Plan for the Large Coil Program

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MASTER

OAK RIDGE NATIONAL LABORATORY

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FUSION ENERGY DIVISION

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This Plan incorporates ideas on building and testing large coils from many people throughout the U.S. superconducting magnet community. Their ideas are so interwoven in the fabric of the Plan that it is impossible now to give credit in detail. This broad interaction is, in large part, due to the guidance and encouragement of C. D. Henning and E. J. Ziurys, of the Magnetism Branch, USERDA-DMFE. Other specific contributions, which the authors of this report gratefully acknowledge, are as follows.

In the early planning from which the Large Coil Program evolved, H. M. Long was responsible for defining many of the coil testing requirements and for the compact torus concept. Several in the Superconducting Magnet Development Program, notably M. S. Lubell, P. L. Walstrom, and J. K. Ballou, helped resolve the basic considerations in the use of sub-size coils to test designs, materials, and fabrication techniques for reactor scale coils. R. E. Stamps and J. R. Moore, of UCC-ND Engineering, were responsible for generating most of the detailed information for the comparisons and provided original insights into the magnetic and mechanical constraints of various test arrangements. Finally, a workshop on large coil testing, at which portions of the first draft of this report were presented, produced constructive criticism which resulted in several revisions in this final version.

1. INTRODUCTION

Development of specialized superconducting magnets for fusion reactors is a major activity in the D&T program of the USERDA Division of Magnetic Fusion Energy. Timely development of effective, reliable, and economical magnets for tokamaks requires the early resolution of existing uncertainties by the design, fabrication and testing of several different large, superconducting toroidal field coils. This is being accomplished through the Large Coil Program, established specifically for this purpose at the Oak Ridge National Laboratory. The program plan for the LCP has evolved from ERDA-sponsored reviews of the U.S. magnet development program, discussions between DMFE and ORNL, and detailed analyses and comparisons by ORNL.

This document has been prepared by the Large Coil Program to make generally available the information that has been generated up to this point and to indicate the direction of future work. Chapter 2 is a summary of objectives, general strategy, and implementation of the LCP. Subsequent chapters give expanded descriptions of program content, technical requirements, selection of testing arrangements, tentative schedule and method of preliminary cost estimation.

2. SUMMARY

2.1 Objective

It is the primary purpose of the Large Coil Program to accomplish the national fusion program objective of fabricating, testing, and demonstrating the reliable operation of superconducting coils that are large enough to prove the design principles, materials, and fabrication techniques proposed for the toroidal magnet of a tokamak fusion reactor. The program will move as quickly as practicable into fabrication of several different large toroidal field coils in order to identify, to confront realistically, and to solve the spectrum of new and/or greater problems involved in design and fabrication of large superconducting tokamak magnets. Testing of the LCP coils will permit a choice to be made among the different designs so that detailed criteria can be prepared for fullscale reactor coils that are optimal from the standpoints of fabricability, performance, cost, and dependability.

The long-range focus of the Large Coil Program at its inception in 1976 was the Experimental Power Reactor (EPR) that was being considered for construction around 1985. It has since shifted to the needs of The Next Step (TNS), which now appears in U.S. fusion program plans as a D-T ignition device somewhat smaller than the EPR. Studies presently in progress to define TNS reference designs indicate that most likely the toroidal field coils must be superconducting, with an opening about 5 x 7 m, and producing a peak field of 8 to 12 tesla. The LCP is being counted on to produce experimental data supporting TNS design decisions in 1980.

Achievement of the broad objective of the LCP involves the following accomplishments:

- resolution of reactor magnet requirements,
- origination of coil concepts meeting these requirements,
- application of technology and engineering to produce detailed designs of test coils capable of proving the most promising concepts,

- fabrication of test coils of these designs,
- thorough testing of these coils,
- demonstration of reliable operation of coils and supporting systems under simulated reactor conditions, and
- recommendation of design criteria for TNS coils.

2.2 Strategy

The strategy or general program outline shown in Fig. 2.1 was laid out to accomplish the LCP objective. The Large Coil Program is managed by an ORNL team with magnet technology, design engineering, project engineering, and management skills. The capabilities of U.S. industry will be utilized and the results of R&D in the Superconducting Magnet Development Program (SCMDP) will be disseminated by contracting for the conceptual design, detailed design, and fabrication of the large coils. Guidance, technical input, and evaluation will be provided by ORNL, with reviews and approvals by DMFE. The Superconducting Magnet Development Program will perform the basic R&D and in addition will perform coil design and developmental fabrication concurrently with the industrial work in LCP.¹ ORNL will be responsible for design and construction of a test facility and conduct of the tests.

2.3 Implementation

The principal technical decisions that were made and approved during 1976 are summarized in Items 2.3.1–2.3.6. A Technical Specification (TS14700-01) has been issued by Union Carbide Corporation Nuclear Division (operator of ORNL and other ERDA plants at Oak Ridge) giving detailed requirements on the first test coils to be procured. A conceptual design for the test facility has been developed by ORNL and is being incorporated in a Major Project Proposal to be submitted to ERDA-DMFE.

2.3.1 Number of Different Test Coils

Several promising concepts for reactor coils were originated in the EPR conceptual designs and the EPR-TF studies in the LCP. These employ

Fig. 2.1 Principal Features of Large Coil Project Strategy

different combinations of coolant conditions (forced and natural convection), conductor configurations, methods of winding or installation of conductors, and ways of incorporating structural materials. Because there is presently insufficient experimental basis for choosing the best design for reactor coils and concentrating all efforts on it, it was decided that three concepts would be chosen for fabrication, testing, and demonstration.

2.3.2 Peak Field

The first industrial coil subcontracts will produce coils operable at a peak field of at least 8 tesla. Consideration will be given to subsequent procurement of test coils that can produce substantially higher fields and the test stand is being designed to permit testing at peak fields up to 12 tesla.

The 8-tesla criterion was chosen in view of information from TNS studies and the status of high-field conductor and magnet technology. Decisions on higher field coils will be made on the basis of progress in these areas that is expected in FY-1977.

2.3.3 Conductor Material

The specification for the 8-tesla coils permits prospective subcontractors to propose use of either NbTi alloys or Nb₃Sn as the conductor material. The choice of concepts to be pursued in the first coils will take into account both the probability of timely achievement of the 8-tesla goal and the relevance of the fabrication and testing results to possible subsequent higher-field coils.

2.3.4 Test Coil Size and Shape

The 8-tesla test coil specifications define a coil shape approximating a "pure-tension D" and having 2.5 x 3.5 m winding bore dimensions.

Analyses of test coil requirements by ORNL and the EPR-TF study contractors indicated that a coil bore of approximately 3 meters represents a reasonable compromise among factors that argue for larger or smaller test coils. Conceptual studies of tokamak reactors agree that the TF coils should be elongated in the vertical direction to fit the enclosed components in the most economical and practical manner. The shapes

avored by reactor designers on the basis of structural and fabrication considerations are either a "pure-tension D" or some variation from it.

2.3.5 Test Arrangement

The reference test arrangement is a 6-coil toroidal array, in which the peak field in one coil reaches 8.0 tesla when that coil is operated at rated current density and the other five coils are operated at 0.8 of rated current density. The test stand will permit testing with only three 8-tesla coils in place (at lower peak field). The test stand structure is also being designed to permit testing of one or more coils with high-field conductor and more ampere-turns at a peak field of 12 tesla.

2.3.6 Principal Vacuum Enclosure

The multiple coil test arrangements will be enclosed in a single, large vacuum chamber of the simplest, most economical design consistent with coil test requirements.

2.4 Schedules

The schedule for the early stages of the Large Coil Program is shown in Fig. 2.2. The schedule for subsequent stages of the program will depend upon the times required by the industrial contractors for design, procurement and coil fabrication. The fusion program goal is to provide evaluated test results for selection of TNS design criteria in FY-1980.

Fig. 2.2. Schedule for Early Stages of Large Coil Program

3. SCOPE AND CORRELATION WITH OTHER PROGRAMS

3.1 Scope

The Large Coil Program (LCP) provides for the design, fabrication, testing, evaluation and demonstration of large-bore, superconducting, toroidal magnet coils.

An early activity of the LCP, which supplied input for selection of test coil design criteria, was the generation by three industrial contractors* of concepts for the toroidal magnet of the tokamak Experimental Power Reactor (EPR), including both moderate- and high-field options (8 and 11-16 tesla peak fields). Smaller test coils will be designed so that their fabrication and testing will prove leading design concepts and manufacturing capabilities, provide necessary design data, and constitute a basis for choice of design criteria for full-size reactor coils. It is anticipated that three concepts will be pursued through conceptual design, detailed design, fabrication, and testing.

Industrial superconducting magnet design and fabrication capabilities will be utilized in test coil conceptual design, detailed design, and fabrication under subcontracts with Union Carbide Corporation - Nuclear Division. ORNL has produced specifications which provide functional requirements, guidelines, and conceptual criteria to the subcontractors and ORNL will monitor their efforts. As part of the LCP, ORNL will also perform conceptual design, evaluate alternative testing arrangements and sites, design the test facility and oversee its construction, and perform program planning and management functions. Coil testing will be accomplished under the direct supervision of the Superconducting Magnet Development Program.

* Westinghouse, Magnetic Corporation of America, and a team of General Electric and Intermagnetics General Corporation.

3.2 Correlation with Other Programs

The Large Coil Program is an essential element of the overall ERDA-DMFE program for development of superconducting magnet systems for fusion power reactors. It is closely integrated with the other activities in the tokamak-oriented Superconducting Magnet Development Program at ORNL, which includes conductor selection and test, coil shielding and protection, structural analysis, coil design, cryogenics, developmental fabrication, and testing.¹

The functional requirements of reactor coils were obtained from the scoping studies and preliminary conceptual design for the EPR that were conducted at ORNL, Argonne National Laboratory, and the General Atomic Company²⁻⁵ and from the studies on The Next Step that are being directed by ORNL and General Atomic. The results of concept evaluation, fabrication, and coil testing in the Large Coil Program will provide input for the ongoing TNS design efforts. The experience in fabrication of large conductors and toroidal magnet coils will benefit all subsequent superconducting magnet activities.

The Large Coil Program will utilize to the maximum practical extent the results of superconductor development under the DMFE-sponsored programs at Lawrence Livermore Laboratory directed at magnets for high-field mirror reactors and at Los Alamos Scientific Laboratory directed at magnetic energy transfer and storage.

To the extent provided for in agreements among governments, there will be information exchange with programs developing superconducting magnets for fusion power in other countries. There is an ongoing exchange under the US-USSR program of cooperation in fusion power development and an agreement for more substantial cooperation under the auspices of the International Energy Agency is under consideration.

4. TASK DESCRIPTIONS

The program outlined in Fig. 2.1 and scoped in Chapter 3 has been broken down into ten major tasks. A brief description of each follows.

Task 1 — Management. The management task in essence is to develop and execute program plans to achieve assigned objectives in a timely, effective, and economical manner. It includes organization and planning; preparation of program and budget proposals; evaluation and generalization of reactor magnet requirements from various conceptual studies; administration of industrial subcontracts, including technical input and evaluation; coordination and liaison with the SCMDP; interaction with the USERDA; and general guidance and monitoring of the program.

Task 2 — EPR TF System Conceptual Studies. The Large Coil Program, in cooperation with the three EPR design teams at ANL, GA, and ORNL, extracted from the preliminary conceptual studies of the tokamak EPR the principal requirements placed on the magnet systems. The LCP staff reduced these requirements to a consistent set of guidelines, conceptual criteria, and design data. The USERDA then let contracts to industrial organizations with experience and capability in superconducting magnets to produce conceptual designs of toroidal field coils meeting these EPR requirements. These conceptual designs, together with those produced by the reactor design teams, provided a reference base for further coil design in the Large Coil Program.

Each contractor was required to produce two concepts, one with a peak field of 8 tesla, the other with a peak field as high as practicable (in the 11-16 tesla range). An important consideration was the reliability of magnet system operation, which requires coils that are thermally stable and protected against disabling damage in any credible event. At the completion of the conceptual study, each contractor prepared and delivered a written report that describes his concepts, identifies major uncertainties, and recommends research and development to minimize the uncertainties. Included in the last point is the contractor's recommendation of the smallest coil that can provide a conclusive demonstration of the practicability of the concept. Each contractor also made an oral presentation of interim results and engaged in a workshop discussion.

Task 3 — Testing Plans. Concurrently with the EPR studies in Task 2, the LCP developed plans for coil testing. The test coil size required for confident extrapolation of test results to the TNS was also analyzed. Different testing arrangements (e.g., cluster and compact torus) were compared on technical and economic grounds.

Task 4 — Conceptual Design (Oak Ridge). ORNL and UCC-ND Engineering forces performed conceptual design of test coils and a facility required to test three different test coils. These conceptual designs and detailed cost estimates based upon them are being incorporated in a formal Major Project Proposal (Task 5). Results will also provide a basis for evaluation of industrial proposals and conceptual designs (Task 6) and input to SCMDP subprograms (coil design, fabrication, and testing) to be conducted at Oak Ridge.

Task 5 — Major Project Proposal. A proposal meeting the requirements for such a major project^{*} will be prepared for review and approval by ERDA-DMFE before the heavy commitment of funds to LCP detailed design and fabrication (Tasks 7-9).

Task 6 — Conceptual Design (Industry). Each of three industrial subcontractors will develop a conceptual design of a test coil that will prove a selected reactor magnet concept. In conjunction with conceptual design, the contractor will identify uncertainties and the further development and testing that will be required before fabrication of the test coil. He will propose those component tests and fabrication development that should be performed by him under a subsequent stage of his contract. Results and proposals will be reviewed and decisions made for further work by selected subcontractors under Task 7.

Task 7 — Detailed Design, Component Tests, and Advance Procurement. Each selected subcontractor will perform preliminary design (corresponding to Title I Engineering) on a test coil of a specified conceptual design. Concurrently he will also perform those fabrication tests that have been

^{*} Procedures Governing the Initiation and Fabrication of Major Projects and Major Devices within the Controlled Thermonuclear Research Program, ERDA-5 (February 1975).

proposed and approved. Final design (equivalent to Title II) will proceed as test results become available. Advance procurement of materials can begin during this task whenever the specifications can be determined. This task will culminate in a Final Design Review.

Task 8 - Coil Fabrication. Each contractor will specify and procure materials and fabricate one test coil of an approved final design. Additional coils will be fabricated as required for the test arrangement; choice of designs and fabricators for these coils will be made after review of the results of earlier stages.

Task 9 - Test Facility. This task will cover the detailed design, procurement of test support equipment and other materials, building modifications, and construction required to provide for testing and demonstration of the test coils.

Task 10 - Assembly. This task will include receipt, inspection, installation, and performance of preliminary checks on the test coils.

Further Tasks. Testing and demonstration of LCP coils will be performed under the Coil Testing and Evaluation subprogram of the SCMDP.

5. COIL CONSTRUCTION AND TEST REQUIREMENTS

5.1 General Considerations

The purpose of the Large Coil Program is to complete an adequate base for confident design of the toroidal field coils in a tokamak reactor. The requirements which must be met before the technologically complex toroidal field coils can be regarded as fully developed and proven must be arrived at by consideration of the specific points which involve substantial advances in technology and engineering and the service conditions that the reactor coils will be required to meet. The latter will include primary and secondary performance characteristics, operating life cycles, environments, and interaction with connected systems under normal and credible failure conditions. A detailed review of all requirements leads to a determination of the specific method and test conditions necessary to verify that all requirements have been met.

Verification is generally accomplished by a sequence of inspection, testing, analysis, and demonstration. Inspection will serve to verify dimensional accuracy or that the materials, parts and processes used are proper. Development tests are conducted for design evaluation purposes, to determine design feasibility and margins, functional parameters, technological data, and to verify assembly and fabrication techniques. The tests are oriented to verify that performance requirements have been met, to indicate critical areas where design improvements are required, and to prove that the test item is capable of operation in the specified environments. Analyses can be employed to expand basic test-derived information or to calculate related items such as stress from measured strain or deflection data. Demonstration might be defined as operation that is sufficiently extensive in conditions and time to show conclusively that the item or system, as designed and built, is capable of meeting all service requirements with a high degree of reliability.

5.2 Fabrication

Fabrication of the LCP test coils will serve to develop and to demonstrate the manufacturing technology that will be required for the EPR toroidal field coils. The test coils must therefore be designed so that the extrapolation in size from the test coil to the TNS coil will be within the state of the art. This general guideline leads to the following specific requirements.

- The electrical conductor used in the test coil should be identical to that expected in the TNS coil. This choice will result in a significant fabrication information base for specific candidate conductors before the final selection for the TNS.
- The electrical insulation should be of a type that meets TNS requirements including resistance to irradiation damage.
- The fabrication practices and quality assurance procedures should be prototypical of TNS practice. This will involve assignment of quality levels and development of standard practice procedures that are appropriate for fusion reactor magnets.

The nature of the program places the following additional requirements on coil fabrication.

- The test coils must be amenable to transportation from the fabrication site to the test site without resultant damage.
- Fabrication must include incorporation of appropriate instrumentation for monitoring coil behavior during testing.
- For future reference, a record of design decisions, analysis, procurement, manufacturing procedures and inspections must be maintained and provided to the LCP management at appropriate intervals.

5.3 Test Coil Size

A basic premise of the Large Coil Program is that subsize test coils can be designed to produce the data that are necessary and sufficient for the design of much larger coils for a tokamak reactor. A thorough understanding of the modeling and scaling relationships for large superconducting coils is essential to assure that the data from the test coils is unequivocally applicable to the design of the full size coils.

From the viewpoint of the large coil detail design, the most important design elements to be retained are those related to the conductor and its performance in an operating coil. This is true not only from the standpoint of electrical and thermal design but also from the standpoint of structural design. A review of structural stiffness relationships between large and small coils indicates that a reasonable match of strain, bending, and shear criteria can be made provided the winding cavity cross sections are nearly the same. The uncertainties of simulating a large coil design in a small test coil can be minimized if both the conductor size and winding cavity dimensions can be preserved within a reasonable range, say $\pm 10\%$. This would allow evaluation of the large coil conductor, arranged in the proper number of columns and rows within the winding cavity. Detailed analyses of the large coil designs structural responses must be taken into account in the design of the test coil structure to provide similar interface characteristics between the coil case and the windings. If the test coil bore is made smaller than approximately 2-1/2 to 3 m, however, then the winding itself becomes so relatively stiff that it is difficult to reach the strains of the full-size coil simply by reducing the coil structure.

A second criterion essential to the relevance of coil test data to larger coil design is a reasonable match of field and force distributions around the coil. This can be accomplished in a toroidal array of test coils if the aspect ratio (major radius to coil horizontal bore radius) can be held to a value corresponding to the large toroidal magnet. As described in the following paragraphs, a study was made of toroidal testing arrangements in which the winding cavity cross section dimensions and

the aspect ratio were held close to those in the EPR to determine the minimum acceptable size test coil. The result turned out to be approximately 3 meters.

The study involved the application of the following approach. Beginning with a full torus of twenty coils with the proportions of the ORNL EPR Reference Design,² reduce the coil bore until the coil aspect ratio is 10% beyond the design point. In order to limit the change in field and force distributions, further reductions in coil bore are accompanied by decreases in the major radius which maintain the coil aspect ratio within a 10% band. This is accomplished by reduction in the number of coils, which allows the remaining coils to be moved radially inward to the most compact arrangement permitted by structural clearances. Minor variations in winding cavity dimensions and proportions permit adjustments to be made to maintain the peak field value at the design current density.

A reasonable limit to this process is reached when the number of coils has been reduced to six. Although further reduction in the number of coils is possible, the central clearance at the coil noses for the six-coil case is considered to be the minimum consistent with providing proper simulation of external support interfaces. Two versions of such a 6-coil compact toroidal array were evaluated with respect to variations in coil bore size. Both versions were required to meet the peak field, current density, and winding cavity cross section size. In one version, referred to hereafter simply as the compact torus, the specified peak field can be reached in one coil if it operates at a current density (over the winding) of 2500 A/cm^2 while the five other identical coils are operating at 2000 A/cm^2 . In the other version, the peak field is reached only when all six coils operate at 2500 A/cm^2 . Less conductor is required in this version which is called the "minimum compact torus" in this report.

A simple performance index consisting of the ratio of radial forces at the coil midplane inboard leg (coil nose) to the radial forces at the coil midplane outboard leg was used. It was assumed that this ratio of forces is sufficiently indicative of the distribution of forces around the coil. This simplified the comparison of forces over a range of test coil sizes and aspect ratios with the value calculated for the full size EPR

reference coil set. Detailed force values were calculated for two specific test coil sizes and relationships established to corresponding values of the average field strengths at the coil leg midplanes. Subsequent calculations for varying coil size were made based on average field calculations with force ratios determined by application of the previously determined correction factors. The results are presented in Figs. 5.1 and 5.2.

Figure 5.1 indicates that a narrow range of coil aspect ratio exists in which the force ratio would be within $\pm 20\%$ of the EPR reference magnet value. These aspect ratios are somewhat lower than in the EPR reference case due primarily to the reduced number of coils in the compact tori.

Figure 5.2 presents the force ratio versus coil bore size. Within the assumed allowable range of radial force ratio of $\pm 20\%$ from the reference coil design point, the smallest coil would be about three meters in horizontal bore for a compact torus or about two and one-half meters for the slimmer coils of the minimum compact torus. A coil size of three meters for the minimum compact torus would result in a force ratio value close to the reference EPR point.

In summary, various considerations lead to a minimum coil size of approximately three meters if the conditions of large coil winding cavity size and aspect ratio preservation are required. While many other variations and comparisons are possible, the approaches used lead to a logical conclusion while emphasizing retention of the major design elements of a large coil.

5.4 Demonstration

Although the test coil may be only half the size of the coils eventually required for tokamak reactors, a multicoil test assembly of 3-m coils with 8-tesla maximum field and asymmetric forces of many meganewtons is itself a substantial step upward from what has been accomplished previously. The initial operation of the test facility will demonstrate in detail how well the LCP coils meet their design parameters, e.g., that the cooldown proceeds at design rate in all portions of the apparatus,

Fig. 5.1 Radial Force Ratio versus Test Coil Aspect Ratio

Fig. 5.2 Radial Force Ratio versus Test Coil Bore

that the heat inputs at joints and leads are as predicted, that coil dump occurs as planned, and that design current is reached when ambient conditions (field, field change, coolant temperature, strains, and heater power) are simultaneously at design values. Achievement of full field will be an obvious demonstration that the analysis, design, and fabrication of coils and facility were adequate, and that the quality of the production materials was satisfactorily known or predicted from test samples. This latter point is particularly important in the case of the conductor, but is not trivial for the other materials.

If the LCP coil system is demonstrated in this way it greatly enhances confidence in the application of the design analysis and construction techniques to larger coils, but only if the design remains essentially the same. Therefore, all design concepts which are candidates for use in larger systems must be constructed and demonstrated as part of the LCP, and there must be a sufficient number of promising candidates to give confidence of having at least one final success.

Successful operation at design values will not, however, give sufficient basis for extrapolation to more severe ambient conditions or to larger currents. For this reason subsequent testing is required to determine design margins, and the testing must be arranged so as to minimize any such extrapolations required to reach TNS conditions.

5.5 Testing

In this phase the factors determining coil performance will be elucidated by varying selected operating conditions and making detailed measurements and analyses of coil responses. Both the nature of the responses and the ultimate limits on coil performance will be compared to qualitative and quantitative predictions. Predicted and observed behavior will be analyzed to identify reasons for the discrepancies.

Testing must be penetrating and thorough in order to provide the greatest benefit to the magnet development program. Instrumentation must provide adequate data which can be thoroughly analyzed and evaluated in order to resolve all key questions. Conclusions can then be drawn which

can be translated into improved coils. Unanticipated behavior that reflects deficiencies in methods of prediction must lead to efforts for improvement which will bring calculated predictions into line with observations. If deficiencies in materials or fabrication are indicated, improvements in quality must be sought in subsequent coil manufacture.

An example of the investigation of response and operating limits will be the measurement of the tolerance for overall heat input. An extensive system of heaters will be built into the test coil to simulate the heating of a reactor coil by neutrons and gamma rays and pulsed fields. In a series of tests, the magnitude and duration of the heater power pulses will be stepped up while the changes in helium pressures, temperatures, and other variables are measured and compared with predictions. This escalation will be continued until finally a limit is reached at which the coil quenches. The design of the test coils will be such that their limiting conditions should be at least slightly more severe than the normal operating conditions for the first tokamak reactor coils. Thus, the design of the reactor coils will be based, as far as possible, on measured rather than extrapolated data.

The test coils will be tested to determine responses to a sequence of fault conditions of increasing severity as well as to normal operation.

For convenience in the evaluations described in Chapter 6, we have divided the following discussions of parameters and conditions influencing coil performance into two groups: the second group dependent on test geometry for its attainment, the first relatively independent of test configuration. In some cases a clearcut distinction cannot be made.

5.5.1 Requirements Independent of Test Arrangement

1. The conductor-coolant configuration and the design heat fluxes in the test coil should be the same as in the larger coil. This is necessary primarily because of unavoidable uncertainties in heat transfer calculations for the different configurations, orientations, surface heat fluxes, and dimensions (length and cross section) of coolant channels encountered in the coils.

2. The design current density over the winding of the test coil should be equal to that of the full-size coil. This is a critical factor

in determining the adequacy of the coil design from the standpoint of stabilization.

3. Full size conductor shall be used in the test coil. The combination of requirements 1 and 2 demands this.

4. Helium pressure, pressure drop, and quality should duplicate conditions in the large coil. The helium temperature should be controllable from below the value for the full size coil (for study of conductor instability and increase of critical current) to above (to define operability limits).

5. Radiation heating in the reactor coil shall be simulated; radiation damage will not. The heating effect can be simulated by heaters which affect at least a full cooling circuit, but there appears to be no practical way of simulating neutron damage to the completed test coil.*

6. Local heat inputs shall be provided to test the coil's electrical, thermal, and mechanical responses and to measure stability margins, recovery currents, and velocities of propagation and contraction of the normal front. To this end, local heaters will be built into the coil.

7. For test coils with cooling by forced flow down the conductor, the flow path length must be the greatest anticipated for a full scale coil, approximately 1 km. At the same time there should be at least two adjacent parallel paths to check their interaction. Thus the test coil should have a minimum total conductor length of approximately 2 km. There should, of course, be intermediate helium taps so that the coil could be tested with a larger number of shorter flow paths.

8. For test coils cooled by boiling of a fraction of the helium, whether the circulation is entirely natural or is slightly forced to aid in bubble removal, provision must be made to simulate the effects of a larger winding by varying the overall pressure, introducing helium of controllable quality, and energizing properly located heaters. The objective

*The resistivity of the matrix will increase and the mechanical and electrical properties of the insulation will degrade during extended reactor operation.

will be to reproduce, as nearly as possible in a subsize coil, the overall patterns of circulation, quality, and pressure in a full size pancake or layer, so that each part of the winding is in its correct environment.

5.5.2 Requirements Dependent upon Test Arrangement

The test requirements that are more or less dependent upon the specific test arrangement are summarized as follows.

1. Provide design peak field in test coil winding when test coil current is at design value.
2. Produce a pattern of stresses and strains in test coil similar to that in full size coil.
3. Produce maximum strains in conductor of test coil the same as in full size coil.
4. Provide pulsed fields at test coil winding equal in magnitude and similar in orientation to those in tokamak application.
5. Provide specific stored energy of 6 J/g in test coil.
6. Accommodate test coil in vertical plane, with longer axis vertical, as in a tokamak.

Each of the above requirements is discussed in the paragraphs which follow.

1. The magnetic field degrades the basic physical parameters of superconductor critical current vs temperature and electrical and thermal conductivities of the stabilizing metal. Thus it is essential that the test arrangement provide design maximum field when the test coil current is at design value.
2. Conductor critical current, insulation and conductor integrity, efficacy of the adhesive, potting, or bonding, structural stability, and local heat inputs due to internal slippage, cracking, plastic flow or other inelastic behavior, are all dependent on the forces on conductors produced by the interaction of the magnetic field with the coil current. These magnetic loads can be accurately calculated, but any deviation from the characteristics of the composite structure that were used in design can result in strains different from those that were predicted. An objective

of testing is to observe the effects of such behavior. Therefore a pattern of loads and strains should be produced in the test coil as nearly as practicable like those in the full size coil.

3. The test coil structure should be designed to translate the load distribution into an approximately correct strain distribution, and the thickness or Young's modulus of the structure should be adjusted to give the proper magnitude of strain. Strain gauges can be used to verify elastic strain calculations, but an omnipresent system (perhaps sonic triangulation) may be required to determine the locations where slip occurs.
4. The full size coils will be exposed to pulsed fields which tend to drive the coil normal by increasing its temperature and may shorten its life by cyclic loading. The character of these pulsed fields in the EPR cannot be predicted with a high degree of accuracy since they will depend on presently unresolved factors of plasma startup requirements, and such design features as shielding windings and eddy current shields. A field change of 0.2 tesla in 1 sec, which is presently being used as a design criterion in the LCP, represents a reasonable upper limit. If it should prove to be prohibitively expensive to produce this field over the whole volume of the test coil, the test arrangement must at least provide a pulsed field over a large enough region to produce magnetic loads on the test coil such that fatigue testing may be carried out. The heat produced by the pulsed fields in the affected regions of the coil will be measured and compared to the calculated value. From this a power level will be set for the global "pulse heaters" which simulate the overall heating effect of a pulsed field. Coil operation with the pulsed field, "pulse heaters," and "nuclear heaters" will show under what condition a normalcy is caused by local heating (presumably via transition from nucleate to film boiling), local pulsed heating (same mechanism, different values), and global heating (via increase of temperature or quality of the helium). In summary,

the test arrangement should provide parallel and perpendicular pulse fields of 0.2 tesla in 1 sec, over about a meter length of the test coil, without quenching the background coils.

5. During quench, a coil may be damaged as a result of either high temperature or high voltage. Since merely changing the dump resistance aggravates one problem while rectifying the other, the full size coils most likely will be electrically subdivided for dump purposes. However, each resulting section requires current leads to the warm environment, and so there will be as few sections as possible. The test coil should have more stored energy than one section of the large coil, approximately 150 MJ, to establish the performance limits of the dump circuitry and the coil. One can release a large fraction of the stored energy as heat in the coil by reducing the dump resistance, thus testing for hot spot temperature and thermal strain. Alternatively, one can raise the dump resistance and verify adequacy of the turn-to-turn and coil-to-ground insulation. However, this is best done when there is still sufficient energy released in the coil to raise its temperature significantly, since insulation electrical performance may be seriously influenced by strain and helium bubble formation. Assuming that 90% of the stored energy is removed by the energy dump, that the heated region of the coil is restricted by thermal isolation to 10% of the coil, and that the desired final temperature is 80K then the test arrangement should provide a specific stored energy Q/M of approximately 6 J/g, where Q is the change in total energy in the magnetic field as the test coil current is reduced to zero, and M is the mass of the test coil winding. This value of Q/M should provide ample helium gas while the magnetic forces are still large, and with a packing fraction of 0.8 represents a Q/V of 43 joules per cm^3 of winding volume, which is nearly two-thirds the EPR value. However, these values are not sufficient to produce large thermal strains, and we conclude that still larger values of Q/V would be useful.

6. Because of heat transfer considerations, in any test arrangement the test coil must be oriented with respect to gravity as will the large coil, i.e., the coil axis should be horizontal and its largest diameter vertical.

6. SELECTION OF A TESTING ARRANGEMENT

Several different testing arrangements were proposed as having the potential of meeting the requirements of the Large Coil Program that are described in Chapter 5. Different advantages were claimed for each of the arrangements, and cursory comparisons were inadequate to show which was the best overall choice. A methodical comparison in depth was required. The method that was laid out involved first a numerical scoring on specific criteria, then a choice from among those with highest scores, taking into account factors that are not amenable to quantitative evaluation, such as prospects for funding.

The first step was the generation of a list of criteria pertaining to specific testing goals, facility requirements, costs, and risks that could serve as a basis for evaluation and comparison. Each criterion was assigned a weight that reflects its importance to the accomplishment of overall program objectives. Each candidate testing arrangement was then evaluated and awarded a rating (between zero and ten) on each criterion. The product of the rating and the criterion value is the score for that arrangement on that criterion.

This section gives the criteria, descriptions of the candidate arrangements, the ratings and how they were arrived at, a discussion of more subjective evaluations and judgements, and finally our recommendations.

6.1 Test Arrangement Criteria

Table 6.1 is an annotated list of criteria, selected upon the basis of considerations which are discussed in other chapters. Despite the difficulties inherent in assigning rational weights to criteria that differ widely in kind, the weights that are shown in the table are regarded as a well-balanced assessment of the relative importances of various benefits and of costs, risks, and problems. They were arrived at by a version of the Delphi method,⁶ and represent the collective judgement of ORNL personnel involved in the technical management of the Large Coil Program.

Table 6.1 Criteria Used as Basis for Comparing
Large Coil Testing Arrangements

Criterion	Assigned Weight	Comments
<u>Benefits</u>		
1. <u>Coil Test Realism</u>		
1.1 Field distribution in winding	7	Relation between field vectors and conductor axes affect critical current. Field reversal in outer turns affects location of peak force in windings.
1.2 Field distribution around bore	8	Field variation around coil affects normal zone propagation.
1.3 Radial pressure in winding	10	Distribution and magnitude affects bending forces; magnitude, the radial compression of windings.
1.4 Out-of-plane forces	9	Distribution and magnitude affects bending; magnitude, the lateral forces in windings.
1.5 Total stored energy	6	Relevant to energy handling by protection system.
1.6 Unit stored energy	8	Affects propagation of normal zone, heatup on dump.
1.7 Pulsed fields	7	Realistic pulsed fields are essential; criterion measures practicality of providing.
2. <u>Coil Test Versatility</u>		
2.1 Capability for higher field	8	Measures feasibility of test coil with more amp turns reaching 11T while other coils are at <7.5 T.
2.2 Adaptability	6	Practicality of testing different intercoil structures, individual dewars, etc.
3. <u>Demonstration Value</u>	9	Value of system operation as visible evidence of maturing technology for tokamak reactors.

Table 6.1 Criteria Used as Basis for Comparing
Large Coil Testing Arrangements

(continued)

Criterion	Assigned Weight	Comments
<u>Costs</u>		
<u>4. Program Costs and Schedule</u>		
4.1 Scheduled test completion	6	Earliest date to completely test three different test coils.
4.2 Scheduled early results	4	Earliest date for test data for one test coil at full field and current.
4.3 Estimated program cost	10	Total program cost through start of testing.
4.4 Investment in non-relevant coils	5	Relevance measured in value of fabrication and test data to design of superconducting tokamak.
4.5 Conductor production rate	4	Measure of practicality of producing required conductor in time comparable to coil winding time.
<u>5. Program Risks</u>		
5.1 Impact of low performance	7	Probability and possible consequences of coil(s) not operable to full design field and current.
5.2 Impact of fabrication delays	8	Delay in test data due to delay in delivery.
<u>6. Facility Problems</u>		
6.1 Stray fields	4	Extent of fields of significance to personnel health and equipment operation in normal and abnormal operation.
6.2 Coil weight	2	Practicality of handling coils in test facility.

6.2 Descriptions

The five arrangements identified briefly below were selected for detailed comparison. All appeared to have promise of meeting at least the minimum requirements for testing either oval or D-shaped coils and each offered some advantage in one area or another.

- A. Compact torus of six "identical" coils in which the specified peak field is reached in a single coil when it operates at design current and the others operate at a lower current.
- B. Minimum compact torus of six "identical" coils designed for achieving the specified peak field when all coils operate at the full design current.*
- C. Cluster of three "identical" coils in which the two outside coils are operated at lower current density and field.
- D. Cluster of three coils, one test coil, and two background coils which operate at lower field and current density.
- E. Split eccentric array of three coils, one test coil and two background coils which operate at lower current density and field.

Consideration has also been given to another arrangement, recently proposed by the General Atomic Company, in which a racetrack-shaped background coil is located on either side of and at right angles to a D-shaped test coil. From the appearance in plan view, this is referred to as a "T" arrangement.

6.2.1 Reference Concept of Test Coil

For the purpose of making a quantitative comparison it is necessary to adopt a set of reference dimensions for the coils to be tested. For the comparison of arrangements A - E, it was assumed that the test coils would have the same shape as the TF coils in the ORNL EPR reference design.² One basic specification for all of the test coils was that they

*"Identical" here means that the coil size shape, and design current density are the same. Details of internal design could be quite different.

operate at a current density (averaged over the windings) of 2500 A/cm^2 * and a peak field in the winding of 7.5 tesla. The coil currents (and winding cross sectional areas) of the test coils vary somewhat depending upon the demands imposed by the geometry of the arrangement. Most of the test coils provide about 5 MA-turns; two have somewhat lower currents.

It should be noted that the comparisons and choice of testing arrangement will not be invalidated if the actual test coils should turn out to be of a somewhat different size and/or shape than the reference test coil. Most of the quantities of interest either do not vary or can be easily scaled. In the discussion which follows some of the calculated values are scaled to a coil height/width ratio of 1.5 while others are calculated only for a coil with ratio 1.34.

The coil shape and some dimensions of the test coil used in the numerical comparisons are shown in Fig. 6.1. Other dimensions specific to the testing arrangement are indicated in Figs. 6.2 and 6.3.

6.2.2 Testing Arrangements

A. Compact Torus. The compact torus concept that is now under consideration[†] consists of six coils, uniformly spaced in a toroidal array, having the same coil shape, size, and ampere-turns. Compatibility is insured by making these characteristics the same; internal designs of the coils could be quite different. Sufficient winding cross section is provided so that any one coil can be operated at its design field and current density while the other coils are operating at lower currents. (Each coil in turn can be tested in this way.) Figure 6.2 shows dimensions of coils for a compact torus in which the test coil operates at 2500 A/cm^2 and a peak field of 7.5 tesla while the other five coils operate at 2000 A/cm^2 .

* 1700 A/cm^2 is the value of current density averaged over the total area of winding and coil case of EPR thickness.

[†] Earlier considerations included toroidal arrays of 5 to 8 coils, in which one or two were test coils and the others were background coils of less advanced design, operating at lower current density.

CURRENT DENSITY	2500 A/cm ²
MAXIMUM FIELD	7.5 TESLA
A	3.0 m
B	4.0 TO 5.0 m
B/A	1.3 TO 1.5 m
WINDING AREA	0.20 m ²
AMPERE TURNS	5.1 x 10 ⁶
AMPERE METERS	70 x 10 ⁶

Fig. 6.1 General Characteristics of Test Coils

		Meters					Winding Area (m ²)	Current Density (A/cm ²)	Amp. Turns Per Coil	Amp. Turns For Test	Ampere Meters Per Coil	Ampere Meters For Test
		R ₀	d	a ₁	a ₂	2b						
Minimum Compact Torus	All Coils	2.33	.05	1.50	1.883	.524	.2007	2500.	5.02 x 10 ⁶	30.1 x 10 ⁶	66.2 x 10 ⁶	397 x 10 ⁶
Compact Torus	Test Coil	2.51	.05	1.50	1.948	.532	.2383	2500.	5.96 x 10 ⁶	29.8 x 10 ⁶	79.8 x 10 ⁶	479 x 10 ⁶
	Other Coils							2000.	4.77 x 10 ⁶			

Values are for 1.5 Aspect Ratio Coils.

Fig. 6.2 Compact Torus Tests Data

The maximum field in the other coils in this situation is 6.5 tesla. If all six coils were operated at 2500 A/cm^2 , the peak field in each would be 8.1 tesla. The proportions were chosen to permit an array with near minimum aspect ratio consistent with a near-square winding cross section.

B. Minimum Compact Torus. The minimum compact torus is also composed of all test coils. The difference is that each coil is designed to carry fewer ampere-turns at the design field than are the coils in the compact torus. Figure 6.2 shows dimensions used in the quantitative comparisons; in this case a peak field of 7.5 tesla is produced when all coils are operating at 2500 A/cm^2 .

C. Cluster of Identical Coils. The dimensions of this arrangement, assuming 7.5 tesla peak field in the center (test) coil when it carries 2500 A/cm^2 and the outside coils carry 2000 A/cm^2 , are shown in Fig. 6.3. (The peak field in the outside coils is 5.6 tesla.) The angle, ϕ , between coils and the offset distance Δ can be varied to affect the field and force distributions. The values chosen afford a reasonable approximation of the distributions in the EPR coils.

D. Cluster with Background Coils. If the background coils can be different from the test coil, they can be tailored to reduce the total amount of conductor required to test a given test coil. Figure 6.3 shows a cluster test in which the test coil is the same as in arrangement B (minimum compact torus) but the background coils are smaller in both the horizontal and vertical dimensions.

E. Split Eccentric. By moving the background coils as close as possible to the test coil, the conductor requirements can be further reduced. In the split-eccentric arrangement, the test coil is sandwiched between two parallel background coils as shown in Fig. 6.3. As in arrangement D, the background coils are smaller than the test coil. (A split eccentric using three identical coils is less attractive than a cluster of identical coils; i.e., $\phi = 0$ is not the best in this case.)

T Arrangement. The basic idea of this concept is to use two background coils that are specially shaped and positioned so as to minimize the conductor required to provide a specified field at a given test coil. Figure 6.4 depicts the particular arrangement proposed by General Atomic,

		Meters						Winding Area (m ²)	Current Density (A/cm ²)	Amp. Turns Per Coil	Amp. Turns For Test	Ampere Meters Per Coil	Ampere Meters For Test
		d	Δ	φ	a ₁	a ₂	2b						
Cluster of Three Identical Coils	Test Coil	.12	.25	20°	1.50	2.04	.42	.2268	2500.	5.67×10^6	14.8×10^6	77.6×10^6	233×10^6
	Other Coils								2000.	4.54×10^6			
Cluster Test With Background Coils	Test Coil	.12	.65	20°	1.50	1.883	.524	.2007	2500	5.02×10^6	13.8×10^6	66.2×10^6	172×10^6
	Background Coils				1.25	1.913	.332	.2200	2000	4.40×10^6			
Eccentric Test With Background Coils	Test Coil	.12	.32	0°	1.50	1.883	.524	.2007	2500.	5.02×10^6	13.6×10^6	66.2×10^6	164×10^6
	Background Coils				1.34	2.08	.29	.2146	2000.	4.29×10^6			

Values are for 1.5 Aspect Ratio Coils

Fig. 6.3 Three-Coil Test Configurations Data

Fig. 6.4 General Atomic Test Bed Concept

in which the test coil has a straight inner leg and the background coils are racetrack shape, at right angles to the test coil.

Two test configurations that are similar to the GA concept but which are capable of testing somewhat larger coils have been defined and evaluated. To allow meaningful comparison with other LCP candidates under consideration, the current densities are $2,000 \text{ A/cm}^2$ in the background coils and $2,500 \text{ A/cm}^2$ in a test coil the size of a minimum compact torus coil. Space is not allowed for structure, which means that the actual current density in the winding area will be higher than the nominal figures just quoted or the coils must be further apart which means that more ampere-turns will be required. Figure 6.5 shows schematically the arrangement and size of the coils in the two configurations. The hole in the center of the first configuration reduces the radial field component in the outside corners of the inner leg of the test coil. The second configuration does not have that hole and consequently has smaller background coils.

Vacuum Enclosure. The vacuum required for the thermal insulation of the coils and cold structure can be provided either by a single chamber ("bell-jar") surrounding the entire assembly or by closer-fitting enclosures ("dewars"). The diameter and height of the minimum size bell-jar for each of the arrangements are listed in Table 6.2. Section 6.4 discusses the relative advantages and disadvantages of bell-jars and dewars.

6.3 Performance Data

Figures 6.2 and 6.3 summarize characteristic dimensions and data that are pertinent to a comparative evaluation of arrangements A — E. (Data for arrangements like that proposed by General Atomic are presented later.) Other pertinent information is presented in Figs. 6.6 — 6.16.

Magnetic field and force distributions for each of the testing concepts were calculated using the computer code BOVAL, which takes full account of the winding cross section and coil shapes. The magnetic field distribution in the nose region of the coil windings are shown in Fig. 6.6. The stray fields in the vicinities of the different test setups are shown in Fig. 6.7. This figure shows that the fields around the compact torus

Fig. 6.5 Alternate GA Configurations

Table 6.2 Vacuum Enclosure Requirements

Configuration	Vacuum Bell Jar Size	
	Diameter — m	Height — m
A. Compact Torus	10.4	9.3
B. Minimum Compact Torus	10.4	9.3
C. Cluster of Identical Coils	8.3	9.5
D. Cluster with Background Coils	8.3	9.5
E. Split Eccentric	7.2	9.8

Fig. 6.6 Magnet Field Distribution in Coil Nose Midplane

CLUSTER TESTS

PARTIAL COMPACT TORUS TESTS

Contours at 100
gauss intervals

Contours at 10
gauss intervals

Fig. 6.7 Stray Field Distributions

Fig. 6.8 Comparison of Axial Magnetic Field at Coil Mid-Plane; Compact Tori.

Fig. 6.9 Comparison of Axial Magnetic Field at Coil Mid-Plane: Three Coil Arrangements

Fig. 6.10 Comparison of Axial Magnetic Field at Coil Inner Bore: Compact Tori.

Fig. 6.11 Comparison of Axial Magnetic Field at Coil Inner Bore: Three Coil Arrangements.

Fig. 6.12 Comparison of In-Plane Force per Unit Winding Area of Coil: Compact Tori.

Fig. 6.13 Comparison of In-Plane Force per Unit Winding Area of Coil: Three Coil Arrangements.

Fig. 6.14 Comparison of Out-of-Plane Force per Unit Winding Area of Coil: Compact Tori.

Fig. 6.15 Comparison of Out-of-Plane Force per Unit Winding Area of Coil: Three Coil Arrangements.

Fig. 6.16 Comparison of Out-of-Plane Force per Unit Winding Area of Coil: Cluster of Three Identical Coils

with one or more coils deenergized are higher than in its normal operation, but still lower than for the other kinds of arrangements.

Figures 6.8 and 6.9 show radial profiles of the toroidal field strength across the horizontal midplane of test coils in the various arrangements. Shown for reference are the toroidal field distributions in the ANL and ORNL EPR reference designs. (The distribution in the GA EPR design is not shown because it is practically the same as in the ANL design.) From the standpoint of coil structural design, the field variation around the winding is of greater importance. This is shown in Figs. 6.10 and 6.11.

The vector product of the toroidal field and the conductor currents are the in-plane forces on the windings. Figures 6.12 and 6.13 compare forces per unit area at the outside of the winding, assuming that none of the force is restrained by the winding, but is transmitted to a surrounding structural hoop. This shows the magnitude of this component of the winding stress-strain problem.

Figures 6.14 and 6.15 show out-of-plane forces on test coils in the various arrangements and in the EPR coils for the case in which one adjacent coil is completely deenergized while other coil currents remain constant. In normal operation of the cluster test arrangement, the outside coils are subjected to large out-of-plane loads as shown in Fig. 6.16.

The T arrangement was analyzed by calculating fields and forces in the test coil, using the computer program BOVAL. Figures 6.17 and 6.18 show the field values at the coil midplane and the lateral fault load distributions compared with the corresponding distributions of other arrangements. Both T-type configurations have a maximum field of 7.2 tesla compared with 7.5 tesla for the other configurations that were evaluated. Table 6.3 compares these two T-type test arrangements and the original GA version with the other LCP candidates with respect to ampere-meters of conductor required. The values in the table for the two modified test arrangements have been scaled up from the 7.2 tesla values to 7.5 tesla values.

Fig. 6.17 Comparison of In-Plane Force per Unit Winding Area of Coil: GA Concept.

Fig. 6.18 Comparison of Out-of-Plane Force per Unit Winding Area of Coil: GA Concept.

Table 6.3 Comparison of "T" Arrangements with Other Concepts

Configuration	Max. field in test coil	Amp-meters in test coil ^a	Amp-meters in "background" coils	Total amp-meters in test
Minimum Compact Torus	7.5	66.2×10^6	331×10^6	397×10^6
3 Identical Coil Cluster	7.5	77.6×10^6	155×10^6	233×10^6
General Atomics Original Concept ^{b,c}	7.9	23.9×10^6	183×10^6	207×10^6
T-type Adaptation I ^c	7.5	66.2×10^6	178×10^6	244×10^6
T-type Adaptation II ^c	7.5	66.2×10^6	128×10^6	194×10^6

^aAll test coils have 3.0 x 4.5 meter inner bore.

^bMaximum field in the background coil of 9.1 T.

^cNo space allowed for coil structure.

6.4 Vacuum Topology Considerations

In the design of the LCP test facility, the type of vacuum enclosure that is chosen not only affects the design of auxiliary vacuum and cooling systems, but also constrains the range of experiments that can be performed in the facility. The following is a general discussion of factors which have been considered in deciding which type of vacuum enclosure to recommend.

Two systems were considered: (1) a large, cylindrical vacuum vessel (bell jar) which would enclose the entire assembly of coils and structure, and (2) a form-fitting dewar consisting of a small central vacuum cylinder housing the noses of all the coils with individual coil dewars extending from it. The factors involved in the comparison include fabrication, interfaces and penetrations, cost, pumpdown and cooling tradeoffs, adaptability to experiment variations, and relevance to operational tokamak installations.

Fabrication - The detailed design and fabrication of a bell jar enclosure would be very similar to that of numerous vacuum chambers that have been built for the aerospace industry and others. The bell jar could therefore be designed and constructed with a minimal amount of risk or delay. A fitted dewar, on the other hand, would require innovative design and possibly some new construction techniques.

Interfaces - Plumbing, thermal isolation of supports, and vessel penetrations would all be simpler in a bell jar design. The entire coil array and its associated structural support system would be within the bell jar. Therefore, interfaces for instrumentation and control leads can be designed as typical vacuum wall penetrations entering at just a few selected points without constraints due to interactions with coil designs. Thermal isolation can also be accomplished efficiently by grouping items to minimize heat leaks.

With a fitted dewar, special thermal isolation supports would be required to transition from the coils and support structure to an external foundation. Also, plumbing and diagnostics penetrations could be expected to be more numerous.

Cost — Preliminary conceptual design studies have been made and the fabrication tasks sketched out to provide an approximate estimate of costs of material and labor to construct a bell jar or a fitted dewar. In the estimates, the increased cost of labor due to complicated sealing surfaces and contours in the fitted dewar make up for larger material costs of the bell jar. As a result the estimated total costs are within 20 percent of each other. A considerable degree of uncertainty exists in the estimates for the fitted dewar because they are based purely on limited conceptual studies of a complicated system and might be expected to increase when the design is more fully engineered. The bell jar costs, on the other hand are directly related to cost data received in response to preliminary inquiries to industry. The conclusion is that because of uncertainty in the cost estimates, no significant cost advantage can be ascribed to either the bell jar or the dewar.

Pumpdown — The pumpdown volume in a bell jar is estimated to be about three times that of the fitted dewar. However, the bell jar will have substantially better conductance than the dewar and will require less than three times the pumping capacity. The surface area for outgassing and thermal (radiation cooling) considerations is approximately the same in both cases. Pumpdown times and cold wall requirements are essentially equal for the two concepts. The physical building space required is also nearly identical for both systems.

Adaptability — The dewar system does not easily lend itself to variations in coil shape, size, or test arrangements. Modifications to the coil design or test arrangement would have to consider dewar restrictions rather than only coil related options. In a bell jar, various test arrangements and coil shapes could more easily be accommodated. For example, a bell jar designed for a compact torus could accommodate any of the other arrangements.

Relevance — Conceptual studies have not yet firmly established the optimum boundaries of the vacuum enclosure in a tokamak reactor. It is already clear, however, that a simple, all-encompassing bell jar will not be suitable. Separate dewars, closely fitted to each coil are also unlikely. Most probably the reactor vacuum enclosure will house the toroidal

field coils, their intercoil structure and helium piping, and at least some parts of the ohmic heating coil system. The fitted dewar in a Large Coil Test may not model a reactor enclosure in all regards, but clearly many more of the engineering design problems of this type of enclosure would be encountered than if a bell jar were used. Because the solutions of these problems would be relevant to the design of a reactor, the fitted dewar would offer more benefits in this particular regard.

Conclusions — The use of a fitted dewar for vacuum enclosure entails more design and fabrication problems than does a bell jar, with increased risk of cost overruns and delays. The testing program can be more quickly accomplished in a bell jar, especially if the test arrangement requires shifting the positions of coils. The bell jar would allow greater flexibility for different sizes of coils or arrangements. On the other hand, solutions of the engineering problems of the fitted dewar would be of greater benefit to reactor conceptual design.

6.5 Discussion and Ratings

The ratings of the different test arrangements against each criterion were arrived at by considering the data shown in section 6.3 in light of the basic significance of the criterion as presented in Chapter 5. On each criterion the best arrangement in that particular regard was awarded a rating of 10. For criteria where there is little practical difference among the arrangements, the range of ratings was rather narrow. For other criteria, arrangements with substantially poorer performance were rated as low as 3.

Table 6.4 summarizes the ratings and scores of each arrangement. Discussion of the considerations of the three-person rating panel follows.

Field Distribution in Windings — The field strength profiles through the windings at the coil midplane, shown in Figs. 6.6, 6.8, and 6.9, reveal field reversals both in the EPR cases and in all the test arrangements. The magnitude of the reversed field is greater in the test arrangements than in the EPR.

Table 6.4 Ratings and Scores

[illegible]

Examination of Fig. 6.6 shows that the field distribution in the nose region of the test coil in any of Cases A-E is qualitatively quite similar to that in the EPR coils. The principal difference is that the gradients of the fields are oriented somewhat differently near the sides of the windings. Associated with this is a larger radial component of the field in these regions. Because some flat conductors have a lower critical current in the presence of a large field component perpendicular to the face, this characteristic of the test coils results in a somewhat more stringent condition than will be encountered in the EPR.

It appears that any of arrangements A-E would satisfactorily meet this criterion, little practical difference among them.

Field Distribution Around Bore — In none of the test arrangements is the ratio of maximum to minimum fields as high as in the EPR. Higher ratios are generally preferable, but the rating of arrangement E was penalized because the shape of the curve (Fig. 6.11) is less like the EPR distributions.

Radial Pressure in Winding — From the standpoint of testing the winding in radial compression, the higher the peak equivalent pressure shown in Figs. 6.12 and 6.13, the better. The significance from the standpoint of the structure is related to both the magnitude and the shape. Arrangement E is perceptibly poorer in both regards.

Out-of-Plane Forces — This criterion relates both to testing the structure for out-of-plane bending and to observing the effects of lateral forces in the windings. In the ratings the former was considered more important. Thus Arrangement E, although it offers the highest lateral pressure, is rated low because the distribution around the coil is markedly different from that in the EPR tori. Arrangement D is also rated low because the shape is only slightly better and the pressure is lower. Arrangement C was given top rating because the out-of-plane forces on the two outside coils, which are also test coils in this case, are very close to the equivalent pressure and distribution of forces on an EPR coil when an adjacent coil is deenergized. (See Fig. 6.16.)

Total Stored Energy — The ratings here are proportional to the magnitudes of the stored energy. (See Table 6.5.)

Table 6.5 Stored Energy Comparison

	Total stored energy of array (Mega Joules)	Energy per unit volume of winding in test coil (MJ/m ³)
ORNL-EPR (scaled to 7.5 tesla)	14,000	73
ANL-EPR	15,000	67
A. Compact Torus	670	48
B. Minimum Compact Torus	700	44
C. Cluster of three identical coils	390	55
D. Cluster with background coils	310	52
E. Split eccentric test	420	67

All test coils assumed to have 3.0 x 4.5m inner bore.

Unit Stored Energy — These ratings are also proportional to the magnitudes. (See Table 6.5.)

Pulsed Fields — It is an essential requirement that the test coils be subjected to pulsed fields similar to those in the EPR, and all five arrangements permit this. The difficulty of providing for the pulsed fields differs among the arrangements, however. Because conceptual design has not been done in sufficient detail to permit determination of the impact on project cost, the same allowance for providing pulsed fields is included in the approximate cost estimates for all arrangements. The ratings on this criterion therefore reflect basically the relative freedom of the test coil bores from special structure that would interfere with installation of the pulsed windings.

Capability for Higher Field — All five arrangements can accommodate test coils in which the peak field reaches 11 tesla while the peak field in the other coils is 8 tesla or less. As shown in Table 6.6, however, there are considerable differences in the conditions in the other coils and the amount of conductor required for the high field test coil. The minimum compact torus was rated lowest because the other coils must operate at the highest current density and field (2500 A/cm² and 8.0 tesla) in order to achieve the desired 11 tesla in the test coil. The ratings of arrangement A and, to a lesser extent, that of C were penalized for the greater amount of conductor required.

Adaptability — The layouts of the clusters and tori are quite compatible with testing individual dewars modeling those in a tokamak; the split eccentric test is not. On the more important point of testing various intercoil structures, the clusters are best because the angle between coils is nearest that in a tokamak. The split eccentric, with parallel coils, is poorest.

Demonstration Value — Any of the arrangements would demonstrate the successful fabrication and reliable operation of a superconducting magnet system exceeding in many important regards anything yet built. Those arrangements for which two coils of a single design are produced in sequence will provide information on reproducibility and the improvements due to

Table 6.6 Comparison of Higher Field Test Coil Capability
(11.0 tesla test coil parameters)

	a ₁	a ₂	2b	Current density of test coil	Ampere turns	Ampere meters	Current density of background coils	Maximum field in background coils (T)
A. Compact Torus	1.00	1.948	.534	2500	12.7 x 10 ⁶	149 x 10 ⁶	2000	7.1
B. Minimum Compact Torus	.98	1.883	.524	2500	11.8 x 10 ⁶	135 x 10 ⁶	2500	8.0
C. Cluster of three identical coils	0.95	2.04	.42	2500	11.4 x 10 ⁶	135 x 10 ⁶	2000	5.9
	1.05	2.04	.42	2500	10.4 x 10 ⁶	128 x 10 ⁶	2500	7.1
D. Cluster test with background coils	1.05	1.883	.524	2500	10.9 x 10 ⁶	130 x 10 ⁶	2000	5.2
E. Eccentric test with background coils	1.10	1.883	.524	2500	10.3 x 10 ⁶	123 x 10 ⁶	2000	5.4

learning. This is a plus for the tori and, to a lesser extent, for arrangements D and E which each use two background coils.

As an easily recognizable demonstration of progress in fusion power development, the value of test operations will depend on how closely the essential features of the system approach those of a tokamak reactor. The full torus would seem most like a complete tokamak magnet, although the intercoil angle in the clusters is more representative and the cluster of identical coils thus resembles a sector of a toroidal field magnet. Reliance upon background coils, which run at lower current density than a single test coil, is felt to detract. The split eccentric test is rated lowest because its configuration is least like that of a tokamak magnet.

Schedule — Presumably the delivery date of the first coils would be the same in any case. Test program schedules were laid out in order to estimate times from start of coil installation to the two milestones of completion of full-field testing on one test coil and completion of all testing on three test coils. All necessary steps, such as changing the center coil in the three-coil arrangements, were included in the time-lines.

On criterion 4.1, arrangements A, B, and C all received top rating, since completion dates were all within one month of each other. (Full-field testing starts sooner with C but takes longer because of the necessity of shifting coils.) Test completion dates for D and E are 8 to 9 months later, reflecting the time required to fabricate the second background coil on the same line as the first. (The delivery date of the last coil is the same as for the the 6-coil tori, but the testing takes longer.) These two were rated at 6.

The cluster of identical coils (arrangement C) promises the earliest completion date for full-field testing of a single coil and therefore received top rating on criterion 4.2. Because of the delay for the sequentially produced background coils, the first full-field test data from arrangements D and E would be 8-9 months later, so they were rated considerably lower. The tori were rated at 8 because they can provide partial-field test data from three different test coils at about the same time as full-field data from one coil in arrangement C. (Substantial fields and forces can be obtained with only three of the six coils installed in the torus framework.)

Estimated Program Cost — Clearly the lower the better and the lowest rates a 10. The question of how low to rate the higher cost arrangements, on the other hand, must be answered in light of one's perception of the feasibility of increased funding. If several arrangements are at least acceptable from the technical standpoint, several million dollars difference in cost could be regarded not merely as penalizing but as absolutely prohibiting the higher cost alternatives. We assumed that any of the five could be funded and arbitrarily assigned a rating of 5 to the most expensive.

Non-Relevant Coils — Arrangements D and E must be penalized here, but since even the background coils have substantial value in advancing the technology, a rating of 6 was awarded.

Conductor Production Rate — The required production rate of 15 tons/month for D and E, while practical, will impose much more strain on capabilities than the 9 tons/month for Arrangement B. A rating of 5 was therefore assigned to the highest rates.

Impact of Low Performance — This criterion combines the probability of a coil or coils achieving substantially less than required current and the severity of the depreciation of the test results under reduced conditions. In the minimum compact torus, failure of any coil to reach its nominal current rating would diminish the field attainable at the other coils, but would not preclude all testing. For this reason it was given a rating of 5. In the compact torus and the cluster of identical coils, if one or two designs of test coil reached only 80% of nominal current rating, the other design(s) could still be tested at full field. The same is true of arrangements D and E, but because there is the added possibility of deficient background coils, they were rated at 8.

Impact of Fabrication Delays — The question here is how much delay there would be in getting a full-field test of the other coils if delivery of one kind of coil were delayed. In the compact torus, it would be possible to run up the current in the available coils, compensating to a large degree for the missing coil. In cases D and E delay of one test coil would make no difference on the others; delayed delivery of a background coil would, of course, hold up testing. For the cluster of identical

coils, all three test coils must be available before the first can be tested so this arrangement was rated poorest.

Stray Fields — In normal operation, the tori produce very low stray fields and only moderate stray fields with one coil deenergized. The 3-coil arrangements, on the other hand, produce high stray fields at all times and were therefore given a rating of 4.

Coil Weight — Although there are differences in coil weights, all are within the capability that can be easily provided. All arrangements were therefore given a rating of 10.

A detailed point-by-point evaluation of the T-type arrangement was not made to the same degree employed in rating the other candidate arrangements. However, comparisons were made for the criteria which carry substantial weights in order to rank this concept relative to the other candidates. Where possible, calculated data were used in this comparison. The result of this review indicates that these concepts would fall in the same range of scores developed for candidates D and E. This conclusion applies to both the category of benefits as well as costs and program risks. The conclusions reached for the candidates which employ background coils will apply equally well for these concepts.

6.6 Conclusions and Decision

Salient conclusions from the scores in Table 6.4 are as follows:

- The total scores in the area of benefits are not greatly different for the two compact tori and the cluster of identical coils. The cluster with background coils is slightly less attractive and the split eccentric is clearly the poorest.
- Total scores in the general area of costs and risks favor the compact torus and the cluster of identical coils. The other three are about even.
- In view of the inexactness of the rating process, the very small differences among the grand total scores for the compact torus, the minimum compact torus, and the cluster of identical coils cannot be regarded as significant. The score for the cluster

with background coils is distinctly lower and the split eccentric test is lowest of all.

Analysis of the scores on individual criteria in the area of benefits shows that the tori are in some technical respects more "realistic" than the cluster of identical coils and were judged to have greater demonstration value. The cluster is more "versatile" and provides an especially realistic test of out-of-plane forces, but these scores are not enough to offset lower ratings in total stored energy and simplicity of providing pulsed field windings. In the area of costs, risks, and problems the totals for A, B, and C are not far apart. As might be expected from superficial considerations, however, there are quite large differences in scores on individual criteria. The biggest advantage of the cluster is in program cost, although it also rates top score on impact of a low-performance coil. It suffers with regard to impact of late delivery and stray fields. The rationale for the compact torus shows in higher scores relative to the minimum torus in the impact of a low-performance or late coil.

The foregoing analysis showed that some of the pivotal scores involve judgements. That is, they depend upon the perception of values to the broad program of fusion development and the importance of costs and schedules. Thus, although the scores were the results of a rational process and reasonably unbiased, they were useful primarily as a mechanism for drawing attention to different advantages and disadvantages of the various test arrangements; i.e., the definition and weighting of the criteria and the discussion of the ratings promoted a better understanding of the technical issues.

The final decision on the type of test arrangement was based upon an understanding of the differences among the arrangements, and was made in light of the demand of the fusion program for early, definitive results and the prospects for funding. It was recommended by ORNL and accepted by DMFE that planning and conceptual design proceed on the compact torus test arrangement.

7. COST ESTIMATION

The procedure used to generate cost projections for each of the candidate testing configurations evolved from several previous studies at ORNL. These include conceptual design efforts on a three-meter bore cluster test arrangement and an eccentric coil test array, investigation of the possible variations in built-up superconductor fabrication costs, and a detailed preliminary cost estimate for a reference conceptual design of a superconducting tokamak.^{7,8}

The projected costs for test coils are particularly sensitive to the conductor cost calculations, which must be regarded as only approximations until coil conceptual designs and conductor fabrication procedures have been determined in detail. The data presented in this chapter are useful for determining relative costs and for establishing the approximate magnitude of total program costs.

For the purpose of scaling and exploring the effects of limited variations in design, the estimated coil costs were broken down into 26 separate items, with each item further divided into material and labor categories as applicable. Rational cost-size scaling relationships were determined for each item, with coefficients determined from previous design data or developed specifically for the item. Several computer programs were used to calculate test and background coil operating characteristics and dimensions, geometric limitations, component part weights, and supporting systems requirements. These data were then used with the appropriate cost relationships to determine a scaled cost for each component and system.

Program costs are divided into the cost of the coils, the special facilities required, standard equipment, assembly of the facility and experimental components, engineering, and contingency. Basic costs are calculated in FY-76 dollars. Appropriate factors for escalation, overhead, and technical support are applied to determine a total program cost.

Coil costs include conductor and structural material and labor for fabrication and winding. In those cases where more than one coil of a

particular type is to be built, a reduction factor is applied to appropriate labor items to account for potential learning associated with fabrication of an identical second item. Engineering design costs for each coil type are only applied to the first coil fabricated of any particular design.

Facility costs include material and labor for all special facilities and the standard equipment that is required. The cost projections for the various test facility configurations include costs associated with remodeling an existing building and coupling to existing utility interfaces. Each test configuration was evaluated separately, with vacuum enclosures, structural supports, and building modifications tailored to each specific concept.

Assembly costs are included for all applicable items. Where the configuration requires that a sequence of coils be installed in a single test coil position, the cost of removing coils is also included. For example, the cluster test with background coils requires assembly of three coils, one test and two background, for the initial test configuration. The program assumption is that a total of three test coils would be tested in the center position. Installation of the second test coil requires removal of the first test coil and installation of the second coil in its place. This must be repeated for the third test coil.

A tabulation of the basic cost elements is given in Tables 7.1 and 7.2, with summary comments relative to the method, source of information, or the cost factors used in developing the cost projections. The four items in Table 7.1 are related to the costs of the test coils and the different conductor types which were used in determining the costs to be used for this study. Table 7.2 lists test stand cost items, other than the test coils themselves, with summary comments relative to the source of information used in developing cost projections. The paragraphs that follow develop in more detail the process followed in determining the costs for each of the items in Tables 7.1 and 7.2.

Table 7.1 Cost Elements for LCP Test Coils

Item No.	Item	Form of Cost Factor
1.	CONDUCTOR (BUILT-UP CONCEPTS)	
a.	Composite (NbTi + Cu)	\$/kg
b.	Additional Copper	\$/kg
c.	Fabrication (estimate on basis of detailed analysis of time and complexity of process steps, then express as function of conductor characteristics)	\$/A-m
2.	COIL FORM (BOBBIN)	
a.	Material (stainless steel in reference designs)	\$/kg
b.	Fabrication (estimate cost of machining, welding, etc., then express as function of a characteristic dimension, namely mean perimeter)	\$/m
3.	WINDING (CONDUCTOR ON BOBBIN)	
a.	Special Tooling (fixed cost)	
b.	Labor Cost (expressed as a function of conductor characteristics)	\$/A-m
4.	STRUCTURE (HOOP CLOSURE)	
a.	Material (stainless steel)	\$/kg
b.	Fabrication (estimate labor costs, then express as function of mean perimeter)	\$/m

Table 7.2 Cost Elements for LCP Test Stand

Item No.	Item	Source of Cost Data
5,6, and 7	Coil Support Structure: (restraints, gravity supports)	Engineering design, analysis and cost estimates for each of the contending configurations. <u>Function of:</u> Number of coils (N), configuration
8,9, and 10	Vacuum System: (vessel, pumps, insulation, cold wall)	Eng. design, analysis, cost estimates for each configuration, supplemented by responses from industrial inquiries. <u>Function of:</u> N, configuration
13	TF Power Supplies:	Cost based on previous estimates. <u>Function of:</u> N
11, 12, and 14	Pulsed Coil System: (coils, supports, power supplies)	Engineering preliminary design, analysis and previous similar concepts cost estimates <u>Function of:</u> Pulsed coil weight, arrangement, and duty cycle.
15	Machine Supports: (base supports other than building foundation)	Engineering analysis and cost estimate supported by previous cost estimates. <u>Function of:</u> Configuration and coil weight.
16	Instrumentation and Controls: (sensors, conditioning, readouts)	Engineering estimates relative to number and type of sensors required for test coils and facility. Average costs for sensors, conditioning equipment, and readouts based on previous cost estimates. <u>Function of:</u> N
17	Data Handling (computer hookup and control room equipment)	Based on previous cost estimates. <u>Function of:</u> N

Table 7.2 (continued)

Item No.	Item	Source of Cost Data
18	Cryogenic System: (tie-in to existing facility, LN ₂ , LHe)	<u>Constant</u> cost based on previous cost estimates
19	Building Power Mods:	<u>Constant</u> cost based on previous cost estimates.
20	Utilities: (water, GN ₂ , air, LN ₂ piping)	<u>Constant</u> cost based on previous cost estimates.
21	Building Modifications: (H and V, control room, etc.)	<u>Constant</u> cost based on previous cost estimates.
22	Standard Equipment:	<u>Constant</u> cost based on previous cost estimate.
23.	Maintenance Equipment:	<u>Constant</u> cost based on previous cost estimate.
24	Electrical Special: (busing, cables, wiring, etc.)	<u>Constant</u> cost based on previous cost estimate.
25	Civil and Architecture Special: (machine foundations)	Engineering design, analysis and cost estimate, supported by previous cost estimates.
26	Mechanical Special: (fixtures, handling equipment)	Engineering design supported by previous cost estimates. <u>Function of:</u> weight of coils

1. Conductor — Costs were developed using the following approach. The cost of the superconducting composite portion of the conductor, which is made up of superconducting filaments plus some copper, was determined based on data for present costs in dollars/kg. Added to this is the cost of additional copper required to achieve the desired overall copper to superconductor ratio. Fabrication costs to convert these basic elements into a finished built-up conductor were then determined. This cost was estimated on the basis of a detailed analysis of the time and complexity of process steps and reduced to a characteristic of the conductor, namely ampere-meters. Four different conductor types were evaluated and cost factors determined for each. Coil costs for the program assume use of three different conductors and include the conductor types which resulted in the highest and lowest fabricated costs and an averaged value based on the two other conductors that were evaluated.

For the purposes of cost scaling the sum of superconducting composite, additional copper, and the fabrication process costs have been combined into a single term and expressed as a function of ampere-meters. This allows calculation of conductor costs with variations in coil size and current density.

2. Coil Form (Bobbin) — These costs were developed in two parts. The first element is the amount of material (stainless steel) required which is determined from material thicknesses derived from stress calculations. The cost of this portion of the bobbin is based on \$/kg of material. The second cost element is the expense associated with fabrication. This cost is based on estimates of machining, welding, and inspection derived from a detailed cost estimate made in support of a previous superconducting coil conceptual design.^{7,8} Cost scaling relationships assume that the fabrication portion of these costs can be reduced to a function of a characteristic coil dimension, namely the mean perimeter of the bobbin structure.

3. Winding (conductor onto the bobbin) — This cost is made up of two factors: special tooling and labor cost. Tooling required includes cleaning, joining, and tensioning mechanisms with costs for these items

assessed only against the first coil manufactured of a given type. Labor costs were estimated based on analysis of tasks required and relative speed and manpower required for each. Assuming that the conductor size remains reasonably constant, the winding costs can be expressed as a function of ampere-meters plus a fixed cost for equipment.

4. Structure (hoop closure) - This cost is developed in a manner similar to that discussed for item 2 above. Material costs are based on \$/kg taking into consideration the heavier section metal required, and fabrication costs are again derived from a previous conceptual design. Cost scaling is based on the mean perimeter of the enclosing structure.

The sum of items 1 through 4 plus engineering costs associated with the design and fabrication of a complete coil represent the cost of a single coil.

The following cost items comprise the test facility, special equipment, standard equipment, and building modifications for the LCP. Cost scaling relationships have been developed for each where necessary to permit cost calculations for the several testing arrangements including variations in coil size.

5. Coil Support Structure (centering force restraint) - A bucking cylinder has been designed to resist the centering forces which is essentially a thick-walled, externally pressurized cylinder where the distributed centering forces are assumed to act as a uniform pressure. The height of the cylinder is taken to be equal to the horizontal bore of the coil. Material cost is based on thicknesses derived from stress calculations converted into the mass of material required and priced in \$/kg. Labor costs are based on fabrication processes including rolling to shape, welding, and machining. Time and manpower estimates were made and costs determined as a function of the radius of the bucking cylinder.

6. Coil Support Structure (intercoil supports) - Wedged-shaped box beam type structure has been assumed for the intercoil supports for the compact torus and cluster test configurations. A system of reinforced plates to react the out-of-plane forces has been assumed for the eccentric test configuration. Previous conceptual designs employing similar

structure have been reviewed to establish appropriate cost relationships for material and labor as a function of coil dimensions or test configuration characteristics.

7. Coil Support Structure (gravity supports) — A system of posts and beams from which the test array can be supported has been assumed for the cluster and eccentric test configurations. This is similar to concepts proposed in earlier conceptual design studies. Gravity support for the compact torus concepts is included in item 15 as machine supports. Material and labor costs are determined for each candidate arrangement as a function of the weight of the coils.

8. Vacuum System (vacuum vessel) — A bell-jar type vacuum enclosure has been assumed and analyzed for each of the test configurations. Stress calculations were used to determine material required and the fabrication steps were reviewed to estimate the amount of forming and welding necessary. A preliminary inquiry was transmitted to industry soliciting inputs relative to cost and schedule for fabrication of a bell jar sized at the mean of the range under consideration. Responses to this inquiry were used to normalize the cost calculations used in this study. Costs were determined for the compact torus, cluster, and eccentric test arrangements as a function of coil size. Apportionment of material and labor costs were based on industry responses to the preliminary inquiry.

9. Vacuum System (vacuum pumping) — Pumping systems were assumed to be identical for the range of vacuum vessel sizes considered. Costs include diffusion pumps, backing pumps, and miscellaneous valving and piping.

10. Vacuum System (liquid nitrogen cold wall) — An enclosure consisting of a liquid-nitrogen cooled copper plate was assumed to provide thermal control within the bell jar. Separate enclosures were designed for each of the test arrays and costs determined as a function of coil size. Material costs are based on the amount of copper plate and tubing with labor costs estimated for the fabrication steps required.

11. Pulsed Coils (coil case and conductor) — A liquid-nitrogen cooled copper coil set in which one coil provides a pulsed field parallel to the

test coil conductor while a second coil provides a perpendicular component has been defined for all the test arrangements. These coils are solenoids with a bore of 1.2 m and a length of 1.0 m. The winding concept is to use commercially available conductor and wind it on a stainless steel coil form. Material costs are calculated based on the weights of copper and stainless steel required with labor costs estimated as a factor times the material cost.

12. Pulsed Coils (supports) - A stainless steel frame similar to the gravity support structure defined for the cluster and eccentric arrays is assumed adequate to support the pulsed coils. Cost factors derived for the gravity supports have been used to calculate the cost for these supports. Material cost is a function of the weights of materials involved with labor costs estimated by factoring the material cost.

13. Power Supplies (test coils) - Power supply costs for the test coils assume that a module consisting of a 25-volt, 20-kiloamp power supply, the electrical protection circuitry and dump resistors, and the necessary bus work, cabling, and installation for a single coil would be provided for each test coil. Component part costs were estimated based on previous conceptual design studies with appropriate labor charges also derived from these earlier cost estimates.

14. Power Supplies (pulsed coils) - Power supply costs for the pulsed coil set assume that two different power levels are required depending on the magnitude of pulsed field desired. Two 300-volt power supplies, one at 5000 amps and the second at 1000 amps rating are included in the cost projections. The costs assigned to these items reflect recent purchase price information for similar items.

15. Machine Supports - This item includes the support structure which carries the gravity load from compact torus coils to ground. The basic concept is an array of structural beam elements fabricated into a grid of circular and radial members. Costs are estimated by calculation of the weight of structural members, which are priced in \$/kg, and labor costs are based on welding and fabrication requirements. Cost scaling

factors were developed as a function of coil size and major radius of the experimental arrangement.

16. Instrumentation and Control - These costs were estimated by a detailed breakdown of elements into the following categories: experiment-related items which include the sensors installed on each coil, the signal conditioning from the coil sensors to the control/display interface, and the controls, readouts, and cabinetry required; facility related items which include sensors associated with the vacuum system, refrigeration systems, power supplies, etc., signal conditioning from the sensors to the control/display interface, and controls, readouts, recorders, and cabinetry required. The number of sensors installed on a coil were investigated for both test and background coils. The number and type of each sensor was determined as well as an estimate as to which may be multiplexed saving on signal conditioning. Costs were estimated for the sensors using present pricing data for similar items. Remaining costs were based on estimates made in support of previous conceptual designs.

17. Data Handling - This item includes the cost of connecting instrumentation to existing computer system and control room equipment. The basis for the costs assigned is a detailed cost estimate made for a conceptual design of a superconducting tokamak.^{7,8} A review of this estimate was made and that portion of the costs related to the toroidal field coils extracted. A cost factor was then derived from this data which allowed a cost projection to be made based on the number of coils involved plus a fixed cost which was related to the facility aspects of the experiment.

18. Cryogenics - This is essentially a fixed cost for all the candidate test arrangements and includes the cost of installation to an existing facility interface. Both liquid helium and liquid nitrogen piping, valving, and interface connection costs are included. Cost estimates are based on previous conceptual design studies of similar experiments installed in the same facility.

19. Building Electrical Power — This cost includes those changes and equipment which must be made to the basic building electrical power system to accommodate the experiments proposed. Equipment costs cover modifications to lighting, emergency power, and substations with labor costs estimated to cover installation charges.

20. Utilities — This item includes civil and architectural effort relative to piping foundations and supports and piping runs required for demineralized water, air, and gaseous nitrogen. Lengths of piping were assumed consistent with hookup to existing facility interfaces within a reasonable distance from the experiment. Cost factors for material and labor were derived from previous conceptual design studies.

21. Building Modifications — This item includes those costs associated with modification of an existing building in the area of civil and architectural changes to heating and ventilation, construction of control room and utility area spaces, and modifications to the high-bay area floor to provide for an assembly area with increased floor loading capacity. Cost estimates were based on previous studies.

22 and 23. Standard and Maintenance Equipment — These are essentially fixed cost items which cover the cost of equipment items. Previous estimates were reviewed to arrive at an appropriate cost for this experiment.

24. Electrical Special Equipment — This cost covers those items of electrical equipment which are considered to be peculiar to the experiment. This includes communication power, busing, cables, motor controls, and wiring. Costs for material and labor were taken from similar previous design studies.

25. Civil and Architectural Special — This item covers the cost to modify the floor structure beneath the experiment which must withstand the combined load of the coils and bell jar. Cost estimates made in previous conceptual designs were reviewed and a cost factor determined based on the weight of the coils plus the bell jar.

26. Mechanical Special - This item covers special handling equipment which will be required to position and install the coils and facility hardware items. Fixture costs developed in support of an eccentric coil test arrangement were reviewed and adjusted for the difference in coil size and weight.

Results - The above outlined elements and procedure were applied to each of the five candidate testing arrangements and program costs determined for each as a function of test coil horizontal bore. Results of these calculations, normalized to the cost of the compact torus at a reference size of three meters, are presented in Fig. 7.1.

Fig. 7.1 Relative Cost of Candidate Test Arrangements versus Test Coil Bore

8. DESCRIPTION OF FIRST TEST COILS

This chapter describes how the basic concepts for the first test coils were chosen and gives a few of the principal features of the technical specifications which the first test coils will be required to meet.

8.1 Basic Concepts

The LCP must prove the most promising concepts of toroidal field coils for TNS. The greatest uncertainty at this time in TNS requirements is the peak field. TNS configuration trade studies and evaluation of confinement physics uncertainties are now under way to quantify insofar as possible the incentives for higher fields. Clearly a peak field of at least 8 tesla is desired and the first LCP subcontracts will be for coils operable at 8 tesla. Decisions on possible subsequent procurement of higher-field coils, which place more stringent demands on superconducting magnet technology, will be based on results of TNS studies and progress in superconducting magnet R&D in 1977.

The bore dimensions of the TNS coils are expected to be about 5 x 7 m and the TNS test coils will be half this size. The conductor and winding cross section of the test coils will be practically the same size as the TNS coils, however. For the same peak magnetic field, the required number of ampere-turns per coil in a compact 6-coil array is nearly the same as in a 16-coil TNS.

The basic features that will be investigated in the first test coils were chosen on the basis of earlier EPR magnet conceptual studies. In the EPR-TF studies connected with LCP, all three contractors chose NbTi as the superconductor for the 8-tesla case, with two concepts using pool-boiling helium and one forced flow to provide cryogenic stabilization. For the high-field case, two contractors chose to use Nb₃Sn conductor cooled by forced flow. Although finding no sharp break point in variation of coil parameters with field, each independently settled on 12 tesla as the "highest practicable" peak field. The third contractor's

"highest practicable field" concept used NbTi conductor cooled by boiling helium at 2.5 K to reach a maximum of 12 tesla. Widely different conductor configurations and structural concepts were envisioned by the contractors.

For the first three LCP test coils, it was decided that one sub-contract would be awarded for the best proposal using "monolithic" conductor* cooled by pool boiling, the second would be for the best proposal using open cable cooled by forced flow of helium through and around the cable, and the third would be for the all-around best proposal by a firm not awarded one of the first two subcontracts.

8.2 Technical Specifications

As a basis for the first test coil subcontracts, detailed technical specifications[†] were prepared to insure that each resulting coil would be consistent with the objectives of the magnet development program and all would fit together in the test assembly. The particulars of the coil design and fabrication procedures were not specified, however, but were left to the firms submitting proposals. Included in this latitude was the choice between NbTi and Nb₃Sn as the superconducting material. The principal requirements of the specifications are briefly identified as follows.

The coil shall be operable at a peak field of at least 8.0 tesla at a design current of 10-15 kA in a 6-coil Compact Torus when the other five coils are at 0.8 of their design current.

The designer must show that his coil is stable against effects on the conductor of all credible events. No design will be acceptable that is not capable of recovery from a sudden normalcy extending over any half-turn.

The coil must lie within a spatial envelope defined in the Technical Specifications. The required winding shape approximates a D while the

* Monolithic here denotes conductors in which there is no possibility for relative motion of strands or other elements within the conductor.

[†] UCC-ND Technical Specification No. TS14700-01.

outside of the coil case is rectangular in profile. The inboard straight edge bears against a central hexagonal post in the test stand and has a vertical tongue that fits a groove in the post to transmit part of the overturning moment from the vertical field that will be imposed. Structural members which will be provided to transmit forces between adjacent coils will bolt to the outer corners of the coil case. The structural, electrical, and coolant interfaces indicated on Fig. 8.1 are precisely defined in the Specifications. The concept of the structure that will be provided as part of the test facility is depicted in Fig. 8.2.

The design of the coil must be consistent with a postulated radiation environment equivalent to that expected in TNS. The stability analysis shall assume that the matrix material will be exposed to a fast neutron fluence of 0.5×10^{17} n/cm². Insulation capable of operation after a dose of 10^7 rads must be used. The thermal design must accommodate a hypothetical nuclear heat source ranging up to 1×10^{-4} W/g, with 5×10^{-4} W/g at local "hot spots."

The test coil must continue to operate in a cyclically imposed pulsed field with peak values of 0.14 T perpendicular to the conductor and 0.10 T parallel to the conductor, ramped up in 1 sec.

Fig. 8.1. Interface Features

Fig. 8.2. Structural Mounting Arrangement

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