25
2-23-77
23-10-77
NTIS

MASTER

BNL 22037

DEPARTMENT of APPLIED SCIENCE

SUMMARY OF THE WORKSHOP ON
STRUCTURAL ANALYSIS NEEDS FOR MAGNETIC FUSION
ENERGY SUPERCONDUCTING MAGNETS

September 1976

Editors: M. Reich, J. Lehner, and J. Powell

BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

INFORMAL REPORT

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

SUMMARY OF THE WORKSHOP ON
STRUCTURAL ANALYSIS NEEDS FOR MAGNETIC FUSION
ENERGY SUPERCONDUCTING MAGNETS

September 1976

Editors: M. Reich, J. Lehner, and J. Powell

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

DEPARTMENT OF APPLIED SCIENCE

BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.

Under Contract No. EY-76-C-02-0016 with the
UNITED STATES ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

sey

TABLE OF CONTENTS

	<u>page</u>
SUMMARY AND CONCLUSIONS	1
BACKGROUND COMMENTS	2
WORKSHOP AGENDA	3
SYNOPSIS OF PRESENTATIONS	5

Wednesday, September 8

A. Recent Experimental Fusion Reactor Magnet Designs	5
1. Oak Ridge National Laboratory (W. Chris T. Stoddart)	5
2. Argonne National Laboratory (Larry Turner)	6
3. General Atomic Company (Robert Thomas)	8
4. Lawrence Livermore Laboratory (Steve Sackett)	9
B. Long Term Magnet Designs	10
1. University of Wisconsin((Warren Young)	10
2. Princeton University (San Gralnick and James Bialek)	12
C. Tokamak Fusion Test Reactor (TFTR) - Structural Analysis Methods (Gray Smith, EBASCO/Grumman)	13
D. National MFE Computer Network - Goals and Future Requirements (Glen Ingram - DMFE)	15

Thursday, September 9

A. Evaluation of Existing and Future Structural Analysis Techniques for Superconducting Magnets	16
B. Application of Composite Theory to Hetrogeneous Magnet Structures	17

	<u>Page</u>
C. Thermal Diffusion Analysis Consistent with Special Composite Element Analysis	17
D. Material Characterization from the Fracture Mechanics Viewpoint	18
E. Fracture Mechanics and Design Criteria for Low Temperature Applications	19
F. Feasibility of Construction	19
G. Buckling and Coupled Lateral Vibrations of Superconducting Magnets	22
H. Structural Standards and Design Requirements	22
 Friday, September 10	
Open Discussion Sessions	24
LIST OF ATTENDEES	25

Summary of the Workshop on
Structural Analysis Needs for Magnetic Fusion
Energy Superconducting Magnets

Summary and Conclusions:

The Workshop on Structural Analysis Needs for Magnetic Fusion Energy for Large Superconducting Magnets was held at Brookhaven National Laboratory, Upton, New York on September 8-10, 1976. The meeting, which was sponsored by DMFE/ERDA, was attended by over fifty participants representing various national laboratories, universities, and industries, making up the MFE community. The purpose of the meeting was twofold. First, it allowed attendees to present and discuss the present state of the art of structural analysis for superconducting magnets. Second, it provided a forum for the mutual exchange of viewpoints leading to recommendations as to the type of advances required for improved analysis of MFE magnet structures.

The technical portions of the meeting were divided into three major sessions as follows:

- I. Review of methods being presently used by the MFE community for structural evaluation of current designs.
- II. Future structural analysis needs.
- III. Open discussions dealing with adequacy of present methods, the improvements needed for MFE magnet structural analysis, and the establishment of an MFE magnet structural advisory group.

Summaries of the individual talks presented on Wednesday and Thursday (i.e., items I and II above) are included following the Workshop schedule given later in this synopsis. These first two items provided a starting

point for the open discussions of the topics listed under Item III. After substantial consideration on Thursday afternoon and Friday, a consensus was reached that the following further work should be pursued:

- A. Develop better homogenization techniques (improve constitutive relationships).
- B. Obtain better data base for material properties.
- C. Develop coupled analysis techniques to account for thermal, electromagnetic and structural interaction.
- D. Adopt fracture mechanics methods to predict failure of metallic components and develop methodology to describe organic material (micarta, glue) fracture behavior.
- E. Verify Items A, B, C and D with experimental techniques.
- F. Create MFE magnet structural advisory group for the purpose of improving current methods.
- G. Evolve procedures for code verification and interchange.

Background Comments:

This Workshop was held in response to a strong consensus for the need to assess current structural methods expressed by members of the MFE community at a previous widely attended workshop held at BNL early in January, 1976. The aim of the symposium was broadened to include a comprehensive and systematic review of the present state of the art together with indepth projection of the future advances and requirements needed for the structural evaluation of proposed MFE superconducting magnet designs that can experience both normal and abnormal loading conditions. Emphasis was also given to material modeling techniques, engineering feasibility studies of particular EPR's, fracture mechanics, fatigue, and failure criteria applicable to various types of EPR and other forthcoming designs, and the establishment of an MFE structural advisory group.

The agenda followed at the Workshop is given below:

Workshop Agenda:

Starting Times*

Wednesday, September 8

Introduction and Welcome (BNL) 9:00

Structural Analysis Techniques in Current Use for MFE
Magnet Designs

A. Recent Experimental Fusion Reactor Magnet Designs
Four lectures given by staff members of the various
laboratories (ORNL, ANL, GA, and LLL) working on the
structural aspects of magnetic fusion reactors and near
term superconducting magnet designs.

1. Oak Ridge National Laboratory (W. Chriss T. Stoddart) 9:15
2. Argonne National Laboratory (Larry Turner) 10:00

***** Coffee Break ***** 10:45

3. General Atomic Company (Robert Thomas) 11:00
4. Lawrence Livermore Laboratory (Steve Sackett) 11:45

***** Lunch ***** 12:30

B. Long Term Magnet Designs

1. University of Wisconsin (Warren Young) 1:30
2. Princeton University (Sam Gralnick, Jim Bialek) 2:15

***** Coffee Break ***** 3:00

C. TFTR (EPR) Structural Analysis Methods (J. Heiftz, G.
G. Smith, I. U. Ojalvo - EBASCO/Grumman) 3:15

D. National MFE Computer Network - Goals and Future
Requirements (Glenn Ingram - DMFE-ERDA) 4:00

Thursday, September 9

Future Structural Analysis Needs for MFE Magnets

A. Evaluation of existing and future structural analysis
techniques, and their application to superconducting
magnets undergoing normal and abnormal conditions.
(M. Reich - BNL) 9:00

B. Application of composite theory to heterogeneous
magnet structures (T. Y. Chang - U. of Akron) - BNL
Consultant 9:45

***** Coffee Break *****	10:30
C. Thermal diffusion analysis consistant with special composite structural element analysis (J. Conner - MIT) - BNL Consultant	10:45
D. Material characterization from the fracture mechanics viewpoint (Steve Floreen - INCO)	11:15
E. Fracture Mechanics and design criteria for low temperature applications (H. I. McHenry - NBS)	11:30
***** Lunch *****	12:00
F. Feasibility of construction (K. Reinschmidt - Stone & Webster)	1:00
G. Buckling and coupled lateral vibration problems of superconducting magnets (F. C. Moon - Cornell)	1:30
H. Structural standards and design requirements (E. P. Esztergar - Consultant BNL)	1:50
***** Coffee Break *****	2:50
I. Open discussion of adequacy of present structural analysis methods for superconducting MFE magnets. Discussion of methods for facilitating code standardization and interchange. Recommendations to ERDA - DMFE will be prepared.	3:00 to 5:00
***** Cocktails (complimentary) *****	7:00
***** Dinner *****	7:45

Friday, September 10

A. Open discussion of improvements in structural analysis methods required for superconducting magnets to be used in magnetic fusion reactors. Recommendations to ERDA - DMFE will be prepared.	9:30
***** Lunch *****	11:30
B. Open discussion of development of ASME type code standards for use in design of superconducting magnets for fusion reactors. Recommendations-to ERDA DMFE will be prepared.	12:30

* Part of the time scheduled for each presentation should be kept open for questions.

At the completion of the Workshop, it was decided that an executive summary should be readied first, with detailed proceedings to follow as soon as possible. All speakers were asked to assist in preparing the executive summary by submitting a synopsis of their Workshop presentations. The synopses of those speakers who complied with our written requests are included in this summary. For those speakers who were unable to send their synopsis on time, it was necessary to abstract summaries from the taped preceedings. These are also presented below.

Synopses of Presentations:

Wednesday, September 8 - Review of methods presently used for structural evaluation of current and near-term superconducting magnets.

A. Recent Experimental Fusion Reactor Magnet Designs

1. Oak Ridge National Laboratory (W. Chris T. Stoddart)

The Oak Ridge presentation given by Chris Stoddart concentrated on the work done by Oak Ridge and its subcontractors, which is centered around Tokamak devices. A brief review of the forces acting on a Tokamak magnet coil and how the forces are influenced by coil shape was given. The advantages of reacting some of the forces to an external-load frame and using circular coils were mentioned as well as the use of oval coils which would decrease the centering forces and the stored magnetic energy.

The ORNL-EPR design calls for toroidal field coils supported in a hub structure. Structural analysis on this coil design was done by ORNL together with Mechanics Research, Inc. using the NASTRAN computer code. Each coil was represented as a single filament beam while the structure between the plates was modeled as a plate arrangement. A combination of plate and shell

elements represented the hub and top and bottom caps. This analysis led to an iteration of the original design since it showed that the original structure, especially in the hub area, was not thick enough. Consultation with people in the neutral beam injection and vacuum pumping fields led to the opinion that 50 percent of the equatorial plane could be covered over with structure without crippling the design. If this design were iterated again, it is probable that shear type structures spanning the distances between coils would be used to reduce the large displacements in the unsupported regions.

The ORMAK upgrade is quite different from an EPR structurally. This is a man-size device smaller than PLT. Water-cooled copper coils are used with the out-of-plane loads resisted by rings around the periphery at top and bottom. A set of codes to look at the linear-elastic behavior of this type of coil set has been generated by ORNL and was presented at the San Diego Conference. The codes use isoparametric elements with orthotropic material properties following the shape of the coil. Comparison of computer results with hand calculations gave good agreement in displacement calculations but differed considerably in stress values.

Verification of computer results for any design was felt to be extremely important. Such verification would include strain gauge tests on models, photo-elastic experiments, as well as destructive testing of coil components.

2. Argonne National Laboratory (Larry Turner)

Larry Turner of Argonne discussed the 1976 Argonne EPR design. In their design ANL tried to extrapolate as little as possible beyond present day technology. The EPR is conceived as a device showing the feasibility of net electrical power with a five to ten year duty cycle. Besides being used for

experiments in plasma physics, reactor technology, and materials radiation testing, it is also envisioned as being used to test breeding concepts and advanced coolants. ANL is working on both a 10 Tesla and 8 Tesla EPR design.

Pertinent coil parameters were given and, the trapezoidal cross-section, with its center rib and jelly roll windings, was discussed. Pure tension shapes for any number of coils around the torus as calculated by DeMichael and Wang were mentioned. Stresses in various coil shapes were calculated with the computer code SOLID-SAP. As expected, the finite number coil constant tension shape had lower stresses than the simple D-shape which in turn was less stressed than a circular coil.

It was found that a D-shaped EPR coil (9.5m x 17m minor and major diameter) would experience about a 10 percent increase in stress if the coil shape was distorted by 5cm in any direction. For example, a 23×10^3 psi stress would increase by 2000 psi if the coil was distorted vertically by 5cm.

Rotational displacements were also investigated with the worst ones in the toroidal direction.

Coil support schemes worked out by McDonnell - Douglas for ANL using the NASTRAN code were discussed. Two basic support schemes decided on were the torque frame and torque shell. In the torque frame concept, the shell forces and torques are taken up by a panel connected at cold temperature between two neighboring coils. This scheme has the advantage of lower total weight and lower cost, but requires disassembly of a torque panel in order to perform any servicing on the blanket or shield. In the torque frame approach, the torques are taken up by a frame on top and bottom and reacted against the

walls of the building. This scheme provides easier access to blanket and shield but has greater weight and probably greater cost.

The speaker expressed the opinion that the MFE community was just at the beginning of MFE superconducting magnet structural analysis and more aware of problems than solutions. Improvement in analysis techniques would indeed be welcome.

3. General Atomic Company (Robert Thomas)

Bob Thomas talked about the General Atomic EPR design sponsored by EPRI. GA is faced with the requirement of designing an EPR which must achieve net power, so the design had to include the entire power conversion system. Aside from a modular blanket and shield, the most unique feature of the GA design is the non-circular or double cross-section. One advantage of the double cross-section is that a smaller machine can achieve the same thermal output as a larger circular plasma machine. With the doublet configuration, the field shaping coils are inside the toroidal field coils. This means the shaping coils are normal coils, take a lot of power and are hard to wind, but they have the advantage of effectively shielding the plasma current and so lessening the impact of the poloidal fields. This means no AC losses and reduced overturning torques and forces.

Costs for an EPR are estimated at one-half to one billion dollars. The parameters of the GA constant tension D toroidal field coils were presented. Stresses in the coil had been calculated but not in great detail. Simple finite element codes for analyzing link-bar stresses, overturning torques and stresses in the coils were used primarily with beam and other 2-D elements. Results were considered adequate for conceptual studies.

In general, Bob Thomas felt that thermal stress problems arising from many varied causes need more looking in to. One such cause would be conductor

motion leading to friction and heat in a superconducting coil. Emphasis should be placed on identifying other as yet undiscovered problem areas of superconducting toroidal field coils.

4. Lawrence Livermore Laboratory (Steve Sackett)

Steve Sackett discussed the structural analysis tools employed at Livermore and showed their application to the MX coil design.

The basic structural analysis code used at Livermore is SAP IV modified somewhat with some in-house modules. SAP IV is limited to linear elastic cases but other codes are available to analyze fault conditions. Other codes used in conjunction with SAP IV are the EFFI code, which calculates the magnetic fields, forces and inductance, and M 3D which graphically displays SAP IV input and output results.

EFFI results for the MX coil were shown. The assumption made for the stress calculations in MX was that the conductor itself had no strength at all with the entire load being taken up by the restraining structure, i.e., the coil case.

Coil sizes of Baseball-2, 2X2, and MX were compared. It was pointed out that in winding complicated coils like these critical stresses cannot be estimated with accuracy.

To prevent welding and possible destruction of the superconductor, the coil itself is wound on a steel inner jacket which provides the vacuum seal. Then the outer case can be almost completed before sliding the coil into it. Curvatures in the current MX design were fared in more smoothly when SAP IV calculations showed high bending stresses in some sharp curvature areas.

SAP IV calculations on the initial design were checked with good agreement by the Boeing Company using the NASTRAN code.

B. Long Term Magnet Designs

1. University of Wisconsin (Warren Young)

The main thrust of this talk was to advocate the use of simple strength of materials relationships to design toroidal field magnets as far as general shape, size and weight and to reserve the use of more advanced and necessarily costly techniques of stress analysis, such as finite element methods, to analyze the details of conductor-structure interface and the final overall stress analysis of the total structure.

In modified outline form the talk covered the following points.

- a. It listed design constraints on Tokamak toroidal field magnets.
- b. UWMAK-II and UWMAK-III configurations were compared to show the reduction in stored energy due to the reduced volume of the high field regions.
- c. Reference was made to the paper "Analytic Expressions for Magnetic Forces on Sectorial Toroidal Coils" by R. W. Moses, Jr. and W. C. Young which was presented at the Sixth Symposium on Engineering Problems of Fusion Research at San Diego, Calif., November 1975.

In this paper the effect of a finite number of coils is introduced in an excellent approximation. Results are given in graphs and fitted polynomials to permit a designer to obtain the desired shape of minimum mass to enclose any desired volume.

- d. The Wisconsin method of designing toroidal field magnets was discussed in some detail.
- e. The advantages of the embedded conductor design were discussed, including:
 1. Positive placement of conductors.
 2. Minimum structure for large magnets.
 3. 100% inspection of each disk at each stage of construction and assembly.

- f. Lateral support of the magnets can be provided by lateral epoxy-fiberglass struts between magnet and dewar and by segmented cast aluminum shells between dewars. A certain percentage of the struts are provided with nonlinear elastic conical springs to provide the elastic lateral requirements for magneto-elastic stability and the necessary resistance to lateral loading from the vertical field and ohmic heating coils. The remaining struts provide support for accident conditions. The cast aluminum shells are provided with slip joints to prevent tensile loads from developing between dewars.
- g. Safety. The following comments were made regarding the effect of a coil failure due to loss of vacuum or helium in a dewar.
 - 1. Each toroidal field coil is in a separate dewar.
 - 2. All coils operate in series with a three-phase Graetz bridge power supply.
 - 3. In case of a fault all but the faulted magnet are put in a persistent mode and the Graetz bridge used to power down the faulted magnet.
- h. Disk construction and design strain levels.
 - 1. Stainless steel as a structure would be rolled or forged and welded. Copper stabilized conductors would be used. Design strain will be approximately 0.2%.
 - 2. 2219 aluminum would be extruded with forged transition sections and welded. High purity aluminum would be used as a stabilizer. Design strain will be approximately 0.4%.
 - 3. Elastically restrained cyclic straining of high purity aluminum has shown a saturation in change in resistance in less than 1000 cycles.
- i. The University of Wisconsin is testing the embedded conductor concept using a split cone mechanical system to simulate magnetic loading.

2. Princeton University (Sam Gralnick and James Bialek)

The presentation of the Princeton Plasma Physics Laboratory was in two parts: Sam Gralnick gave a short review of what PPPL perceived as some of the structural engineering needs of the fusion community. He was followed by Jim Bialek who presented some current research on laminated beam theory as applied to toroidal field coil designs.

Gralnick covered the following points:

1. Careful consideration must be given as to whether the D-shape, given its constraints, is indeed the ideal shape for a toroidal field magnet in a Tokamak device.
2. We must make full practical use of the existing structure in the machine.
3. A practical support structure is needed to withstand the centering forces of the coils.
4. Questions of fabrication such as winding stresses and handling of these huge coils must be addressed.
5. Duct clearances on beam driven machines must be scrutinized more carefully.
6. The entire reactor structure, including shield, blanket, etc. must be viewed also from a structural engineering view.

Jim Bialek explained the large toroidal field coil deflections observed during the PLT power test which were due to the poor shear behavior of the insulation material used between layers of copper. Standard techniques for analyzing such laminated structures do not account for this effect. He presented an analysis of laminated beams that corrected this deficiency. The analysis explicitly modeled the mechanical behavior of each layer in a laminated beam and hence avoided the pitfalls involved in any averaging technique. In particular, he found that the shear modulus of the epoxy in a laminated beam

(consisting of alternate layers of metal and epoxy) may span the entire range of values from zero to classical. The solution of the governing differential equations defines the stress, strain, and deflection for any point within a laminated beam. Bialek summarized the governing equations and also included a parametric study of a simple laminated beam.

C. Tokamak Fusion Test Reactor (TFTR). Structural Analysis Methods

(Grey Smith, EBASCO/Grumman)

Grey Smith of EBASCO / Grumman discussed the structural analysis effort associated with the TFTR TF coils entailing a series of scoping studies to develop a method for external support of the TF coils which minimizes bending and axial stresses in the coil case and copper conductors.

Requirements for the TFTR TF coil were summarized. These coils must be capable of sustaining 100,000 pulses, with a pulse repetition rate of 300 seconds. As a part of this requirement, the coils must sustain 4000 full power DT pulses, at a rate of 1000 per year with up to 96 pulses occurring in any one day.

The machine is to be built in 10 individual segments. The structural design approach must permit the individual removal of any segment for repair or replacement. Since the machine will become radioactive with the introduction of tritium operation, the design must also be compatible with remote disassembly and reassembly of a segment into the machine.

The basic machine geometry was displayed and discussed. The TF coils are subjected to two major operating loads: in-plane and lateral. The design condition occurs when these loads reach a simultaneous peak during each pulse. The interaction of the TF coil current with the toroidal magnetic field results in an asymmetrical running radial load around each coil

which produces a net centering force of 6400 kips for a 5.2 Tesla field.

The interaction of the TF current and the vertical equilibrium field produces equal and opposite forces on the upper and lower halves of the TF coil resulting in a lateral movement of 74,000 inch-kips on each coil.

The centering force will be reacted by two center rings and by upper and lower outer box members which run from coil to coil and which form continuous outer rings when the machine is fully assembled. The distribution of in-plane load between the inner and outer rings depends upon their relative stiffness. The lateral movement is also resisted by the inner and outer support rings.

An additional support, located at the bottom of each TF coil, is used to react the dead load of each coil assembly.

A series of scoping studies were utilized to explore alternative TF coil support methods with the objective of minimizing the internal bending moment and stresses seen by the coil case and copper conductors. Two analytical tools were used in this effort. The first of these is the Structural Design Language (STRU DL) two-dimensional computer program, which provides a means for rapid assessment of alternate support approaches for in-plane loads. A NASTRAN three-dimensional code was used to obtain stresses and deflections due to lateral loads in combination with in-plane stresses and deflections for the more promising candidates.

The key variables that were investigated for this support scheme are: the relative stiffness of the inner and outer support rings; the vertical separation of the inner support rings; and the resulting maximum stresses in the TF case and copper conductors. Use of the "scoping study" approach permitted the evaluation of a large number of cases in a relatively small period of time. Most importantly, the study results served to highlight favorable trends which are used to guide the design effort.

D. National MFE Computer Network - Goals and Future Requirements

(Glenn Ingram - DMFE)

Glenn Ingram spoke on the goals and future requirements of the National CTR computer network. He presented a map of the network as it now stands and sketched a brief history of its development. He pointed out that the primary impetus for the network came from the plasma physics community and, as a consequence, the computer requirements for plasma physics have been the dominant influence in arguing for and planning the expansion of the network. However, the objective of the network is to provide most of the computing for the whole MFE program, so it is important that other groups in the MFE Constituency present their projections of computer needs.

The network as it exists is being used more heavily than anyone expected: after the October, November, December start-up period, the computer has been saturated since January. Future needs will not be served best by the proliferation of 7600 series computers at the center. Instead it appears clear in terms of both quantitative and qualitative requirements that larger class 6 computers are the way to move in the future.

The need for a national network rather than a build up of local facilities is dictated by several considerations. Some of the problems encountered in the MFE field are among the largest known. Consultants agree that class 6 computers are appropriate for the problems encountered. Many smaller groups at universities or some laboratories don't have the computing load that say Princeton does, but individual problems can require the kind of computer that's going to be available only there.

Glenn Ingram wanted the MFE community to consider the following questions in relation to the national computer network.

1. What are the best estimates of computer requirements for this community over the next few years?
2. How should these requirements be met?
3. Are there significant advantages to using the Center and Network for a standard library of codes?
4. What forum should be provided to enable the MFE community to describe its interest and needs to Computer Center management?

Thursday, September 9 - Future Structural Analysis Needs for MFE Magnets.

Eight presentations were made describing present and future structural analysis methods applicable to MFE magnet structures undergoing normal operational as well as abnormal or faulted conditions. Topics A, B, C, D, F, and H are direct outgrowths of limited investigations carried out by BNL during the year. These presentations were thus given by BNL personnel and the various university consultants and industry experts that were contacted during the various phases of BNL's MFE magnet structure studies. Topics F and H describe areas of investigation currently being carried out for ERDA. At the recommendation of ERDA, the speakers for these topics were thus drawn from the particular ERDA contractor personnel. A brief summary of presentations is given below:

- A. Evaluation of existing and future structural analysis techniques, and their application to superconducting magnets undergoing normal and abnormal conditions. (M. Reich - BNL)

This presentation involved an extensive review of current analysis methods and their limitation for complex structures. Various computer analysis of techniques applicable for elastic, elastic-plastic, and failure prediction including fracture mechanics, fatigue, buckling, etc.,

together with the required input information for these computer codes were detailed. In order to further classify the use of the computer methods, sample demonstrative applications using UWMAC-I Designs were presented for cases involving normal operational, as well as abnormal quench conditions. Sample fracture mechanics applications and solution for complex fission reactor designs were also presented. Some of the demonstrative problems were specifically chosen to point out the limitations of these techniques when applied to actual MFE magnet designs.

In view of these limitations several methods yielding improved analysis techniques were discussed. These included:

- a) improved homogenizations techniques and,
- b) time dependent thermal analysis methods that interact with the structural analysis.

Other areas of work looked into by the BNL structural analysis group during FY 76 such as the advisability of an organization to act as an advisory group for MFE magnet structures and an appraisal of CTR constructibility vis-a-vis current fission reactor construction methods were also presented.

B. Application of composite theory to heterogeneous magnet structures.

(T. Y. Chang - University of Akron - BNL Consultant)

This talk concerned itself mostly with complex mathematical formulations needed to develop an improved finite element analysis method based on the composite theory. The methods presented can be applied to evaluate two and three dimensional MFE magnet structures for elastic, elastic-plastic, and slip behavior.

C. Thermal diffusion analysis consistent with special composite structural element analysis. (J. Conner - MIT - BNL Consultant)

This presentation concentrated primarily on the mathematical aspects. Particular attention was given to the treatment of a three-dimensional body containing a large number of zones having different material properties and exhibiting non-linear behavior. Compatibility with the improved composite element was also discussed.

D. Material characterization from the fracture mechanics viewpoint

(Steve Floreen - INCO)

This presentation was intended to serve as an introduction to fracture mechanics applications. Work in the fracture mechanics area has proceeded on two aspects of the problem. The first has been analytical and the second, experimental. The analytical work has been aimed at developing relationships for the local stresses and strains around crack tips. A large number of problems involving many different crack geometries with both simple and complex loading conditions have been solved. Some typical solutions were described during the presentation.

The experimental work has been directed toward determining when fracture occurs in materials. It has been shown that fracture initiates at a critical value of the stress intensity K_c = the fracture toughness. In practice, K_c will vary with sample size, which reflects the size of the plastic zone at the crack tip versus the sample size. If the plastic zone is relatively small, the sample is in-plane strain loading and K_c is independent of sample size. With small samples, or tougher materials, gross plastic flow of the test specimen causes an increase in K_c . Plane strain problems are generally straightforward, but further work is necessary to establish the best technique for treating elastic-plastic loading conditions.

Fracture mechanics test procedures also are used to deal with fatigue, stress corrosion, corrosion fatigue and other fracture problems.

In practice, designers can now build structures that will resist fracture. For example, one can estimate the critical flaw sizes that will initiate fracture in materials. This information can be used to select materials and to establish inspection procedures that will reject materials containing flaws greater than the critical size. Acceptable slow crack growth rates between inspections also can be defined. A close dialogue between designers, inspection and testing people, and materials specialists generally is needed to achieve the best combination of cost, performance characteristics, and resistance to fracture.

E. Fracture mechanics and design criteria for low temperature applications
(H. I. McHenry - NBS)

A brief review of the concepts and applications of fracture mechanics was presented. The purpose of the talk was to show that fracture mechanics is a useful tool for design and provides a reasonable framework for establishing safe working stresses in magnetic fusion devices, the EPR and the CTR plants of the future.

The fracture mechanics approach to design was described. The fracture toughness and fatigue crack growth data available for candidate structural alloys was summarized. The approach and the data for 2-6-9 stainless at 4 K subjected to a 100 minute/cycle operating cycle was discussed.

Design criteria applicable to fracture prevention were presented. This included design life, load history, thermal environment and assumed initial flaw size. Design approaches, material procurement and processing controls, and inspection requirements were also reviewed with respect to fracture prevention.

F. Feasibility of construction (K. Reinschmidt - Stone & Webster)

The speaker indicated that constructibility of commercial size, magnetic fusion energy power plants must be approached with a great deal of caution.

It is obviously quite risky to discuss the construction of a plant which has not yet been designed, or even demonstrated to work in principle. A commercial power reactor built after the turn of the century will undoubtedly differ greatly from current conceptual designs.

However, the examination of the constructibility of Tokamak reactor designs is not merely an exercise in speculation. The objective, of course, is to improve the economy of plant designs by incorporating construction considerations early in the conceptual design process. This is the current practice for individual light water reactors (LWR's) extended to an entire class of advanced power systems.

A major factor in constructibility of CTR power plants is cost. The cost per kilowatt hour of electricity to the consumer will be determined primarily by capital cost. Estimates for light water reactors have varied from under \$100/kWe in the early 1960's to roughly \$1000/kWe today (in current dollars). In addition to this trend, individual plants have frequently overrun their budgets. This level of risk associated with such large sums of money has undoubtedly deterred the construction of light water reactors. Whether the rapid cost increases shown by LWR's are applicable also to fusion reactors, or whether this represents a one-time escalation due to increased emphasis on safety, remains to be seen. A reasonably reliable cost estimate requires, in addition to defined design concepts, a plan for construction sequencing. No network schedule apparently yet exists.

Construction of the magnets is a crucial factor. UWMAC-II toroidal field (TF) magnets are estimated at 710 metric tons, with a height of about 31 meters. Objects of this size cannot conveniently be shipped over land; therefore, either the construction of CTR's must be limited to sites accessible to barges, or the magnets must be fabricated on site. Winding

the TF coils will require specialized precision equipment. To serve a fusion economy, this equipment should be designed and packaged for rapid movement from site to site by railcar or tractor trailer.

There are several alternate methods for installing the TF magnets in the reactor building. One might be similar to erection techniques used for pressurized water reactors, in which a large construction opening is left in the containment wall through which the reactor pressure vessel is pulled. An alternate approach might follow that used for boiling water reactors in which the reactor pressure vessel is lifted over the top of the containment before the dome is erected. This method would have several advantages for CTR construction.

Erection methods are also influenced by maintenance considerations. If there is a high probability that a TF coil must be removed for repair during operation, then the containment building diameter must be large enough to permit a coil to slide out of the torus and to be moved circumferentially to the hot cell for repair, rewinding, etc. This will also necessitate a large equipment hatch in the containment wall and a permanent TF coil-handling system.

In general, the large forces which can be induced in the structure by magnetic pulsation, failure of a TF coil, thermal expansion/contraction, and other factors, imply that the large, heavy magnets be constructed and placed with great precision. Very close tolerances must be achieved if actual stresses are to approximate those computed by sophisticated analysis methods. Cryogenic structures will be highly susceptible to damage during construction. High quality welds on materials not common in current construction will be required. Conditions which are achievable in labora-

tory or shop conditions will be difficult to attain in field construction. Consequently, highly skilled manpower will be necessary, and field quality control requirements will greatly exceed those for current LWR's.

A satisfactory appraisal of CTR constructibility requires the development of a feasible construction sequence. No such plan has yet been developed. As noted above, several possible alternate sequences can be envisioned. Selection among these alternates, and others, will depend upon the establishment of manpower requirements and durations for specific construction activities. With this information, an optimum construction schedule could be developed. This would permit a better estimate of construction time and cost, and a better assessment of the constructibility of various conceptual Tokamak designs. A forecast of future construction technology would also be useful in appraising the construction equipment which might become available at the time commercial CTR plants would be built. Although construction estimates will be conceptual as the design on which they are based, further analysis of constructibility would improve CTR designs and hasten the day in which commercial fusion power becomes economically viable.

G. Buckling and coupled lateral vibration problems of superconducting magnets
(F. C. Moon - Cornell)

The vibration and elastic stability of a set of discrete superconducting toroidal field magnets arranged to form a "bumpy" torus was examined. The mutual destabilizing magnetic forces between magnet pairs were calculated using a numerical differential inductance technique. It was shown that the mutual attractive magnetic forces can produce elastic buckling if the entire toroidal set. The vibration modes of the set were also found as functions of the coil current. The response of the set of magnets to an earthquake type motion of the toroidal base was calculated. These calculations have been incorporated in a computer code.

Measurements were made of the lateral stiffness of a flexible, planar, superconducting coil between two rigid coils in series. These tests show a dramatic decrease in the natural bending frequency with subsequent elastic instability or "buckling" at a critical value of the current in the coils. These observations support a magnetoelastic analysis which shows that proposed designs, of toroidal field coils for Tokamak fusion reactors, have insufficient lateral support for mechanical stability of the magnets.

H. Structural standards and design requirements (E. P. Esztergar - BNL Consultant)

In the past decade the research on CTR physics problems has progressed to such an extent that fusion technology has reached the stage where the problems of building reliable and economical power reactors are seriously considered. The presently studied plasma confinement devices have outgrown the experimental laboratory sizes, requiring large volume, long-lived, and strong magnetic fields. The superconducting magnets considered at the present weigh several thousand tons each, carry currents on the order 10^4 amperes and magnetic fields on the order of 100 kilogauss that generate radial forces on the order of 10^7 kilograms (twenty million pounds) and several thousands of psi pressure. The systems are typically cooled by liquid helium at 4°K containing on the order of 10^5 liters and confined in double walled vacuum chambers (dewars). The magnitude of the operating forces and the potential energy release rate under abnormal and accident conditions signals the need for a systematic evaluation procedures that will evaluate accident consequences on plant operations.

The present situation, with respect to MFE magnet structures, is similar in many aspects to the conditions prevailing in the early stages of fission

reactor history or to even more recent developments in breeder reactor technology. The former required the conception of an entirely new safety philosophy based on failure mode analysis; and the latter, by introduction of complex time dependent effects, the development of material data base, and analysis methods. The standardization effort, which involved the ASME code bodies, industrial and research organizations, and regulatory agencies, resulted in the formulation of interim design criteria and provided the framework for the development of long-term research programs. This brought about the systematic solution for the outstanding problems, eliminating needless duplication.

To be realistic, the development of MFE magnet structure standards is a long-term effort requiring many years (i.e., the ASME fission reactor standards took approximately twelve to fifteen years to develop). Input from physicists, designers, analysts, and materials, fracture mechanics, welding, testing, and manufacturing engineers will be needed. In view of this, the speaker sketched out several possible routes for the initial establishment of an MFE structural advisory group to concentrate on the improvement of current evaluation methods.

Thursday, September 9 and Friday, September 10 - Discussion Sessions

Lively discussion sessions chaired by Chris Stoddart and Chuck Brinkman of ORNL took place at the end of Thursday's presentations and throughout Friday morning. Most of the attendees were involved in these sessions debating various points brought up in the two days of presentation. At the end of these lengthy discussions recommendations A through G listed earlier in the Summary and Conclusions Section (page 2) were adopted by almost all the participants with many volunteering to serve on one or more working groups of the proposed MFE Magnet Structural Advisory Group.

APPENDIXSTRUCTURAL ANALYSIS NEEDS FOR MAGNETIC FUSION
ENERGY SUPERCONDUCTING MAGNETS

September 8-10, 1976

List of Participants

Bialek, James PPPL	Hsieh, S.Y. BNL	Reich, Morris BNL
Bezler, Paul BNL	Hussong, R.O. ORNL	Reinschmidt, K. Stone & Webster
Brinkman, Charles ORNL	Ingram, Glenn ERDA	Rolf, R.L. ALCOA
Chang, Harry EBASCO	Johnson, Neil Mechanics Research Inc.	Sackett, Steven LLL
Chang, T.Y. U. of Akron	Kouts, H. BNL	Smith, G.E. Princeton U.
Connors, J. MIT	Lanell, Petter Magnetic Engr. Assoc.	Smith, R.A. Westinghouse
Cramer, Bruce McDonnell Douglas	Lehner, John BNL	Stekly, Z. Magnetic Corp. of Am.
Dalder, E. ERDA	Liu, K.C. ORNL	Stoddart, C. ORNL
Doggett, James LLL	Martinelli, A. CEN	Thomas, R.K. General Atomics
Donato, J. GE	McHenry, Harry NBS	Tischler, N. Magnetic Corp. of Am.
Esztergar, E BNL	Moon, F.C. Cornell U.	Turner, L. ANL
Fillo, John BNL	Ojalvo, I. Grumman	Young, Warren U. of Wisconsin
Floreen, Steve International Nickel Co.	Peters, Dale International Nickel	Yu, Wen-Shi BNL
Gardner, Don BNL	Powell, Jim BNL	Vagins, Milton Batelle Pacific NW
Goradia, H. BNL	Prackuktam, S. U. of Akron	Ziurys, E. ERDA
Gralnick, S PPPL	Prodell, Al BNL	<u>ADDITIONS:</u>
Gray, W.H. ORNL	Quay, Robert GE	Chan, S.J. EBASCO
Hackworth, D.T. Westinghouse	Rapperport, E.J. Magnetic Engr. Assoc.	Hung, N.S. "