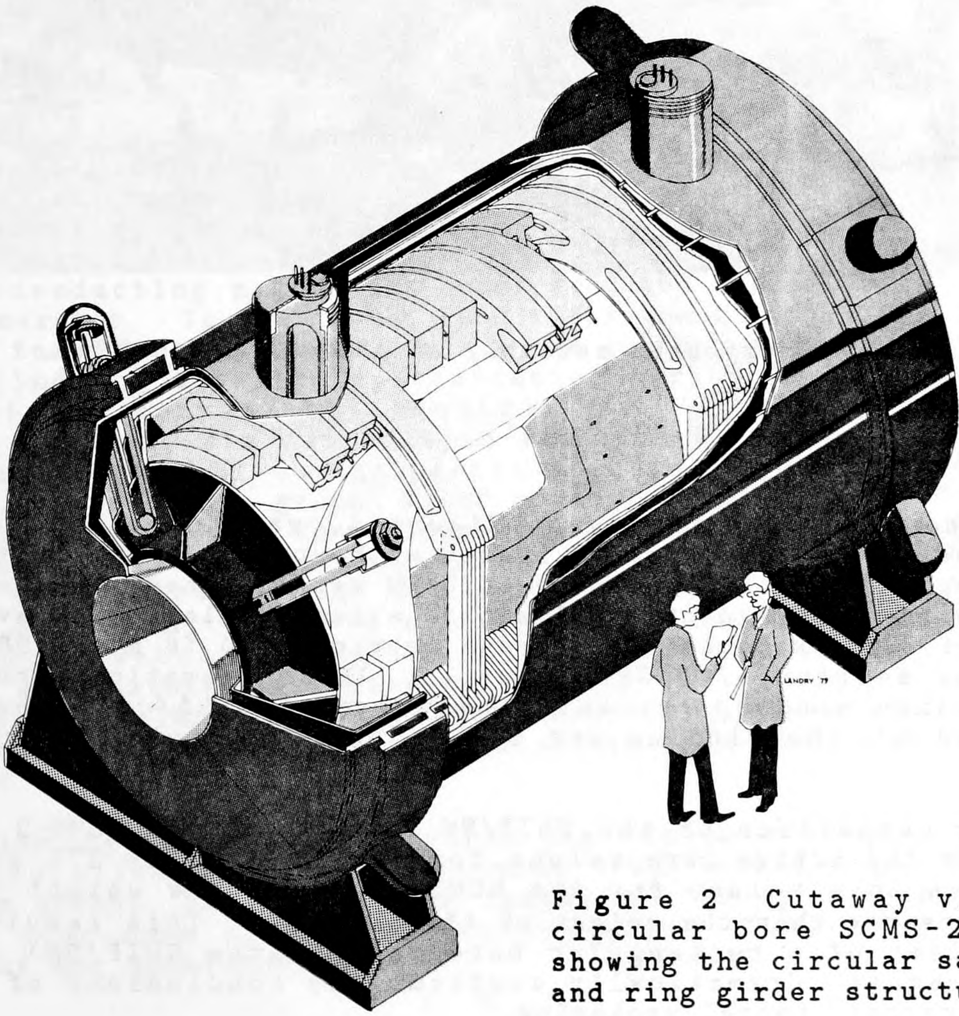


Figure 2 Cutaway view of the circular bore SCMS-2 assembly showing the circular saddle coils and ring girder structure.

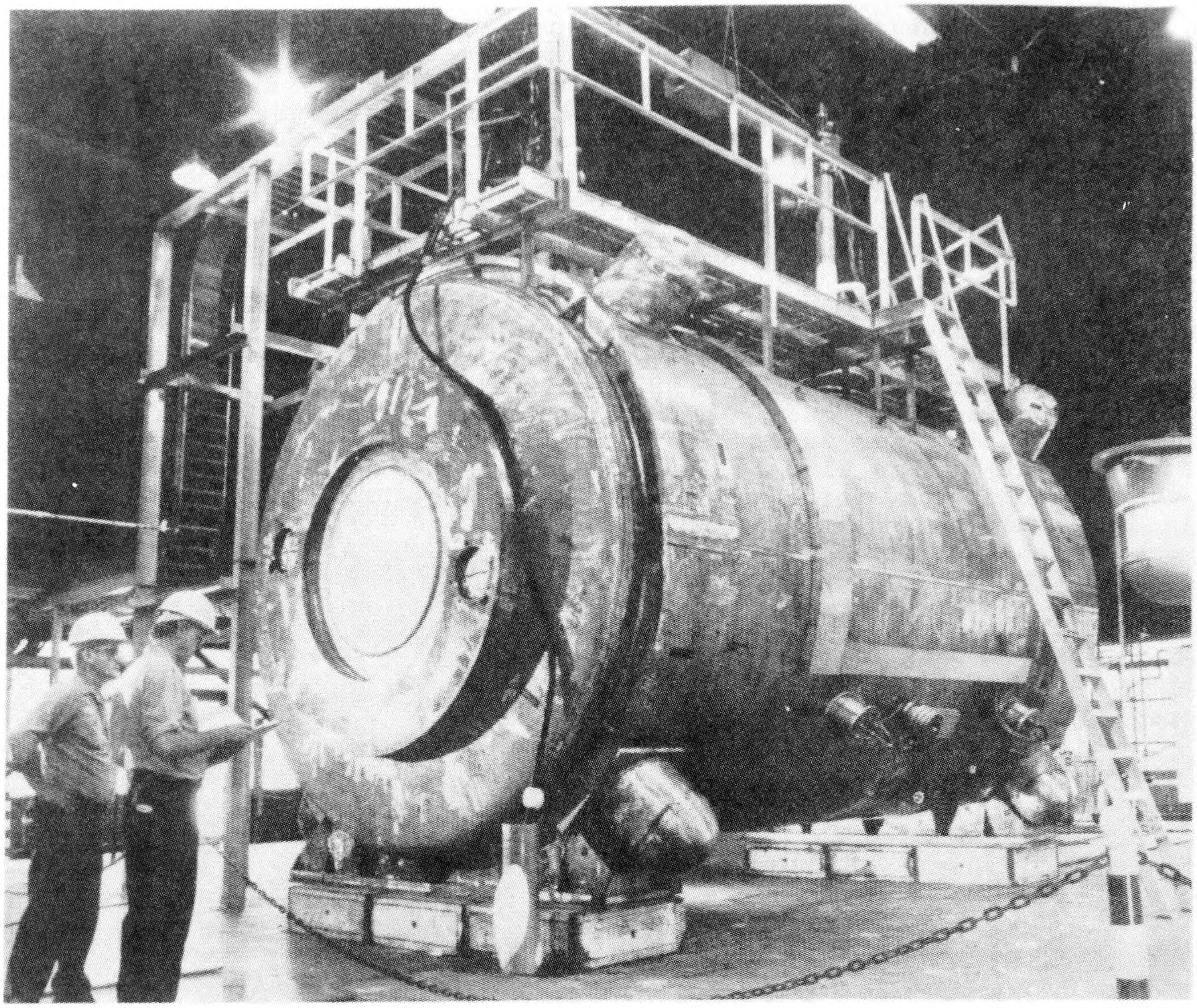


Figure 3 Final cryostat assembly at ANL for the SCMS-2.

CDIF/SM

The CDIF/SM, shown in the drawing of Figure 4, was to be a 144 tonne rectangular saddle superconducting magnet without iron, similar in size and field strength to the SCMS-2. The CDIF/SM was designed to generate a peak on-axis magnetic field of 6.0 T within a rectangular bore having an active length of 3.0 m with an inlet cross section of 0.78 m × 0.98 m and an outlet cross section of 0.98 m square. At an operating current of 6.1 kA, the design winding current density was 1.9 kA/cm^2, the peak magnetic field at the winding was 6.9 T, and the stored energy was 240 MJ.

An interesting comparison of the CDIF/SM design with the SCMS-2 can be made. Note that the active bore volume for the CDIF/SM is 27% greater than the active bore volume for the SCMS-2, while the weight of the SCMS-2 is 20% greater than the weight of the CDIF/SM. This result, due to the comparison of a rectangular bore magnet (the CDIF/SM) with a circular bore magnet, dramatically confirms the conclusions of other studies of MHD magnet/channel packaging.[5]

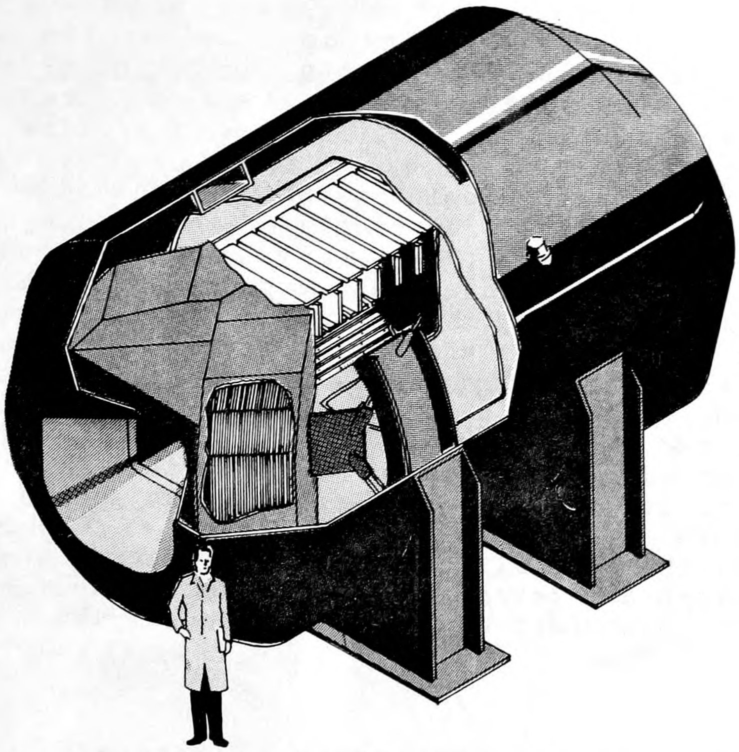


Figure 4 Cutaway view of the rectangular saddle CDIF/SM assembly.

Rather than using its expertise to design and build the CDIF/SM in house, MIT chose to procure the magnet on a competitive basis from industry. Such competitive procurements were a major part of the overall MHD Magnet Program strategy, to develop the industrial base needed for commercial-scale MHD magnet fabrication.[6] It is worth noting that, at that time, the superconducting magnet was considered the highest risk component of an MHD generator. To select the vendor for the CDIF/SM, MIT undertook a lengthy, formal procurement process. A request for proposal was issued which included a detailed specification having proper and adequate technical and contractual requirements. Adequate competition was obtained; in fact, the competition was fierce. Electrical equipment manufacturers as well as aggressive aerospace companies saw this as a chance to get in on the ground floor of commercial MHD magnet design and construction. To win, they teamed with small high-technology companies where the expertise was available at that time outside of the large national laboratories. The top proposals were therefore of very high quality. A substantial effort was expended in evaluating the proposals thoroughly. Detailed evaluation criteria and a numerical scoring procedure were established prior to issuing the request for proposals, and a source evaluation board with supporting advisory committees of experts was established. A major subcontract was thus awarded to GE in early 1978.

Notwithstanding the care with which the vendor was selected (and the evident qualifications of the winning team) and a vigorous technical monitoring effort, the project was characterized by continued cost and schedule over-runs of colossal proportions. In January 1983 the GE subcontract was terminated.

Obviously, there were many important lessons learned from this experience. Perhaps most important is recognition of the need to have both the industrial base and the manufacturing technology that will be required for the retrofit fully developed when it is needed. This is true for many elements of the magnet construction, but it is particularly true of the conductor. While it is generally agreed that the technology of copper-stabilized niobium-titanium superconductors is well understood, this area nevertheless represents one of the major stumbling blocks on the path to success for many large magnet projects. Historically, major difficulties have been experienced with the reliable manufacture of conductors which are required to carry currents significantly greater than that of the "prior art." This was certainly true for the CDIF/SM. With a current level of only 6.1 kA, conductor manufacture was a significant source of technical difficulties, overall schedule slip, and total cost growth. As the size of the magnet increases, the stored energy increases, and safety and protection considerations necessarily drive the required current levels to 20 kA and beyond. If performance and reliable manufacture of the high current conductor required for the retrofit can not be readily demonstrated, then the risks associated with the retrofit will be unacceptably high. At the present time, such a high current conductor does not exist.

HPDE Magnet

The HPDE magnet, shown in the photograph of Figure 5, was a large, 643 tonne iron-bound copper magnet designed to operate in either of two modes: (1) as a 3.7 T continuous water-cooled magnet, or (2) as a 6 T long-pulse nitrogen-precooled cryogenic magnet. In either mode, coolant would flow through conventional hollow copper conductor windings. While not superconducting, the HPDE represented a premier experimental facility which has provided an assortment of valuable lessons and is therefore included in this survey. The bore of the magnet was 0.89 m × 0.71 m at the inlet, 1.40 m × 1.17 m at the outlet, with an active length of 7.0 m. A unique force containment structure (FCS) was designed for the magnet. An aluminum alloy (2219) was selected on the basis of thermal considerations (77 K to 350 K operating temperature range; coefficient of thermal expansion permitting dimensional matching to the coil) and cost. A perspective view of the magnet in an assembled configuration is shown in Figure 6. Figure 7 contains an expanded view of the FCS. These figures provide an indication of the complexity of the FCS, which was assembled using a system of high strength keys and bolts.

In late 1982 the magnet suffered a catastrophic structural failure, which led to brittle-fracture failures in most of the structural components, significant displacements (on the order of a meter) of some of the magnet iron frame components, and similar deformation of the winding with some conductor fracture. The magnet had never been operated beyond 4.2 T, which is well below its full design conditions. The failure occurred at a peak field of 4.1 T.

After the failure, several investigations were performed to determine its cause.[7,8] The original FCS design analyses had identified multiple load paths for support of the total longitudinal forces. The effects of tolerances on the interactions among FCS components increased the complexity of the structural analysis. The chosen structural material was brittle at low temperatures. However, these factors merely contributed to the failure; they were not its cause. The design was conservative with respect to support of the longitudinal loads, but the

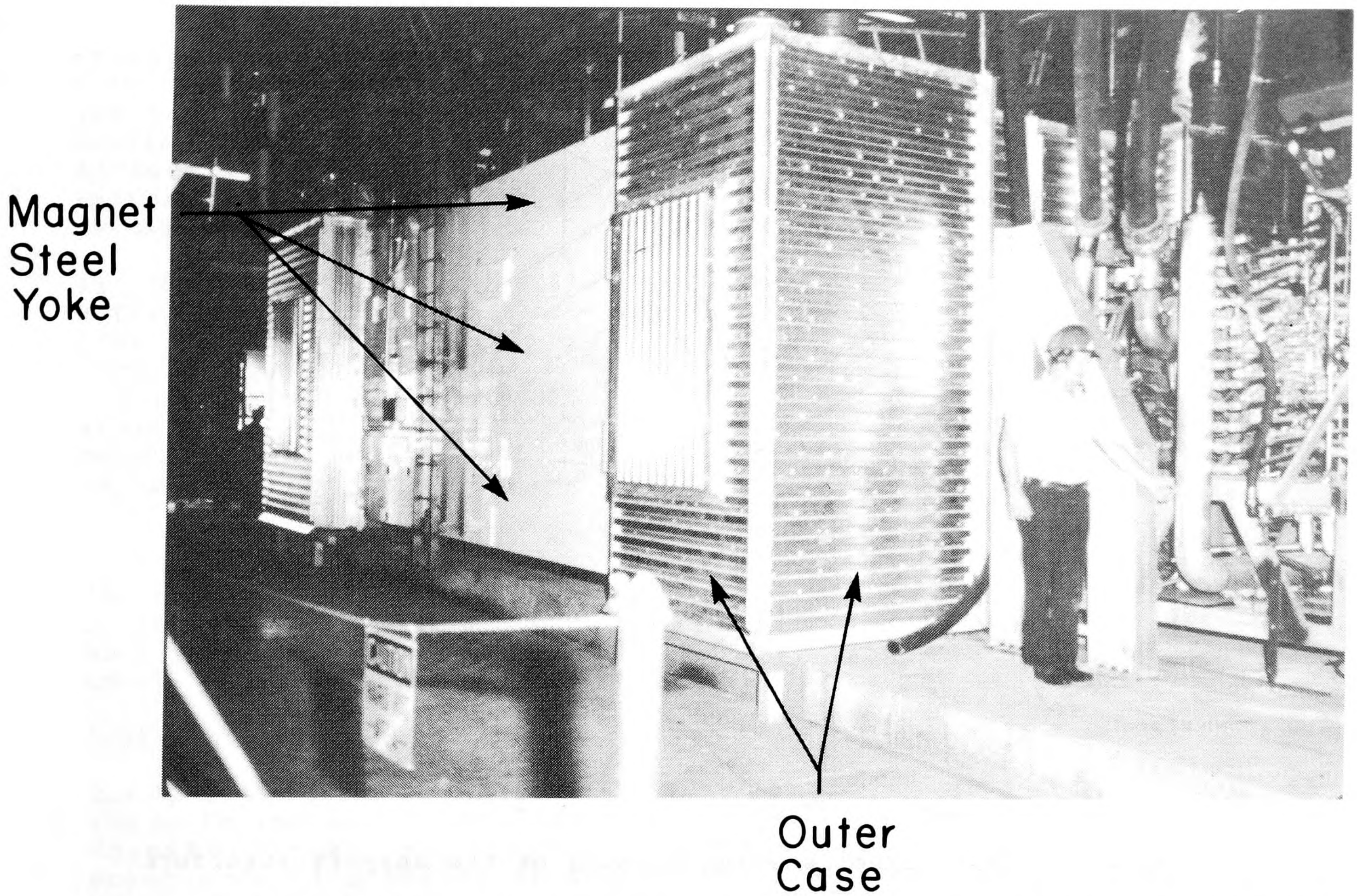


Figure 5 Overall view of the assembled HPDE magnet showing the outer thermal enclosure needed for cryogenic operation.

effects of deflections due to the (comparatively small) transverse loads (in the saddle region) on the longitudinal force support elements were overlooked, resulting in local stresses which exceeded the ultimate strength of the aluminum. The magnet thus failed as a result of design defects that were not detected during the FCS design analyses.

This failure was distressing not only because of its magnitude, cost, and impact on a critical test program, but also because of the care with which the original design and construction had been managed and the technical work performed. Two independent stress analyses were completed, work was regularly reviewed by panels of experts, and more than the usual attention was given to instrumenting the magnet due to concerns over stresses in the FCS. After two years of operation at field strengths up to 4 T, a review of strain gauge data concluded that the FCS was conservatively safe for 6 T operation. Although the design flaw was apparent (after considerable inspection and analysis), to suggest that in this case the designers were not competent or that the project did not proceed in a careful and cautious manner would be unfair to the project staff and management. Furthermore, it would obviate the impact of an important lesson to be learned which is that mistakes can be made, even in well managed, competently staffed programs.

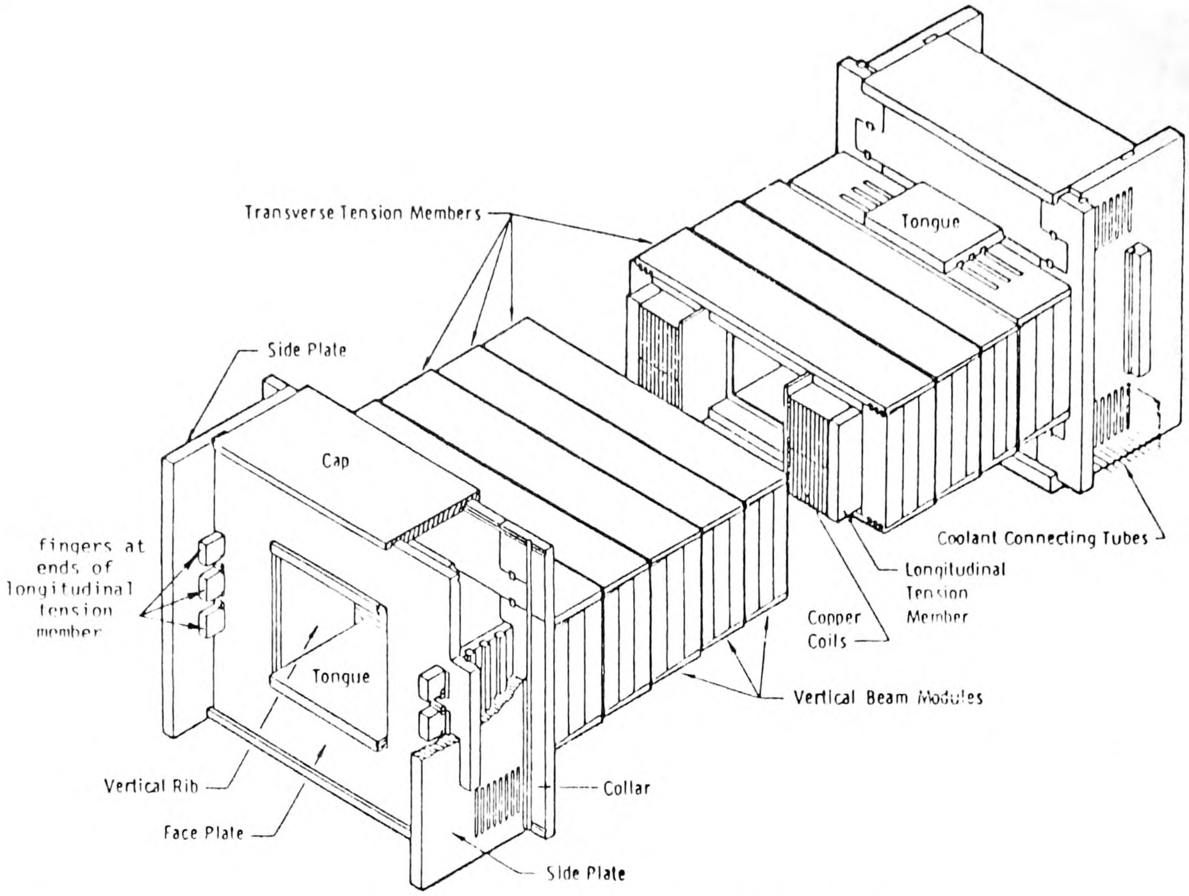


Figure 6 Assembled HPDE magnet showing details of the support structure.

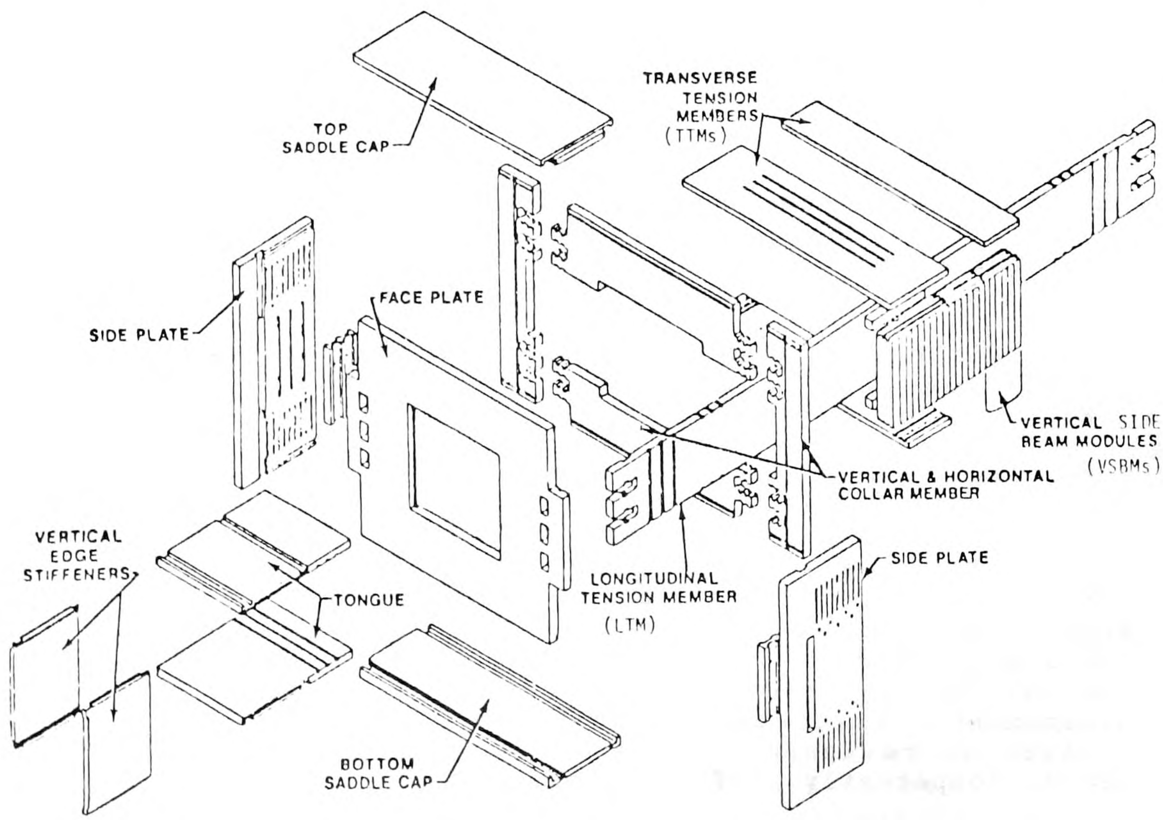


Figure 7 Expanded view of the HPDE magnet force containment structure.

Perhaps the most significant lesson to be learned from this failure is also the simplest: the importance of the magnet to the facility. After the failure, the structure was considered beyond repair. Rework to a conventional magnet limited to 4 T was seriously evaluated but ultimately determined to be beyond the means of an already financially constrained program. Despite the importance and previous success of the HPDE, it was terminated.

An additional lesson to be learned from this failure is the enormous difference in the cost/risk assessment of the magnet as compared to other flow train components. Typically, magnets either work, or they do not work. There is usually no opportunity for operation at reduced output or reduced life, or for modest turn-around time and cost for repair or replacement. If the first commercial MHD magnet does not work, a several hundred million dollar project, a billion dollar total investment, and a valuable energy technology will be in serious jeopardy.

MAGNETS FOR FUSION

Two fusion magnet systems are considered. The first is the yin-yang pair of coils for the Mirror Fusion Test Facility (MFTF) at Lawrence Livermore National Laboratory (LLNL). The second is the Large Coil Program (LCP) at Oak Ridge National Laboratory (ORNL).

MFTF Yin-Yang Magnet

The MFTF yin-yang magnet consists of a pair of crescent shaped coils, as shown in the sketch of Figure 8 and the photograph of Figure 9, which together weigh 340 tonnes. These coils comprise the largest superconducting magnet in the fusion field. At an operating current level of 5.8 kA, the coils generate a peak on-axis magnetic field of 4.3 T, a peak field at the winding of 7.7 T, and a stored energy of 410 MJ.

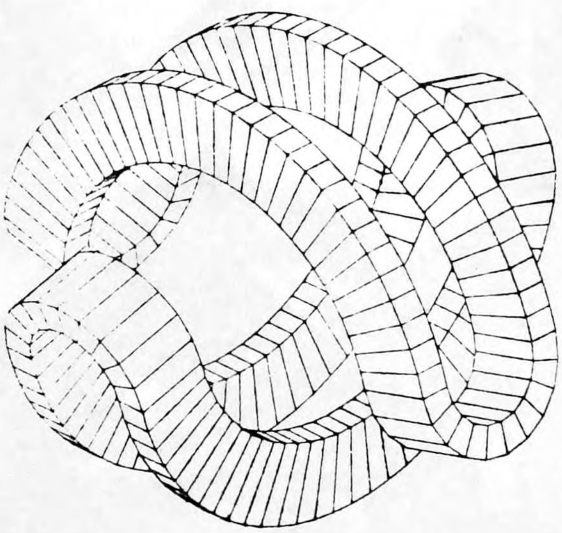


Figure 8 Conceptual sketch of the crescent-shaped MFTF yin-yang coils.

The MFTF yin-yang magnet was completed and successfully tested to full design conditions in early 1982. This magnet has been an enormous success. While MFTF was originally conceived to consist of just these two coils, the experiment has evolved into a tandem mirror called MFTF-B, which is now an axicell design consisting of 26 large superconducting coils including 2 sets of yin-yang pairs, 4 transition coils, 6 axicell coils, and 12 central cell solenoidal coils.[9,10] This configuration, which is now under construction, is shown in Figure 10.

There is no question that this project has been eminently successful. However, its success must be qualified, just as the success of the SCMS-2 must be qualified. The MFTF yin-yang magnet was designed, built, and tested within LLNL, which is a large, experienced national laboratory. The success of the project was dependent on a few key individuals within that laboratory. To date, the magnet has undergone only very limited testing, and its reliability therefore remains to be proven. All of these qualifications are the same as those for the SCMS-2. In addition, it should be noted that after two years of conductor development, LLNL still had difficulty with the procurement of their 5.8 kA niobium titanium superconductor.

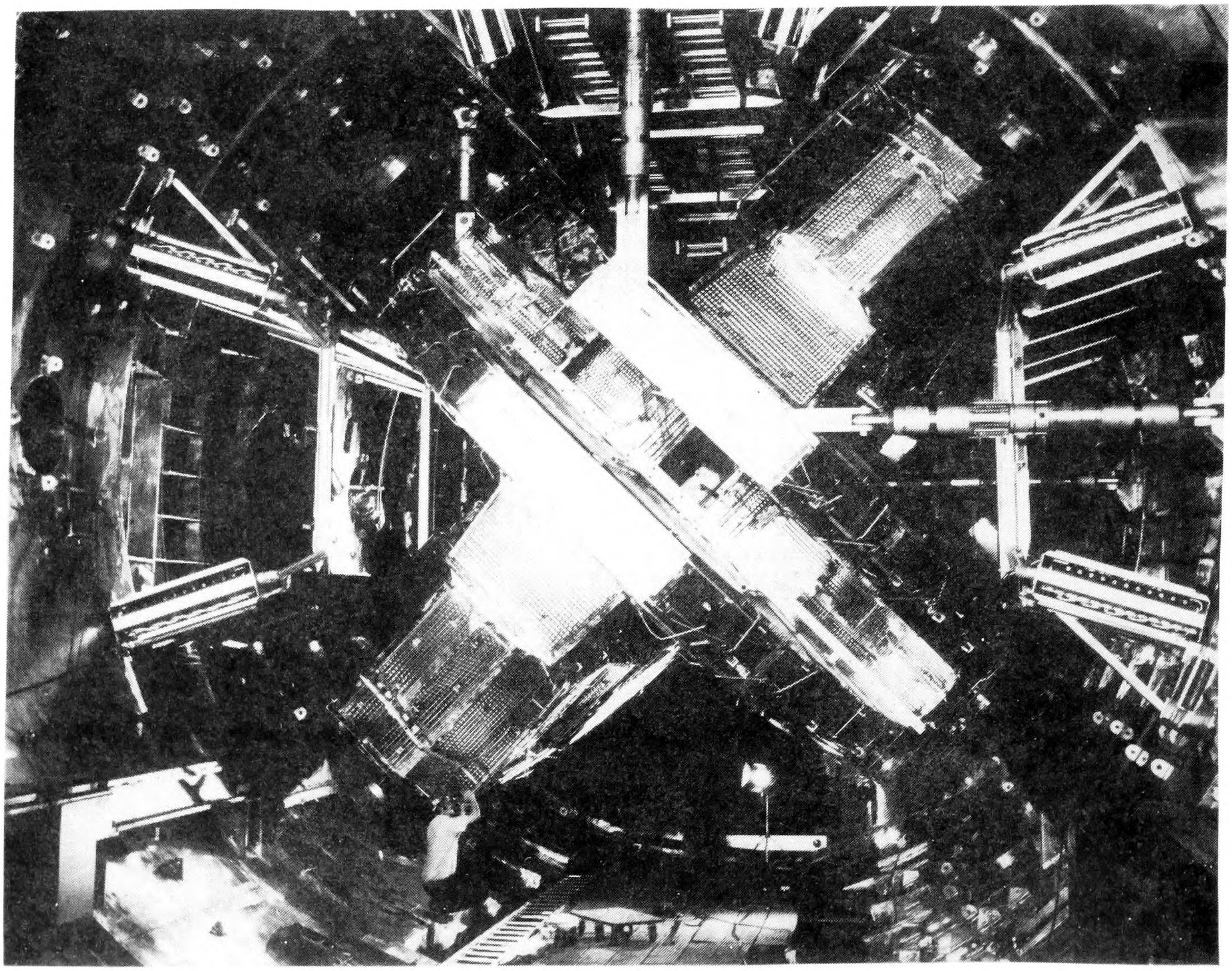


Figure 9 Installation of the MFTF yin-yang coils in preparation for testing to full field.

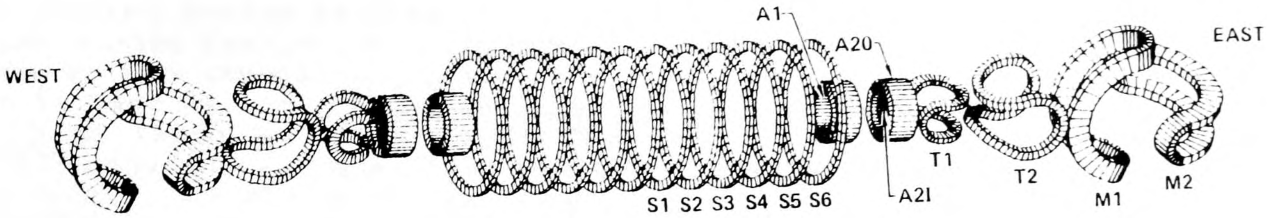


Figure 10 Conceptual sketch of the MFTF-B tandem mirror with an axicell magnetic configuration.

LCP

Within this survey, LCP is the only project that was conceived primarily as a means to develop the technology and the industrial base required to design and build large superconducting coils. Whereas all of the other magnet systems described were specifically tied to the requirements of the experiments for which they were intended, the LCP requirements were established to develop superconducting toroidal field (TF) coils for tokamak fusion reactors.[9] The procurement specifications prepared by ORNL therefore define the performance requirements and specify the interfaces and dimensional constraints, but deliberately leave the design and fabrication concepts up to the vendors. To have alternate concepts is desirable for many reasons: No proven design existed at that time; each concept has its own problems and uncertainties; industrial competition is encouraged; the impact of unanticipated major difficulties in any one concept is minimized; and the potential for enhanced performance can be more thoroughly explored. The coils are required to have a 2.5 m × 3.5 m D-shaped bore, be capable of a peak magnetic field of 8 T when operated in a toroidal array of six coils, and have a design current level of from 10 kA to 20 kA. The coil configuration is indicated in the sketch of Figure 11, which shows schematically the coil interface specifications. Figure 12 is a sketch of the ORNL facility, called the Large Coil Test Facility (LCTF), for testing the large coils. The pulse coils shown in this figure will provide a transient magnetic field for testing the large coils under conditions similar to an operating tokamak. With six coils in place, the test stand will weigh 400 tonnes and, at full field, the system will contain 700 MJ of stored energy, readily surpassing the MFTF yin-yang magnet.

The procurement of the LCP coils immediately preceded the procurement of the CDIF/SM, with results which were similar in many ways. Many of the same companies responded, formed similar teams with small high-technology companies, expended the same levels of effort, and submitted proposals of the same high quality. LCP was essentially the first opportunity for significant industrial involvement in the design and manufacture of large superconducting magnets, and the industrial response was intensely competitive. In early 1977, ORNL issued subcontracts for the design and construction of one coil each to General Dynamics/Convair (GD/C) in San Diego, CA, to the General Electric Company (GE) in Schenectady, NY, and to Westinghouse Electric Corporation in East Pittsburgh, PA.

At the time that these subcontracts were awarded, the potential for an international collaboration on LCP was recognized. By the end of 1977 a formal agreement called the Large Coil Task (LCT) was in place. LCT defines a broad program of R&D on superconducting magnets for fusion, wherein Japan, Switzerland, and EURATOM provide one test coil each while

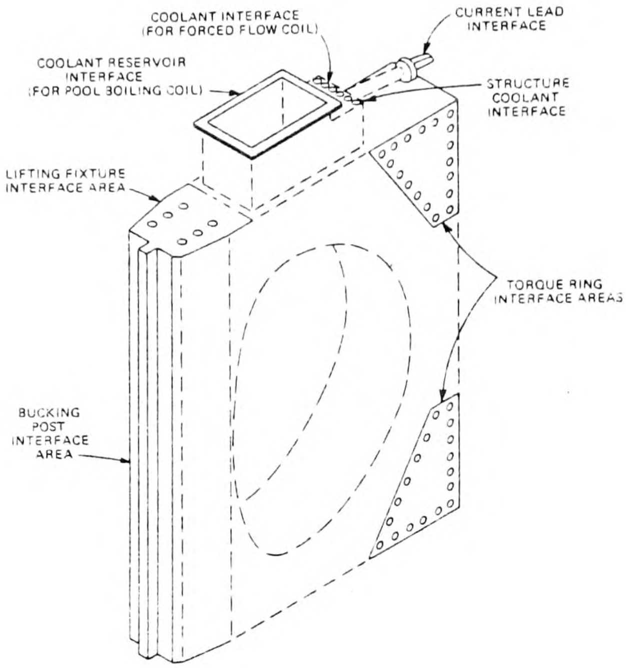


Figure 11 Schematic illustration of LCP coil interface specifications.

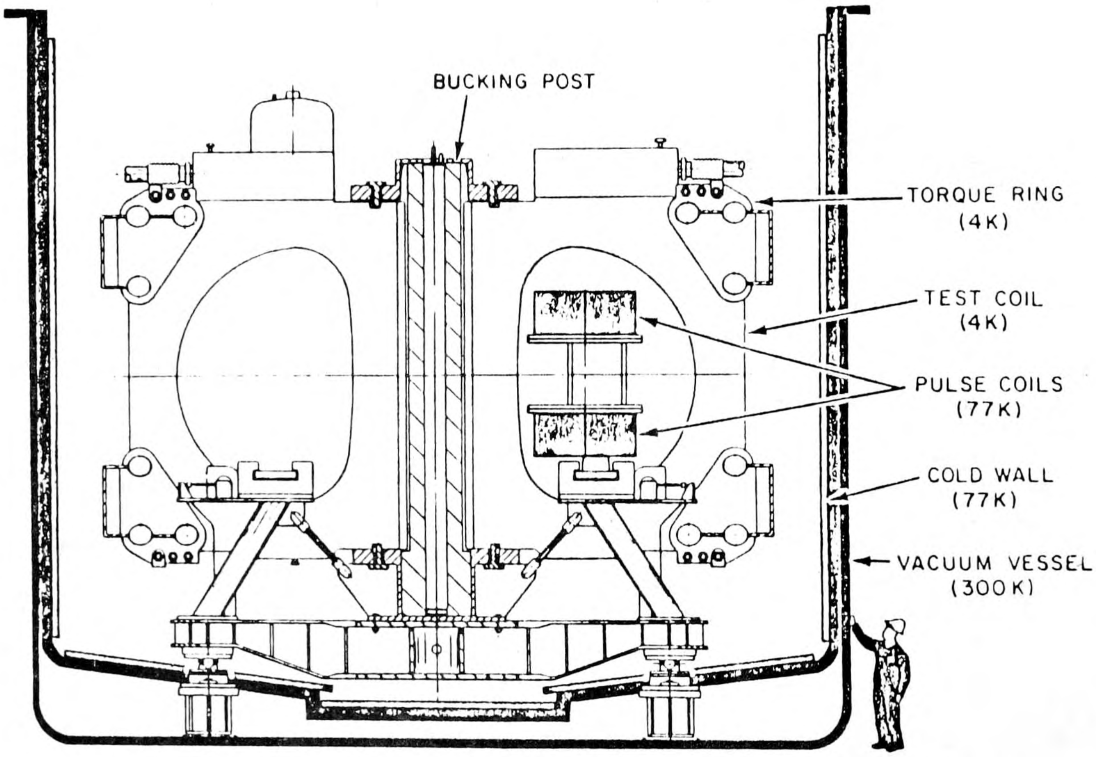
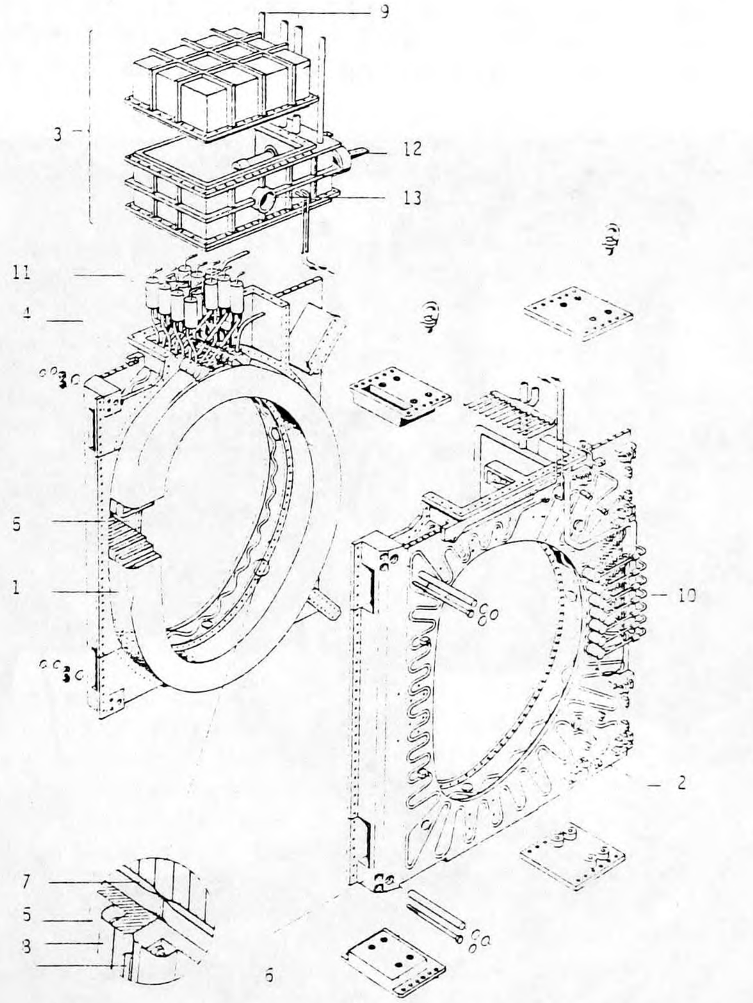


Figure 12 Sketch of the LCTF showing the large test coils in place and the pulse coils for simulating tokamak conditions, as well as various structural, vacuum, and cryogenic components.

the United States provides the LCTF and three test coils. In Japan, the Japan Atomic Energy Research Institute (JAERI) manages the project with Hitachi Ltd manufacturing the coil. In Switzerland, the Swiss Institute for Nuclear Research (SIN) manages the project with Brown, Boveri and Company (BBC) an industrial partner with the Swiss government. The EURATOM project is managed by Kernforschungszentrum Karlsruhe (KfK) with Siemens AG as the principal industrial contractor. A drawing of the EURATOM coil is shown in Figure 13.

For those of us with a long-term interest in large superconducting magnets, LCP has provided a wealth of data. The first coil to be completed was the Japanese coil, which was delivered to JAERI in October 1981, tested to full current at JAERI during May and June 1982, then delivered to ORNL in November 1982.[11] The second coil to be completed was the GD/C coil, which was delivered to ORNL in June 1983.[12] The Swiss coil was delivered to ORNL in February 1984.[13] The EURATOM coil was delivered to KfK in November 1983, testing to full current was completed in May 1984, and the coil was delivered to ORNL in November 1984.[14]



1. Winding pack (7 double pancakes)
2. Coil case with cooling channels
3. Coil dome
4. Outer ring
5. Inner ring
6. Front part (forging)
7. Stainless steel bladders
8. Seal welds
9. Helium ports
10. Helium inlet headers
11. Helium outlet headers and conductor splices
12. Current lead
13. Instrumentation port

Figure 13 Expanded view of the EURATOM test coil for LCT.

The GE coil was never completed by GE. ORNL's experience was essentially identical to our own on the CDIF/SM: There were large cost overruns and schedule slips, and unresolved technical problems. ORNL terminated the GE subcontract and had the coil delivered to ORNL for completion.

Figure 14 is a photograph of the GD/C coil being installed in the LCTF. Although GD/C ultimately delivered an acceptable coil, they experienced very similar technical difficulties to those of GE.[15-18] Schedule performance is also an important issue. At the end of Phase I, the overall GD/C program was to require 33 months, with delivery of the coil to ORNL scheduled for February 1, 1980. The June 1983 actual delivery represents an overall program schedule of 75 months, counting the time required for work on the coil that was deferred until after delivery.[12] While the lack of adequate funding is a typical contractor's complaint which is offered as justification for schedule slip, funding problems are frequently caused when a contractor has unanticipated technical difficulties and can not complete a task within the funds that it estimated would be needed. However, in defense of the LCP subcontractors, there were indeed legitimate schedule slippages due to inadequate funding. The marked difference in contract and project performance between adequately and continuously funded programs versus those with yearly and changing funding allocations has been demonstrated by GD/C.[16]

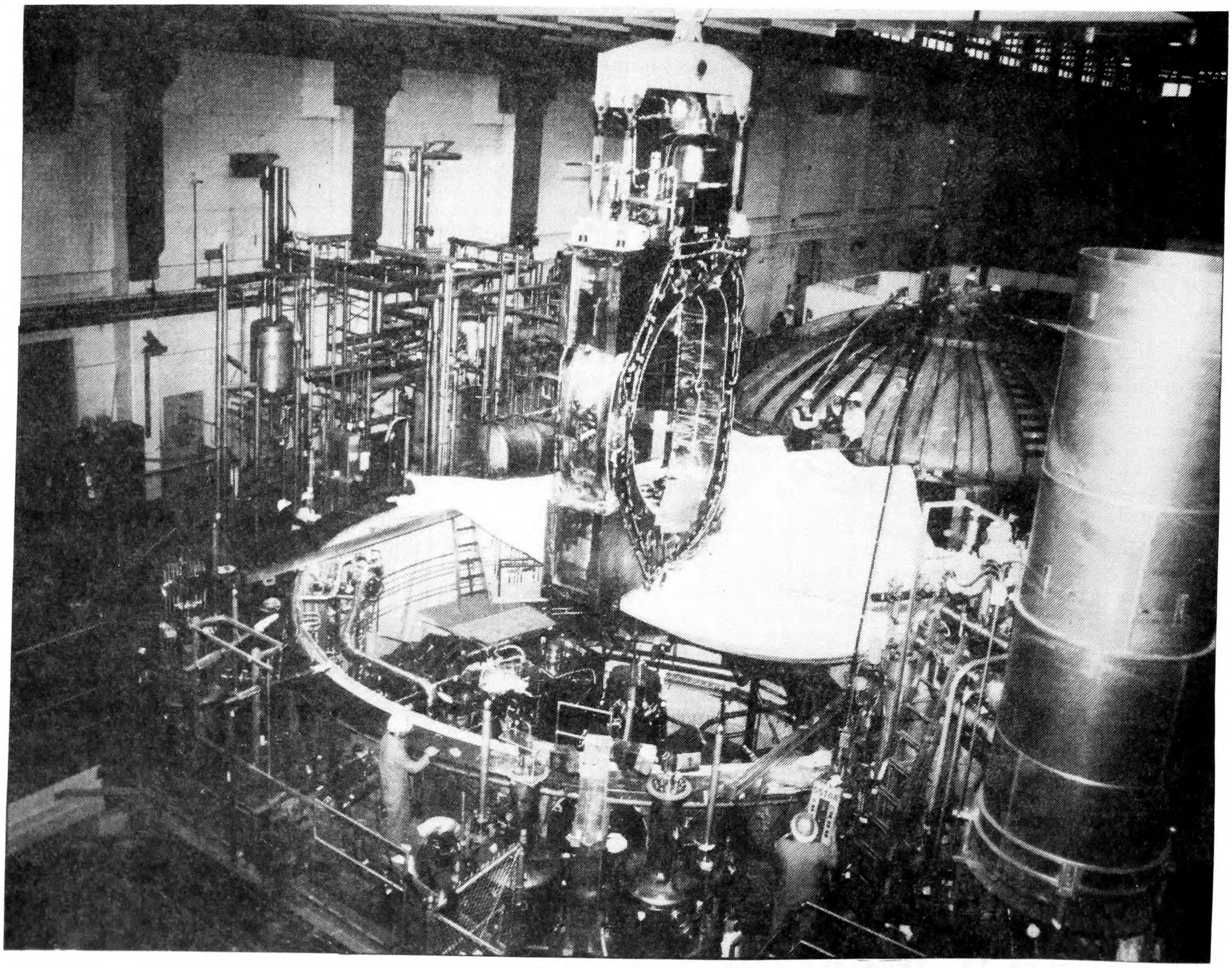


Figure 14 Installation of the GD/C coil into the LCTF.

The Westinghouse coil remains to be completed. It was recognized from the beginning that the Westinghouse concept, based on an internally cooled cabled superconductor (ICCS) using niobium tin, was an advanced concept which would require considerably more development than the GD/C and GE concepts. However, no one thought that it would require as much time and effort as it has. After 8 years, this coil is nearly complete. With the enormous effort that has gone into the ICCS technology, and the promise that ICCS holds for the future of large superconducting magnets, it may well have been worth the wait.

At this time, 5 of the 6 coils have been installed in the LCTF and 3 of the 6 coils have been tested to full current, but not to full field. The Japanese and EURATOM coils were tested individually prior to shipment to ORNL. The GD/C and Japanese coils were tested in the LCTF during August and September 1984.[18,19] The test sequence involved testing each coil separately to full current, then testing each coil to full current with the other coil energized to 40% of full current. These tests were very successful; however, the maximum fields that were generated were no more than 6.4 T. This is only 80% of the full 8 T design value. Considerably more data will be generated during testing of the complete 6 coil array, which is scheduled for later this year.

Obviously, with a project which is the size and scope of LCP, there are many important lessons to be learned which are relevant to MHD. Most important is, again, the recognition of the need to have both the industrial base and the manufacturing technology that will be required for the retrofit fully developed when it is needed. The LCP experience also underscores the importance of having an adequately developed conductor manufacturing technology. The Swiss, for example, attribute a 40% overall schedule slip on the design and construction of their coil directly to unexpected conductor fabrication difficulties.[13] Nearly all of the Westinghouse problems can be attributed to the lack of an existing conductor and to the consequent design constraints imposed on the conductor during its manufacturing development.[20]

It is worth noting that the initially estimated total cost of LCP was very close to that now estimated for the retrofit magnet. That time and cost has approximately doubled, largely as a result of gross underestimates of the time and cost to develop adequate manufacturing technology and facilities for conductor and coil winding.

Among the many benefits to come out of LCP, one of the most important is full recognition of the significant advantages of ICCS for large superconducting magnets and the investment that was made in developing the required manufacturing technology and fabrication techniques for ICCS. This is directly relevant to MHD because the advantages of ICCS for large fusion coils are also applicable to large MHD magnets. These conductors have excellent stability due to unique thermodynamic mechanisms related to their configuration. This allows higher current densities, which yield more compact, less expensive coils. They have excellent mechanical properties. They are extremely rugged, can be adequately insulated, and allow conventional coil fabrication techniques to be used. In addition, they allow for minimal liquid helium inventory and elimination of thick-walled helium pressure vessels which are large, expensive, and difficult to fabricate reliably in the field. Furthermore, they may lead to a substantial simplification of the magnet structure which could significantly reduce the total magnet cost. The

MHD conductor development effort now underway at MIT takes maximum advantage of the ICCS development for LCP by translating the existing fusion-related technology base, which uses niobium tin, to a specifically MHD related niobium-titanium technology base, and then will further that technology through proof-of-concept testing of a 15 m length of prototypical conductor.

MAGNETS FOR HIGH ENERGY PHYSICS

The experience with only one high energy physics project is considered in this survey: ISABELLE.[21-24] ISABELLE was originally conceived as a proton-proton colliding beam facility with an energy of 200 + 200 GeV. Based on the early success with their 4 T magnets for this facility, the energy objectives were increased to 400 + 400 GeV, which required an increase in field strength to 5 T. The upgraded ISABELLE, which was renamed the Colliding Beam Accelerator (CBA), required over 1000 superconducting magnets for the two 3.8 km circumference storage rings. Over 700 of these were to be 5 m long dipole magnets having a warm bore of 0.09 m and an iron return frame. At an operating current level of 3.9 kA and a winding current density more than an order of magnitude greater than the other magnets described in this survey, these were to be very high performance magnets. Construction of the accelerator was started, but the performance of the production magnets did not live up to expectations based on a relatively small number of units which were constructed under laboratory conditions.[21,22] An aggressive R&D program was undertaken, and a workable design was ultimately realized.[23,24] However, it came too late to save the project. The result was termination of the project, loss of $200 million, an unnecessary black eye for the technology of superconductivity, and a serious international embarrassment for the United States high energy physics community. This is failure on an enormous scale.

The relevance of this experience to MHD is to understand why it happened and take appropriate steps to ensure that the same thing does not happen to the MHD retrofit project. It happened because construction was attempted without adequate production design, engineering, and manufacturing technology development. It can be avoided by recognizing the development effort that must be completed prior to final design and construction of the retrofit magnet, and then having it performed.

SUMMARY AND CONCLUSIONS

The fundamental principles of superconductivity are well understood, and there have been several recent successful demonstrations of large scale. However, these successes were in large national laboratories, were based on the specific experience of a very few key individuals, and the systems have been energized only a limited number of times. There have also been a number of serious and very costly failures. The MHD retrofit magnet will be larger than any single coil yet built for MHD, fusion, or high energy physics, and the cost/risk assessment for this magnet will be very different compared to other flow train components: Either the magnet will work, or it will fail, thereby jeopardizing not only the retrofit project itself, but the entire commercialization of MHD as well.

The analytical and physics base for large superconducting magnets is well developed. The design and, in particular, the manufacturing technology base is not. There are two particularly critical elements without which the risk of failure is unacceptably high. First is the demonstration of the performance and manufacturing technology for superconductors capable of reliable operation at a current of 20 kA at 7.5 T and 5 K. Such a conductor does not now exist. Second is the development of a complete and detailed specification for the design and structural basis for large superconducting magnets. In addition, the details of integrating the magnet with the flow train components, and the problems of field construction, must be addressed.

The present MHD ICCS conductor development program at MIT 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 a small fraction of the development effort required prior to beginning the design and construction of the retrofit magnet.

The most optimistic schedule projection for development, design, and construction of the retrofit magnet is six years. This schedule requires funding of $14 million during the first three years.[25] Of this amount, approximately $8 million is required for analysis and development prior to final design and manufacture of the magnet, half of which is needed for conductor development. Consistent with current expectations, a revised nine year plan reduces the funding requirement over the first three years to $6 million. It is obvious that present funding is woefully inadequate and must be substantially increased within the next few years in order to build a retrofit size magnet of any type by 1994. Without the current effort on ICCS, it will be impossible to consider and to reap the benefits of that option.

The decade of experience described herein represents the birth of large scale industrial participation in the design and manufacture of superconducting magnets. The perspective taken by the authors should not be interpreted in any way as intending to lay the blame for the reported cost and schedule overruns solely at the feet of industry. The cost to transfer new technology and to develop the industrial teams and manufacturing facilities to implement that technology has been grossly underestimated at all management levels. The dramatic improvement in the maturity and acceptability of superconducting magnet technology over the last 5 to 10 year period is a direct result of large scale industrial participation. Education during this period has been very much a two way street.

However, it is often true that the perfect vision of hindsight accrues only to those who have suffered through the experience. Whoever manages the design and construction of the retrofit magnet must understand the detailed causes of, and remedies for, the problems described herein.

REFERENCES

1. H. Desportes, "Superconducting Magnets for Accelerators, Beam Lines and Detectors," MT-7, IEEE Trans. on Magnetics, Vol. MAG-17, No. 5, September 1981, p. 1560.

2. D. B. Montgomery, "Superconducting Magnets: Where Did We Go Wrong?" Proceedings of the 6th Symposium on Engineering Problems of Fusion Research, IEEE Pub. No. 75CH1097-5 NPS, San Diego, 1975, p. 122.

3. Argonne National Laboratory, "Design, Construction, and Performance Test of a Six-Tesla Superconducting Dipole Magnet System for Magnetohydrodynamic Energy Conversion Research," ANL/MHD-84-2, June 1984.

4. R. C. Niemann et al, "Cryogenic Aspects of the Experience in Operating the U-25 Superconducting MHD Magnet in Conjunction with the MHD Generator," MIT/FBNML 1978 Superconducting MHD Magnet Design Conference, May 1979, p. 103.

5. MIT Plasma Fusion Center, "MHD Magnet Technology Development Program Summary, September 1982," MIT, Cambridge, MA, November 1983, p. 112.

6. P. G. Marston and R. J. Thome, "The U.S. Department of Energy National Program of Magnet Technology Development for MHD," MIT/FBNML 1980 Superconducting MHD Magnet Design Conference, March 1980, p. 1.

7. R. J. Thome et al, "HPDE Magnet Failure," Safety and Protection for Large Scale Superconducting Magnets - FY1983 Report, MIT Plasma Fusion Center, Cambridge, MA, December 1983, p. 5.

8. J. M. Tarrh and H. D. Becker, "HPDE Magnet Failure," Safety and Protection for Large Scale Superconducting Magnets - FY1984 Report, MIT Plasma Fusion Center, Cambridge, MA, November 1984, p. 47.

9. P. N. Haubenreich, M. S. Lubell, D. N. Cornish, and D. S. Beard, "Superconducting Magnets for Fusion," Nuclear Fusion, Vol. 22, No. 9, 1982, p. 1209.

10. T. A. Kozman et al, "Magnets for the Mirror Fusion Test Facility: Testing of the First Yin-Yang and the Design and Development of Other Magnets," IEEE Trans. on Magnetics, Vol. MAG-19, No. 3, May 1983, p. 859.

11. S. Shimamoto et al, "Domestic Test Result of the Japanese LCT Coil," IEEE Trans. on Magnetics, Vol. MAG-19, No. 3, May 1983, p. 851.

12. P. N. Haubenreich, R. E. Bohanan, J. R. May, and H. E. Miller, "Status of the Large Coil Test Facility," Proceedings of the 10th Symposium on Engineering Problems of Fusion Research, December 1983, p. 1337.

13. G. Vécsey et al, "The Swiss LCT Coil," IEEE Trans. on Magnetics, Vol. MAG-21, No. 2, March 1985, p. 242.

14. W. Herz et al, "Results of the Test of the European LCT Coil in the TOSKA Facility," IEEE Trans. on Magnetics, Vol. MAG-21, No. 2, March 1985, p. 249.

15. J. F. Ellis et al, "Shorts due to Diagnostic Leads," IEEE Trans. on Magnetics, Vol. MAG-21, No. 2, March 1985, p. 1060.

16. R. F. Beuligmann et al, "Engineering Problems in the Design of Superconducting Systems," Presented at the MT-8 Conference, Grenoble, September 1983, Journal De Physique, Colloque C1, supplement au n^{o} 1, Tome 45, janvier 1984, p. C1-569.

17. R. K. Kibbe et al, "Experience Highlights from the Design and Manufacture of U.S. LCT Coils," IEEE Trans. on Magnetics, Vol. MAG-21, No. 2, March 1985, p. 234.

18. J. N. Luton et al, "Preliminary Results of the Partial-Array LCT Coil Tests," IEEE Trans. on Magnetics, Vol. MAG-21, No. 2, March 1985, p. 238.

19. P. N. Haubenreich et al, "Startup of Large Coil Test Facility," 13th Symposium on Fusion Technology, Varese, Italy, September 1984.

20. P. G. Marston et al, "Magnet Failure Workshop," MT-8 Conference, Grenoble, September 1983, Journal De Physique, Colloque C1, supplement au n^{o} 1, Tome 45, janvier 1984, p. C1-637.

21. Magnet Technology Group, "ISABELLE Superconducting Magnets," MIT/FBNML, Cambridge, MA, December 1980.

22. H. Hahn, "ISABELLE - A Progress Report," 1980 ASC, IEEE Trans. on Magnetics, Vol. MAG-17, No. 1, January 1981, p. 702.

23. Magnet Technology Group, "ISABELLE Superconducting Magnets - Second Report," MIT/PFC, Cambridge, MA, 1982.

24. R. B. Palmer, N. Baggett, and P. F. Dahl, "Status Reports on ISABELLE Magnets," 1982 ASC, IEEE Trans. on Magnetics, Vol. MAG-19, No. 3, May 1983, p. 189.

25. MIT Plasma Fusion Center, "MHD Magnet Technology Development Program Summary, October 1982 - April 1984," MIT, Cambridge, MA, September 1984, Appendix G.

ACKNOWLEDGEMENTS

This work was sponsored by the Pittsburgh Energy Technology Center, U.S. Department of Energy, under Contract No. DE-AC22-84PC70512 with the Massachusetts Institute of Technology.