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DETAILED TECHNICAL PLAN FOR TEST PROGRAM ELEMENT-III (TPE-III) OF THE FIRST WALL/BLANKET SHIELD ENGINEERING TEST PROGRAM

by

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1. INTRODUCTION

Fusion experimental devices and reactors use magnetic fields for the confinement, control, and heating of plasmas. Of necessity, the first wall/blanket/shield (FW/B/S) systems of a fusion reactor will experience changes in these magnetic fields as well as in the field from the plasma current itself. These electromagnetic effects have been observed, sometimes forcefully, in currently-operating fusion experiments; and considerable effort has gone into understanding the electromagnetic effects expected in experimental devices under construction, such as the Tokamak Fusion Test Reactor (TFTR) and the Joint European Torus (JET). It is safe to say that, because of their larger size and magnetic fields and because of the presence of a more elaborate first wall, as well as a blanket and shield, reactors of the Fusion Engineering Device (FED) generation and beyond may be subject to much larger electromagnetic effects, which must be understood during the design stage.

Thus, the decision was made to include electromagnetic effects as Test Program Element-III (TPE-III), one of the four elements of the Department of Energy/Office of Fusion Energy (DOE/OFE) program in support of FW/B/S development. Preliminary concepts for TPE-III were refined and supported at an informal workshop on experimental tests of electromagnetic effects in the FW/B/S Test Program, held at ANL in September 1980. Approval was granted by DOE in June 1981 for conducting TPE-III at ANL. Shortly afterward a design review was held at ANL which supported the design of the experimental program and test bed, now called FELIX (Fusion ELectromagnetic Induction eXperiment); recommendations were made for prompt definition of the experimental program and a prioritizing of the suggested upgrades.

Since the design review, refinements to the FELIX test-bed design have been made to enhance its suitability for the planned experimental program and to reduce its cost. Materials have been procured, and winding of the coils has begun. The size of expected effects has been predicted using a computer simulation of early experiments, and selection of instrumentation to measure those effects has begun. All these developments will be described in this report.

The designers of a FW/B/S system can expect to gain the following from the FELIX program:

1. Verified computer codes suitable for calculating FW/B/S electromagnetic effects.
2. Reactor-relevant experimental data which can be used to verify other computer codes.
3. A practical understanding of the segmenting of the FW/B/S and of the separation of the segments.
4. The electromagnetic data needed to choose between alternative concepts: e.g., between thin-wall sections and dielectric breaks, or between eddy-current activated electrical jumpers and more conventional jumpers.
5. Model tests which can be scaled directly to the electromagnetic effects expected in a fusion reactor.
6. Prototype equipment up to 1 m^3 in size which has operated under reactor-relevant electromagnetic conditions.
7. Instrumentation which has been proven to operate reliably in a pulsed magnetic field.

If the upgrades recommended by the design review panel are implemented, the following information can also be provided:

1. An understanding of the behavior of sizable (tens of centimeters on a side) models during a simulated plasma disruption, with fields and field change rates of 0.35 T and 330 T/s, respectively.
2. Testing of prototype components and instrumentation in the magnetic environment likely to be found in a fusion reactor.
3. An understanding of the behavior of ferritic materials and large ferritic objects in crossed saturating and pulsed fields.
4. Synthesis of the response of components to plasma disruption and coil discharges having different pulse shapes in time, and information about the sensitivity of the response to pulse shape.

Some of the effects to be studied, such as the consequences of holes and segmentation, and other geometrical complications, can be modeled using computer codes; some of the others described below in Section 3 cannot. Even the geometrical effects which can be modeled with codes must also be studied experimentally; today's computer codes can treat only the simplest geometries, and the complexities of the FW/B/S system will certainly tax the eddy-current codes of the foreseeable future. This detailed technical plan focuses on a balanced program of experiment and computer code evaluation and development.

In Section 2, the experimental requirements, test-bed design, and computational requirements are reviewed and updated. Next, in Sections 3, 4 and 5, the experimental plan, instrumentation, and computer plan, respectively, are described. Finally, Section 6 treats other considerations, such as personnel, outside participation, and distribution of results.

2. PROGRAM REQUIREMENTS

2.1 Experimental Requirements

The experiments should be conducted in a facility where the values of key parameters are such that significant effects are observed, and these effects can be measured with sufficient precision to allow comparison with theory or computations. The values must be large enough that the results of experiments can be extrapolated to a full-scale system with confidence, but small enough that the cost of the facility is not prohibitive.

The facility should have the following characteristics:

1. A sizable constant field, analogous to a tokamak toroidal field or the confining field of a mirror reactor.
2. A pulsed field with a sizable rate of change, analogous to a pulsed poloidal field or to the changing field of a plasma disruption, perpendicular to the constant field.
3. A sufficiently large volume to assure that large, complex test pieces can be tested, and that the forces, torques, currents, and field distortions which are developed are large enough to be measured accurately.

Analysis shows that for most experiments (measurements of field distortion, forces, and torques, as well as model verification, and component and assembly simulations), the strength and rate of change of the pulsed field and the size of the test volume are the most important parameters; but that for experiments with saturable ferromagnetic materials, the strength of the constant (i.e., toroidal) field is the most important.

2.2 Test-Stand Description

The facility being built meets these experimental requirements. The constant field is modeled by a slowly pulsed solenoid field that has a rise and fall time of 3 s and a flattop of 8 s. The pulsed field is modeled by a pulsed dipole field that has a rise time of 0.4 s or more, a flattop of 3 s, and a variable decay time of 10 ms or more. The repetition rate is 1 pulse per minute.

A horizontal solenoid field of 1.0 T is excited by four solenoid coils composed of a total of 24 pancakes over a cylindrical volume of 0.76 m^3 (radius r = 0.45 m, length P = 1.2 m). The field uniformity of 15% is adequate but less important than accessibility to the desired volume. A vertical dipole field of 0.5 T is excited by two sets of nested dipole coils, with two coils per set. This field is superimposed on the solenoid field; it can be forced to decay with $\dot{B}$ up to 50 T/s. Figure 1 shows an isometric view of the proposed facility. The coil parameters are given in Table 1.

Table 1. Coil Parameters

	Half a Solenoid	Half a Dipole [a]	
	Coil	Inner	Outer
Field Strength (T)	1	0.5	0.5
Inner Radius (cm)	55.2	81.8	81.8
Outer Radius (cm)	74.1	103.7	103.7
Axial Length (cm)	33.3	227.3	273.7
Azimuthal Length (cm)	—	14.0	21.9
Angle to Center (deg.)	—	54.0	18.0
NI (kA)	514	262.1	419.3
Stored Energy (kJ)	618	428	428
Inductance L (mH)	33	20.0	20.0
Resistance R (mΩ)	27.4	35.1	35.1
Peak Current (kA)	6.12	6.5	6.5
DC Voltage Drop (V)	167.7	228	228
Power Consumption (kW at 1 ppm)	171	95.7	95.7

[a] One inner and one outer coil in series

In defining the experiments, several changes in the facility design have been made for easier implementation. The solenoid coils have been repositioned, with a larger axial spacing between the two central solenoids as shown in Fig. 2. The larger gap permits four 30.5-cm-dia. holes, equally spaced circumferentially. The bottom hole provides for external support of the test articles and apparatus as described below. The other three provide

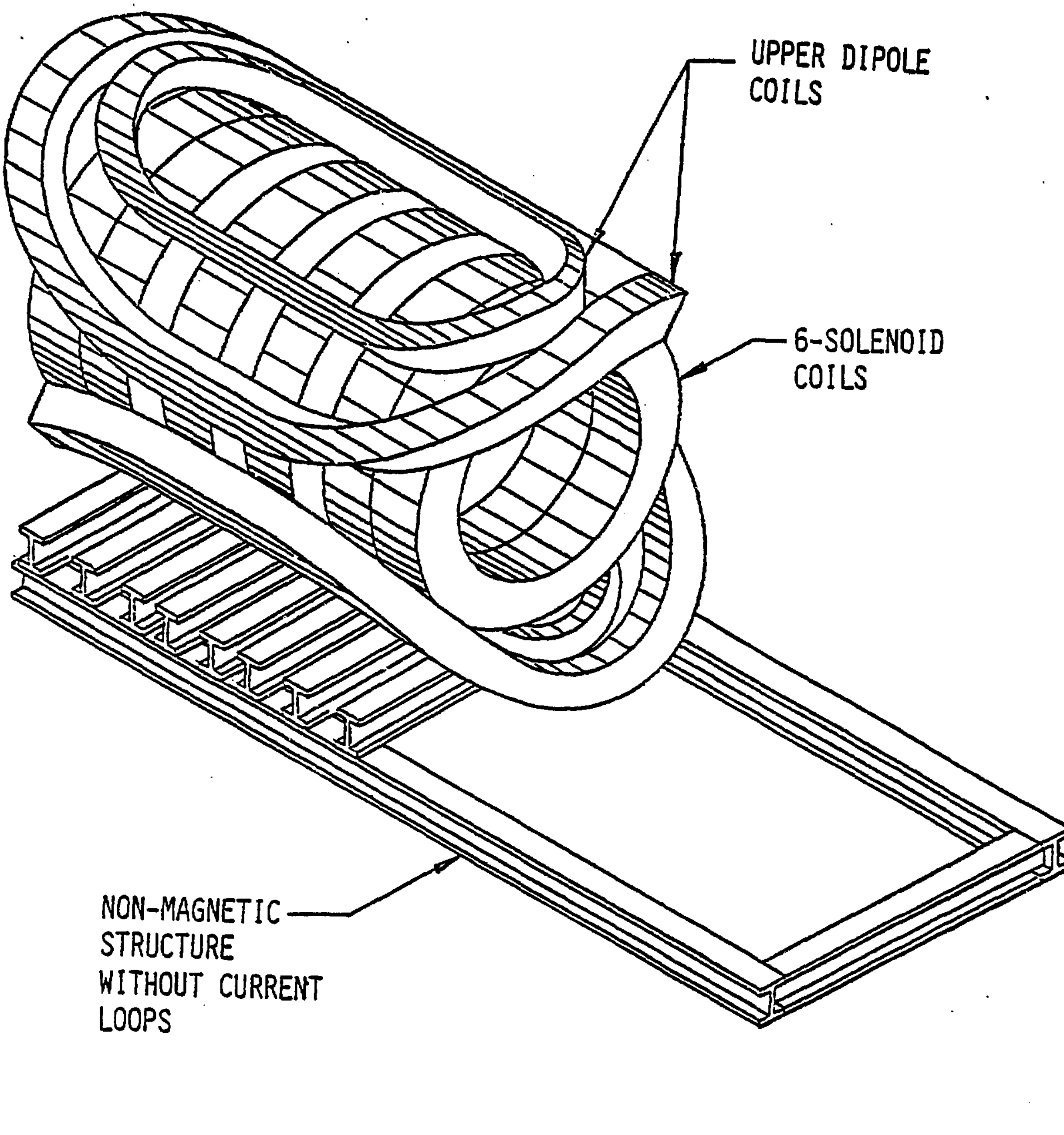

Fig. 1 FELIX Test Stand Concept

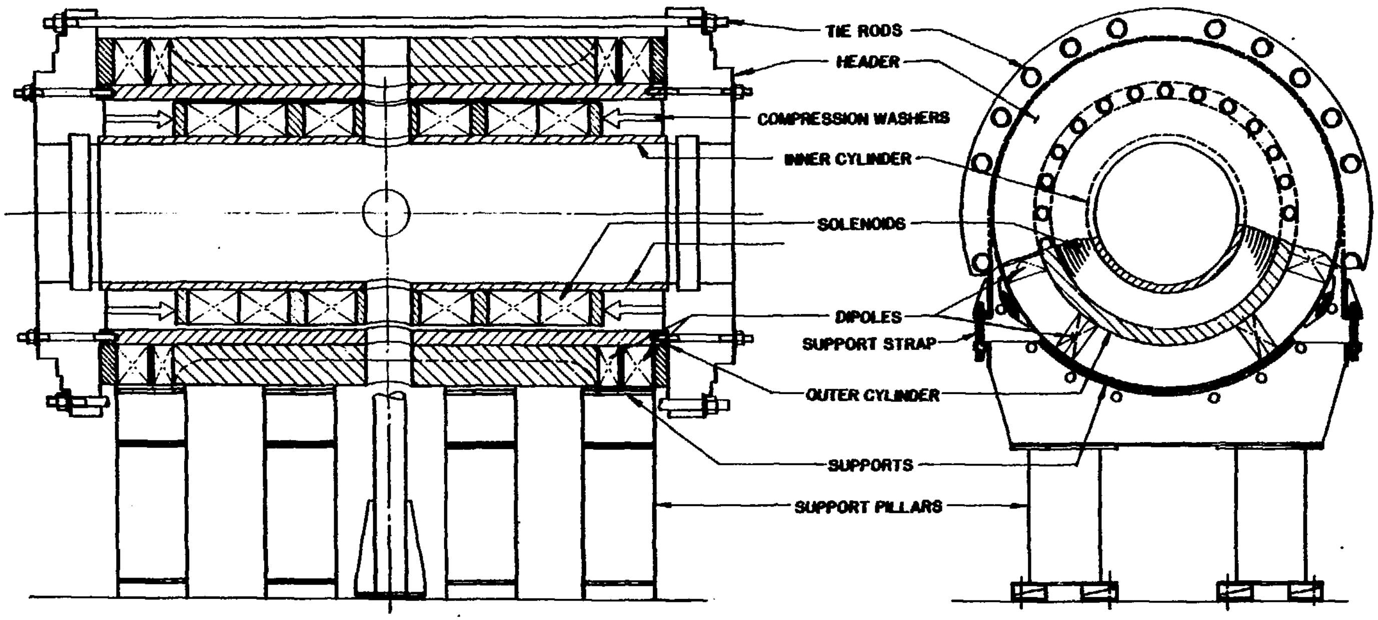

Fig. 2
Cross Section and End Views of Facility

for optical, mechanical, and electrical access to the experiment. If needed, the top hole can be widened into a slot for better access. There is also axial access from the ends of the test bed, and provision for limited electrical access through the narrow (10 cm) gap between each central solenoid and its neighboring solenoid.

2.3 Facility Upgrades

The facility will be upgraded in accordance with recommendations made by the panel convened on June 23, 1981 to review the FW/B/S Electromagnetic Effects Facility (FELIX) design, and experiments will be planned. The time at which upgrading will be implemented will depend on the level of funding from DOE/OFE. Priorities are as follows:

2.3.1 Plasma Disruption Simulation. First priority will be given to simulation of a plasma disruption simulation with 530 kA current pulses in a coaxial test fixture (at $r = 30$ cm, $B = 0.35$ T and $\dot{B} = 333$ T/s). This top priority is assigned to enable simulation of important effects not possible with the baseline facility.

2.3.2 Power Supply Upgrade. As a second priority, equal weight will be given to upgrading the solenoid and dipole field power supplies for operation at 4.0 and 1.0 T, respectively. The resultant factor-of-8 increase in cross-product forces will be sufficiently large to enable destructive tests of prototypical components, for example. (The solenoid tie rods, initially of stainless steel, will be changed at the time of implementation to inconel, to withstand the increased stress levels.)

2.3.3 Frequency Response with Damped Oscillations. The third priority is assigned to measurement of the frequency response of test articles by means of damped oscillations. These tests could be useful in synthesizing the expected behavior of reactor components and in designing feedback loops to control plasma position. It may be difficult, however, to achieve good results in practice.

2.4 Computational Needs

In addition to experimental tests, the development of computer codes is an integral part of TPE-III. Code development will involve the following four steps:

1. Determine the requirements for codes.
2. Compare existing codes.
3. Choose the codes to be used.
4. Determine and implement needed improvements.

Eddy-current codes can be characterized by their dimensionality: one-dimensional (1D) current with two-dimensional (2D) field, two-dimensional plane current with strictly one-dimensional field, two-dimensional shell current with perpendicular field, or truly three-dimensional (3D) fields and currents. They can also be characterized by the method of solution: finite element, finite difference, boundary integral, full integral equation, or a hybrid of these methods. They may deal with steady-state or transient phenomena; they may or may not be able to treat nonlinear (ferritic) materials. Finally, they may be evaluated on their generality, their treatment of disjoint regions, their ease of data preparation, and their presentation of results.

Several eddy-current codes have been developed in recent years. Appendix A lists references to ten codes, prepared by R. Lari of ANL in Spetember 1980, plus a list of eddy-current papers presented at the COMPUMAG-Chicago Conference on Electromagnetic Field Computation in September 1981. The FED Design Center at Oak Ridge National Laboratory (ORNL) has used the codes of G. Bronner of Princeton, which use the mutual inductances of axisymmetric washers, for the electromagnetic analysis of FED and INTOR. H. Vogel of Los Alamos National Laboratory (LANL) has also produced an eddy-current program. Meanwhile, the Rutherford-Appleton Laboratory in England is in the midst of a six-man-year study to create an eddy-current code. They have reached the point of selecting the best method for the computation and held a week-long workshop on this in April 1981.

Unfortunately there is a lack of interaction between the fusion community and the community (e.g., participants in the COMPUMAG conferences) which is developing eddy-current codes. Code developers are not taking fusion reactor needs into account; and, apart from coupled-ring mutual inductance codes, reactor designers are using only a very small number of the available codes (EDDYNET from ANL, the Christensen and Weissenburger codes from Princeton Plasma Physics Laboratory (PPPL), the code of Preis et al. at IPP, the Japanese EDDY series, and a few others) and are not aware of the others.

One of the early and important goals of the FELIX program is to increase the communication between these two scientific communities: to make the code developers aware (by providing them with FELIX results, and other data) of the needs of fusion reactor designers, and to make the designers aware of the codes available (in some cases, verified with FELIX data).

In the selection of appropriate codes for the program it must be understood that the spatial resolution of codes will always be limited. Existing codes treat between a few hundred and a few thousand elements; this number will increase somewhat, but not by orders of magnitude, over the next few years. Thus, a number of specialized codes, and at least one general three-dimensional code, will probably be required. All of these codes must be verified and calibrated by experimental modeling.

The technical plan which follows treats Phase I of TPE-III, and covers the fiscal years 1982, 1983, and 1984.

3. EXPERIMENTAL PLAN AND SCHEDULE

Basically, two different kinds of experimental tests are planned: those to study geometrical effects, and those to study material and assembly effects. These two kinds of experiments have been subdivided into seven series of experiments, to be carried out in a sequence to provide data as needed for the design of FED or similar fusion devices. Figure 3 shows the schedule for these experiments along with the schedule for the construction of the facility, instrumentation, and test-piece support structure.

In the following description, the earlier experiments are described in more detail than the later ones, both because the earlier experiments require more immediate planning and because results from the early FELIX experiments or changes of emphasis in the national fusion program may require changes in these later experiments. A detailed plan and report of each series of experiments will be prepared at the appropriate time. Appendix B contains possible formats for such test plans and test reports.

3.1 Two-Dimensional Experiments

The first series of experiments to be performed when the facility is completed will be of about two-months duration and will study eddy-current effects in flat plates. These two-dimensional geometries will be the easiest to instrument and record data from and the easiest to simulate with computer codes.

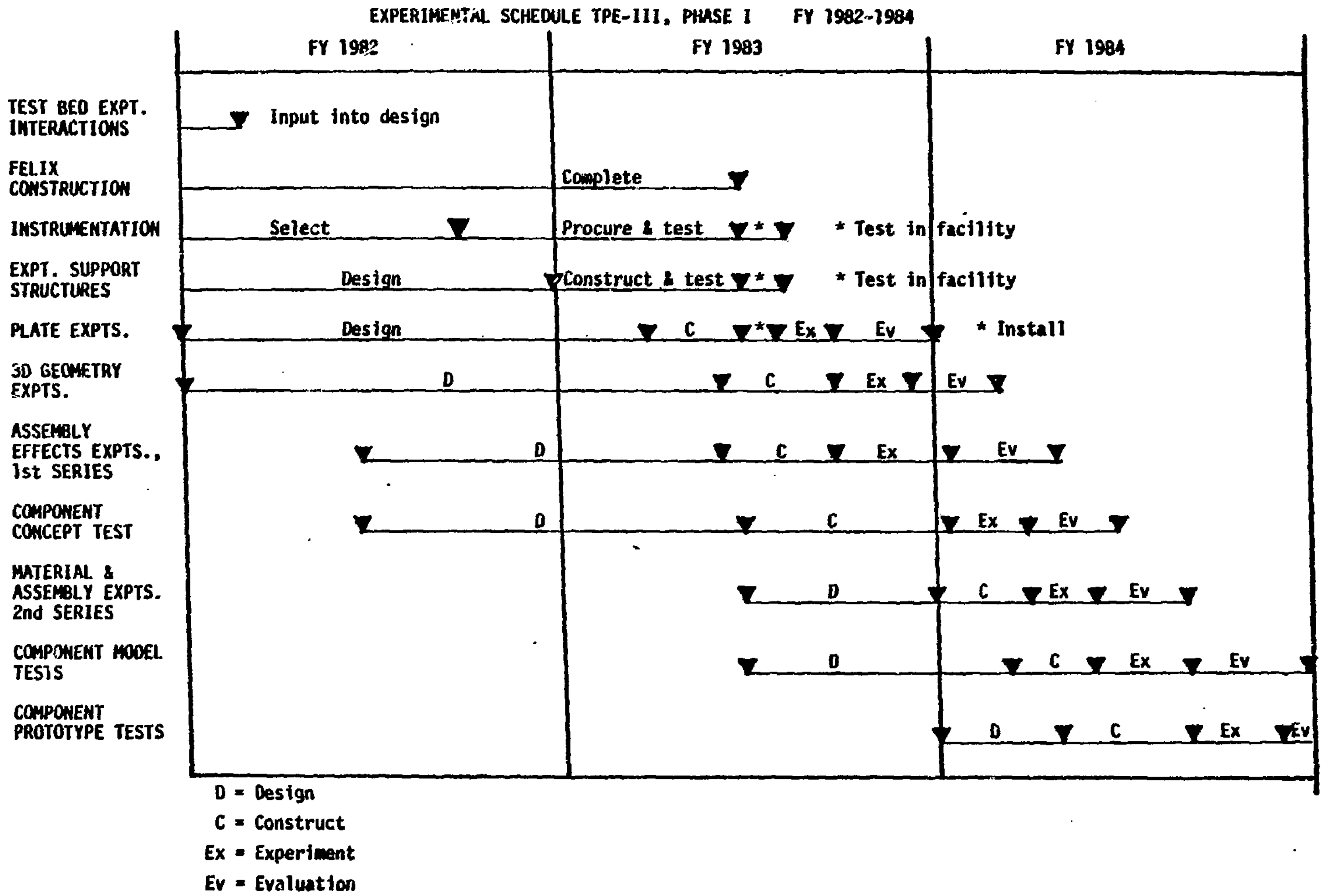

Fig. 3
Experimental Schedule

3.1.1 Objectives: The objectives of the 2D experiments will be:

- To study the 2D eddy-current pattern and the resulting fields, forces, torques, stresses, and heating.
- To study the perturbing effects of slits, holes, and other geometrical features.
- To determine whether a plate (3D geometry in practice) can be modeled adequately by 2D computer codes.
- To evaluate 2D codes on the basis of their accuracy, efficiency, and convenience.
- To evaluate, in fairly simple experiments, instrumentation for measuring field, current, temperature, forces, and stress, which can then be used in more complex experiments.

3.1.2 Description of the 2D Experiments. The test piece consists of a rectangular aluminum plate 1 m by 0.8 m and 1-cm-thick. The plate is perpendicular to the dipole field, and its long dimension is parallel to the solenoid field. The L/R time constant of the plate is roughly twice the 10-ms discharge time of the dipole field, in order that induced-field effects are large but not independent of the discharging field. The 2-ms time constant associated with a skin depth of half the plate thickness is short enough that skin-depth effects should be conceptually separable from other eddy-current effects and unimportant over the times of interest.

An 1100-aluminum alloy has been chosen as the test material, on the basis of its low resistivity of 2.8 μΩ • cm. This choice of material maximizes the signal strength for field, current, temperature, force, and stress measurements. The dimensions of the plate were chosen so that it would fit comfortably within the test volume of FELIX (see Fig. 4.).

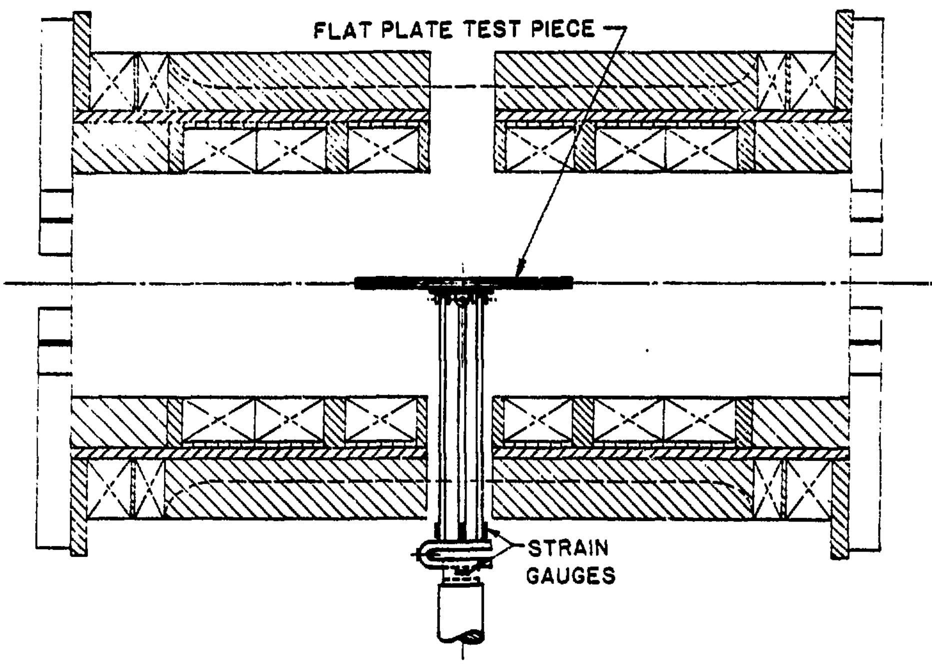

Fig. 4
Flat Plate Test Piece Positioned in Test Facility

The plate will be supported from its center by a support structure extending through a 30-cm-diameter hole between the solenoid coils (see Section 3.8.1). Measurement of overall force and torque can be performed with strain gauges mounted on the support, in a lower magnetic field. This type of mounting is common in wind-tunnel experiments. In the FELIX experiments the mounting has the advantage of isolating the test piece from the displacements and vibrations the magnets will undergo during the field pulsing.

3.1.3 Measurements to be Performed. The strain gauges (on the support, described above) measuring the overall torque and force will not experience the full pulsed field. Other strain gauges will be placed on both sides of the plate, at positions along the symmetry lines, to measure local stresses; these must operate in a pulsed field.

To determine field distortion by the eddy currents, field probes will be placed at several points on and around the plate. Also, pairs of search coils will be placed above and below the plates, to measure the value of the local current density. Current patterns also can be inferred from measurements of temperature rise; such measurements can be made globally with infrared viewing and locally with thermocouples.

Prior to the actual experiments, a nonconducting (lucite) plate will be instrumented in the same way and the field pulsed, in order to measure the electrical noise level and look for sources of systematic error.

For an estimate of the size of the effects to be measured, see Section 3.8. For a further discussion of instrumentation, see Section 4.

3.1.4 Further Experiments. Measurement of the effects of slits and holes is mentioned above. Such measurements will require a concentration of instrumentation in the vicinity of the slits or holes. Interaction with both reactor designers and code developers is needed to make these tests most useful to both.

As a preliminary step for later experiments on segmentation effects, the plate experiment will be repeated with the four quadrants of the plate electrically insulated from each other.

3.1.5 Expected Output of the 2D Experiments. The final output of the 2D experiments will include:

- A summary of 2D experimental results for FW/B/S designers.
- A complete record of data for verifying codes.
- A small number of verified 2D codes.

3.2 Three-Dimensional Experiments

Additional experiments, also about two months in duration, will deal with three-dimensional geometrical effects. Test pieces will include the hollow conducting cylinder shown in Fig. 5 and stacked conducting bricks. The effects of segmentation and the separation between segments will be studied.

3.2.1 Objectives. The goals of the 3D experiments will be:

- To study the shielding by continuous and slit hollow cylinders against changes in the magnetic field perpendicular to their axes.
- To study the current patterns, heating, and forces in such cylinders.
- To quantify the electromagnetic effects of segmenting a conducting solid, and, in particular, the dependence on the size of the separation between segments.
- To evaluate 3D codes on the basis of their accuracy, efficiency, and convenience.

3.2.2 Description of the Experiment. The hollow cylinder in Fig. 5 has two full-length slits located diametrically opposite one another. The pulsed

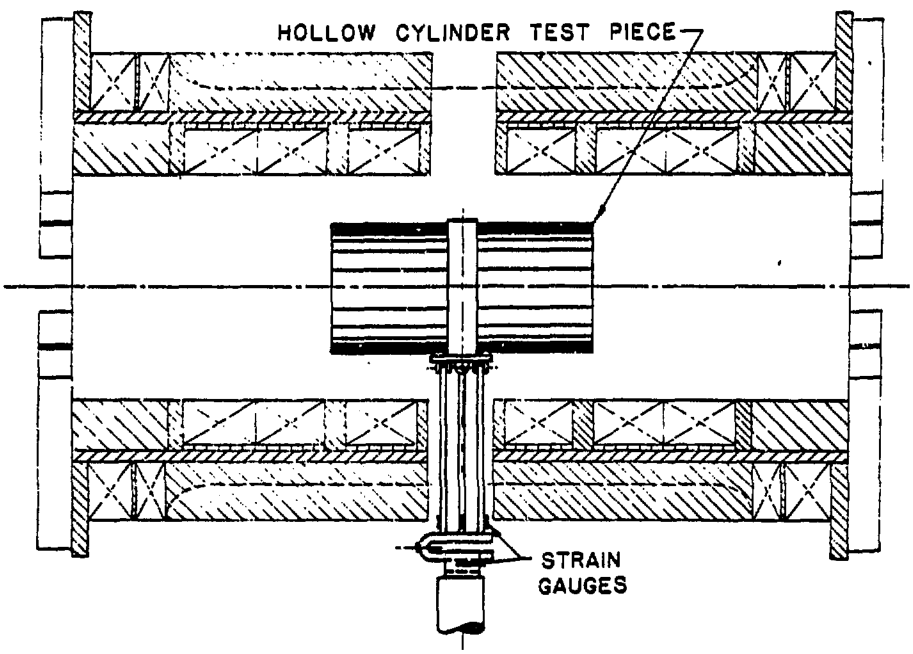

Fig. 5
Hollow Conducting Cylinder Positioned in Test Facility

dipole field is vertical. The cylinder can be rotated so that the slits are at any angular position. If the slits are located in the midplane, they will not impede the eddy-current flow, and two eddy-current loops will cover the full top and bottom halves of the cylinder just as though no slits were present. With the slits at the top and bottom of the cylinder, only smaller eddy-current loops, each covering one quadrant of the cylinder, are possible. Set at an intermediate angle, the slits will lead to asymmetric current loops.

The 1100-aluminum alloy cylinder is 120 cm long, 40 cm in outside diameter, and 0.5 cm thick. As in the plate experiment described above, the dimensions were chosen so that the L/R time of the cylinder is about twice the discharge time of the dipole field, resulting in induced-field effects that are large but not independent of the discharge time. Again, effects of current nonhomogeneity across the thickness of the plate should disappear in a few milliseconds and, thus, be unimportant.

The cylinder is supported by, but electrically insulated from, a ring at its midplane. The ring is attached to the same support structure as the plate in the previous experiment, and overall forces and torques are measured as described above.

3.2.3 Measurements to be Performed. The most important measurements are those of the field at different points along the axis, to determine how the field change soaks through the cylinder with time. The cylinder dimensions, 120-cm-long by 40-cm-OD, were chosen with the expectation that end effects would be small near the center of the cylinder axis. Measurement of current patterns, forces, and torques are also important, because a split cylinder simulates a minimal segmentation of a mirror or high aspect-ratio tokamak FW/B/S.

3.2.4 Further Experiments. A four-by-four array of aluminum bricks will be used in the segmentation experiment. The brick dimensions are 40 cm in the z (dipole field) direction, 30 cm in the x (solenoid field) direction, and 20 cm in the y direction. The insulating spacing between bricks is variable. The most important measurements are the fields in the spaces between bricks, as a function of time. Overall torque measurement is also important for comparision with code predictions.

3.2.5 Expected Output of the Experiments. The output of the 3D experiments is expected to include:

- Detailed results on field shielding by the cylinder, split and unsplit, with appropriate scaling rules, for use by reactor designers.
- Results on current patterns and forces, with appropriate scaling rules, for use by reactor designers.
- Detailed results on segmentation effects, with appropriate scaling rules, for use by reactor designers.
- Experimental data sets appropriate for verifying 3D computer codes.
- A small number of verified 3D codes.

3.3 Assembly Effects

Experiments on assembly and material effects differ from those described above in that the results could not be predicted even if a fully verified code were available. The assembly effects depend on factors such as joint resistance which are not known a priori. After the 2D and 3D experiments described above are completed at the end of FY 1983, there will be a need for a series of assembly-effect experiments to observe the electromagnetic behavior of the connectors being developed under TPE-IV and to provide information needed to make choices in the FED FW/B/S design. If, in fact, such tests do not prove useful at that time, they can be interchanged with some of the component model tests described below.

3.3.1 Objectives. The experiments in assembly effects are expected to accomplish the following objectives:

- To provide the information needed to make an early choice of FW/B/S components exhibiting assembly or material effects.
- To judge the variance among supposedly identical test pieces exhibiting these effects.
- To define needed lifetime tests.

3.3.2 Description of the Experiments. At this time it is impossible to know exactly what assembly effects experiments should be conducted. An example that incorporates several features of such experiments is an electrical connector between two first-wall or blanket modules, designed for remote maintenance. Such connectors are being developed as part of TPE-IV. Figure 6 shows such a test piece consisting of the (unspecified) connector plus a low-resistance loop to generate current in the charging field, and force it through the connector. To simulate reactor conditions, the experiment should be carried out in vacuum, perhaps in a vacuum vessel designed for general use in FELIX experiments.

3.3.3 Measurements to be Performed. The current through the connector and the voltage across it must be measured to yield the contact resistance. The forces and stresses at the connection and the temperature rise in its vicinity should also be measured. Overall forces and field perturbations are less important measurements and may not be required.

3.3.4 Expected Output from the Experiment. It is anticipated that the output from the assembly-effects experiments will include:

- Value and variance of joint resistance.

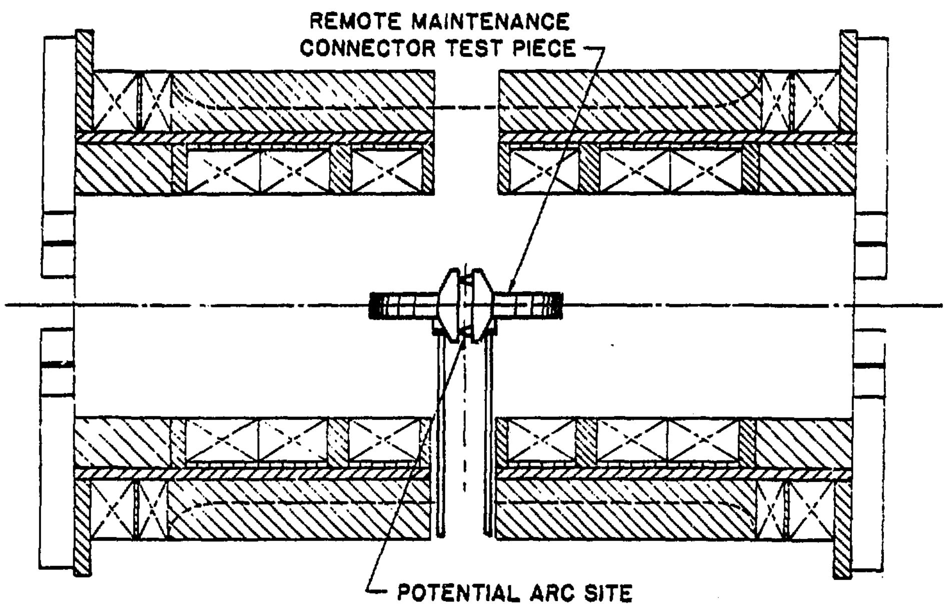

Fig. 6
Typical Test Piece for Assembly Effects Experiments

- Stress dependence of joint resistance.
- Information needed to select a remote-maintenace electrical connection.

3.4 Component Concept Tests.

The component concept tests will be the first to simulate actual FW/B/S components. The test articles will be geometrically similar to the component conceptual design they represent, but will be homogeneous in material and lack details. With a relatively low expenditure of time and money, these tests will permit the comparison of concepts, investigate the requirements for restraint and support, and uncover effects overlooked in the electromagnetic analysis. It is vitally important that these experiments be planned in close cooperation with the designers of the concepts.

3.4.1 Objectives. The objectives of the component concept tests will be:

- To generate the information on electromagnetic effects needed to choose among competing concepts.
- To test the mechanical integrity of a concept, using geometric similarity and actual stress levels.
- To identify restraint and support needs.
- To define electromagnetic effects overlooked in preliminary analysis.
- To provide final verification of computer codes in situations as close as possible to reactor conditions. (Subsequent series of experiments will be beyond the capability of existing codes and will require approximations and multiple codes in their analysis.)

3.4.2 Description of the Experiments. Test pieces might be scale models of different concepts for a FED limiter or different concepts for mounting first walls consisting of arrays of tubes. Stress levels in the models will be the same as those in the operating component; these stress levels will be achieved through the choice of wall thickness or by other means. The test pieces will be homogeneous in material and without bolted joints or other details.

3.4.3 Measurements to be Performed. Measurements of forces, torques, and stresses are most important. The current pattern should also be measured. Measurements of field penetration and perturbation may not be required.

3.4.4 Expected Output of the Component Concept Experiments. These tests should yield:

- Comparison of electromagnetic effects in different concepts.
- Information to refine the concept.
- A reactor-relevant data base for code verification.

3.5 Material and Assembly-Effects Tests

These experiments are similar in concept to, but extensions of, those described in Section 3.3. Comparison of dielectric breaks with thin-walled sections or bellows as inhibitors of circulating currents could be studied. Clamping concepts for remote maintenance of blanket modules, resistivity of packed-bed breeding blanket modules, and electromagnetic forces on a first-wall melt layer might also be studied.

3.5.1 Objectives. The objectives are similar to those for the earlier Assembly-Effects Tests, listed in Section 3.3.1.

3.5.2 Description of the Experiments. Again, low-resistance current loops will provide the currents needed for the tests. Some of the tests will be more meaningful if performed inside a vacuum vessel. Test pieces could include wall sections with bellows or dielectric breaks, clamping pieces, or a model of a packed-bed blanket module.

3.5.3 Measurements to be Performed. Currents, voltages, and contact or bulk resistances should be measured. Force measurements will help define the kinds of support needed. Temperature measurements will indicate whether arcing and welding are likely.

3.5.4 Other Experiments. The behavior, and in particular the electromagnetic behavior, of a melt layer of the first wall following a plasma disruption is currently seen as one of the major uncertainties in the adoption of first-wall material. Experiments in a vacuum vessel with a suitable low-melting point or liquid conductor may shed some light on this behavior.

3.5.5 Expected Output from the Experiments. The tests on material and assembly effects should yield:

- Values and variance of contact and bulk resistance.
- Knowledge of field dependence.
- Data needed to evaluate dielectric breaks, thin walls, and bellows as suitable inhibitors of circulating currents.
- Knowledge of the electromagnetic behavior of a melt layer.

3.6 Component Model Tests

In component model tests, the test pieces will include some of the details and the material heterogeniety of the component design. These tests will identify electromagnetic effects associated with details which were not present in the component concept tests.

3.6.1 Objectives. The goals of these tests will be:

- To study electromagnetic effects in the presence of details and material heterogeneity.
- To study behavior at realistic stress levels.

3.6.2 Description of the Experiments. If the test is to model the FED limiter, the model will include cooling tubes and coating. Thicknesses will be chosen so as to develop stress levels expected in the actual component.

3.6.3 Measurements to be Performed. Forces, torques, stresses, and current patterns should be measured. Temperature and possibly field distortion should be measured at sensitive positions.

3.6.4 Expected Output from the Experiments. The component model tests will yield:

- Characterization of detailed electromagnetic effects.
- Confidence in the component design.

3.7 Component Prototype Tests

Component prototypes will be tested in the FELIX test bed to verify their behavior under reactor-relevant electromagnetic conditions. Reactor instrumentation, electrically driven actuators, FED experimental blanket modules, and other components can be tested.

3.7.1 Objectives. The goal of these tests will be to verify successful operation of the prototype component under reactor-like pulsed and steady magnetic fields.

3.7.2 Description of the Experiments. The prototypes will be mounted in the experimental space, instrumented, and subjected to the crossed solenoid and pulsed fields. Comprehensive reactor operating conditions can be obtained only if the field upgrade plan is implemented. However, even at the lower level, the tests should provide some useful information.

3.7.3 Measurements to be Performed. Most important are measurements of internal and net forces and torques. Temperature, current, and field distortion should be measured in sensitive areas.

3.7.4 Expected Output from the Experiments. It is expected that the experiments will result in verification that the fully representative component can operate under reactor-like electromagnetic conditions.

3.8 Magnitude of Electromagnetic Effects in First Experiment.

In planning the experiments and choosing the instrumentation, it is essential to know the size of the effects to be expected. The first experiment, described above in Section 3.1, has been simulated with the eddy-current code EDDYNET2D, to find the currents and fields expected in the plate. Additions have been made to EDDYNET to permit the calculation of forces, torques, current density, and temperature rise.

3.8.1 Forces and Torques of First FELIX Experiment.

The first experiment planned for FELIX will use a flat, rectangular aluminum plate, positioned perpendicular to the dipole field, with the long side parallel to the solenoid field. Measurements of forces, torques, fields, temperatures, and possibly currents are planned as functions of time as the dipole field decays exponentially.

A post processor program EDDYPOST has been written to calculate the forces and torques acting on the test piece. The calculation is based on the line currents computed by EDDYNET2D and the specified dipole and solenoid fields. The solenoid field was assumed to be uniform and time independent at 1.0 T in the x direction. The dipole field B_d was assumed to be uniform in the z direction, and with time variation:

$$B_d = 0.5 \text{ T} \exp(-t/10 \text{ ms}).$$

Aluminum resistivity was taken to be 2.8×10^{-8} $\Omega \cdot \text{m}$. Because of the symmetry of the experiment, only one quadrant of the plate was modeled, using a six-by-six mesh. A later computation, using an eight-by-eight mesh, gave results that differed from those below by only a few percent.

Figure 7 shows the time variation of the dipole field decay, the peak field in the plate (B_{max}), and the power dissipated in Joule heating in one

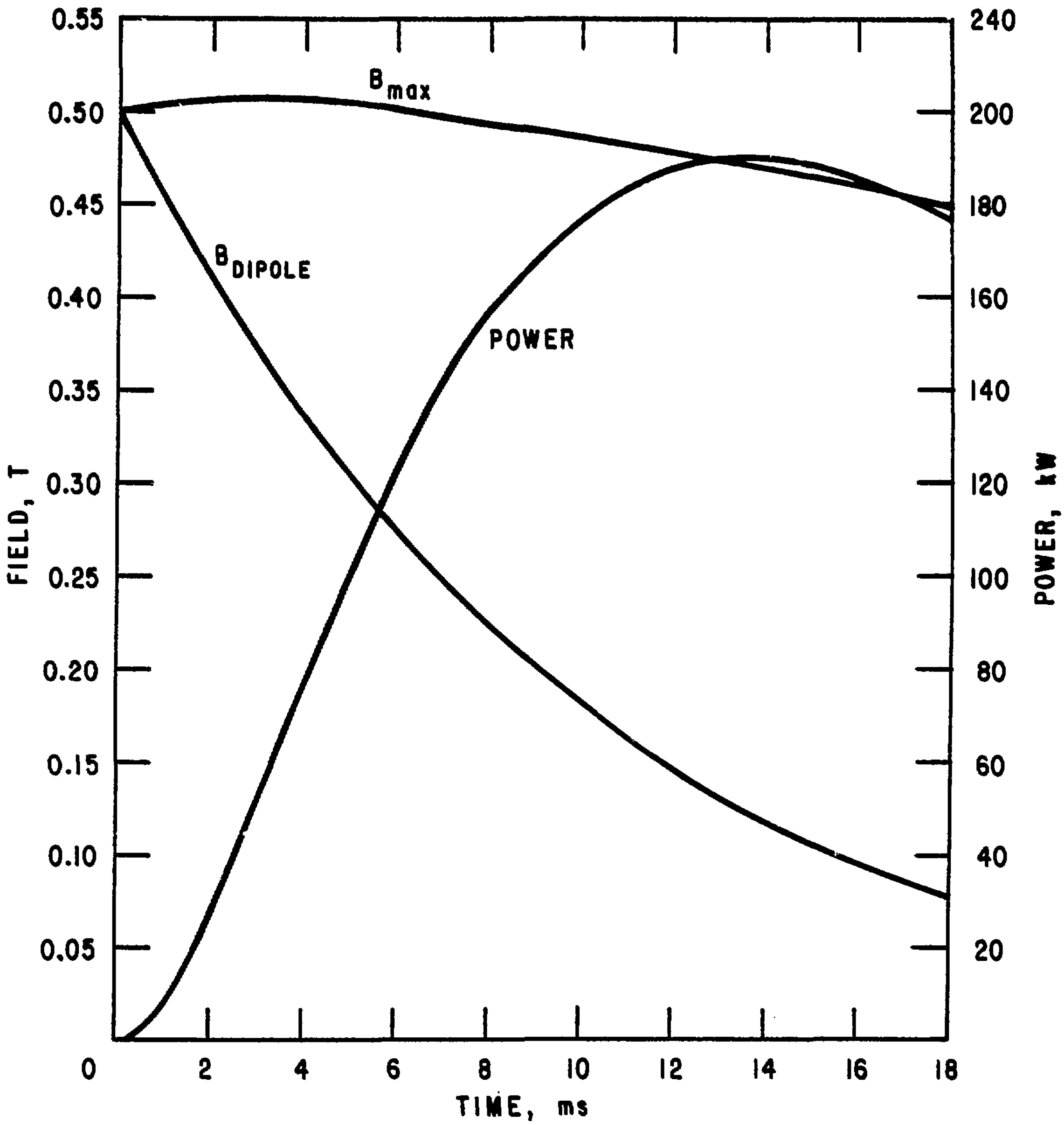

Fig. 7
Applied Field, Peak Field, and Power in FELIX Plate Experiment

quadrant of the plate. The power peaks at 13.4 ms; the peak field in the plate has not decreased substantially in the first 18 ms.

Figure 8 shows the net force components acting on one quadrant of the plate. The x and y components, which arise from the interaction of the eddy currents with the decaying dipole field, reach their peak values at between 8 and 9 ms. The z component, which arises from the interaction of the eddy currents with the time-independent solenoid field, reaches its peak later, at 16.4 ms. The z component is four or five times greater than the x and y components because the solenoid field is larger than the dipole field, and because the current is larger at 16 ms than it is earlier.

The insert sketches in Fig. 8 show the signs of the force components in all four quadrants of the plate. In no case is there a net force on the plate. The x and y components lead to tensile stresses averaging 3.2 MPa (464 psi) and 3.1 MPa (449 psi), respectively. The z component leads to a net torque about the y axis, described below.

Figure 9 shows the net torque components acting on one quadrant of the plate. The z component of torque arises from the dipole field and peaks at 7.6 ms. The x and y components of torque arise from the solenoid field, peak at 15 ms, and are 7 and 16 times larger than the z component, respectively.

Not only is the torque component about the y axis the largest; it is the only one which produces a net torque. All four quadrants combine to yield a total torque of 75.1 kN · m. The torques around the x axis tend to deform the plate into a saddle shape. When viewed from above, it would have a convex curvature for positive x and a concave curvature for negative x.

Another calculation was made with the solenoid field represented by a sum of polynominals. The calculated solenoid field was fit with a combination of the first five polynominals satisfying Laplace's equation and exhibiting axial

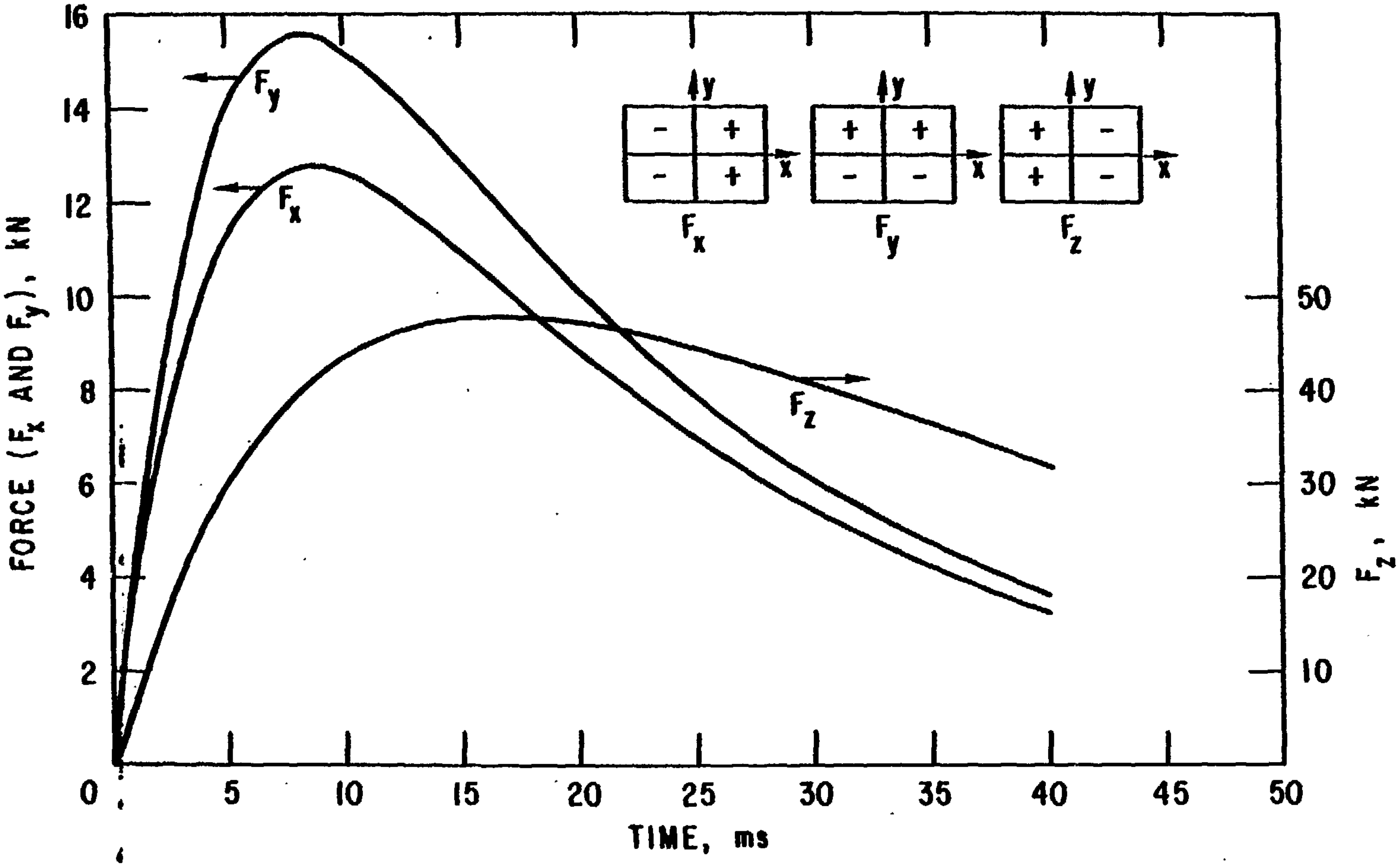

Fig. 8
Forces Acting on One Quadrant of Plate

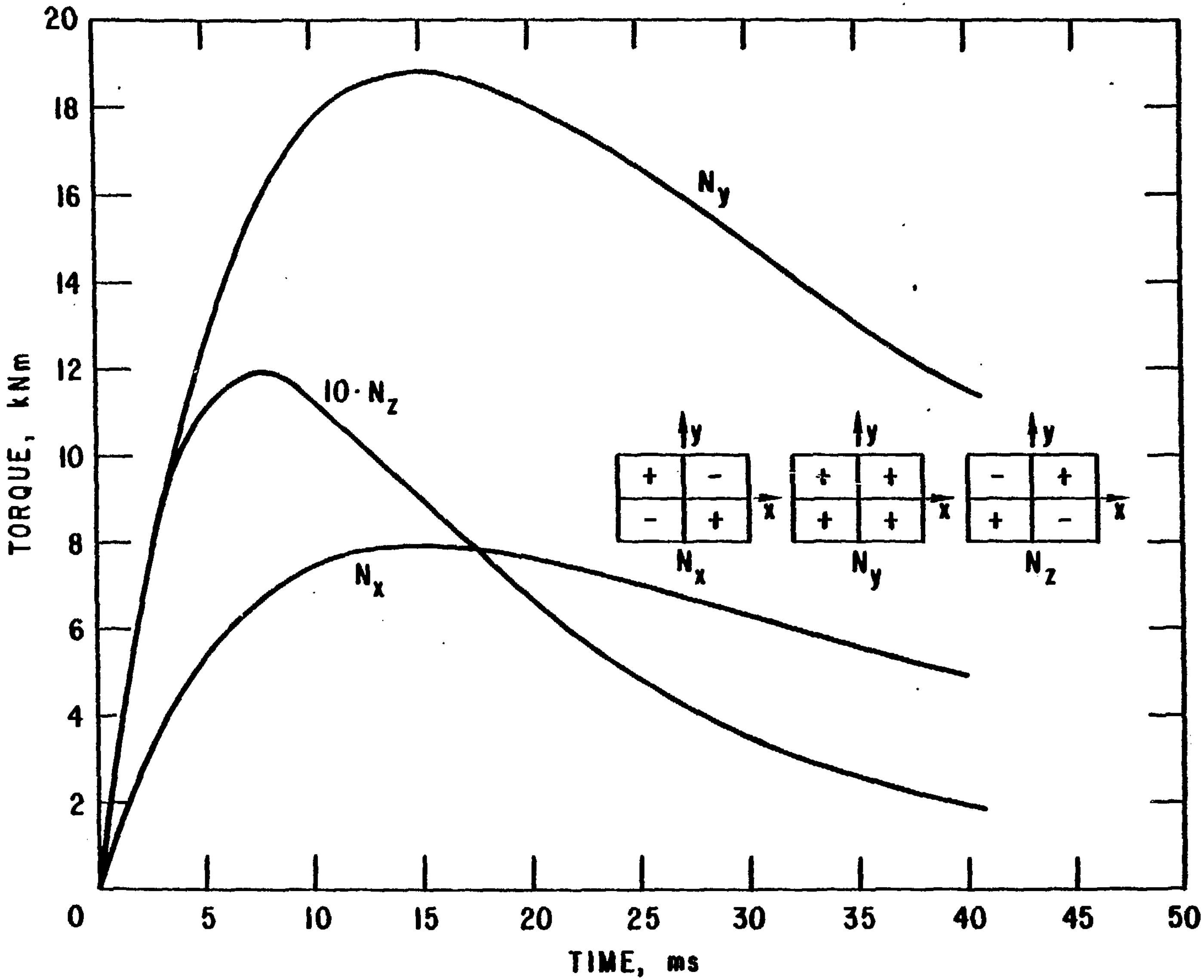

Fig. 9
Torques Acting on One Quadrant of the Plate

mid-plane symmetry. The solenoid axis of symmetry is the x axis of the experiment. The z component of force and y component of torque, which arise from the solenoid field, both displayed maxima values 3.2% higher with the polynominal field than with the uniform field. These results suggest that from a force viewpoint, the homogeneity of the solenoid field is adequate.

As described in Section 3.1, the plate is to be supported from its center. However, stress analysis shows that the forces just described would lead to stresses many times larger that the yield stress of 1100-aluminum. Consequently, the experiments with the plate will be conducted in two steps. In the first step, the plate will be supported only from its center, and the forces and stresses measured at lower values of the dipole and solenoid fields. Next, the aluminum plate will be attached to an epoxy-fiberglass support plate below it (or below it on the positive x side and above it on the negative x side). With this added support, the remainder of the experimental program can be carried out without unduly stressing the plate.

3.8.2 Temperature Rise in First FELIX Experiment. From the beginning of TPE-III temperature measurements have been planned as part of the FELIX experiments. The temperature profile over the test piece is probably the most direct means available of determining the overall current flow pattern in the test piece, although it may be possible to measure current density at particular points by using a pair of coils to measure the difference in tangential field components across a thin test piece. In addition, the temperature rise due to eddy-current heating is a practical concern for some reactor prototype equipment, particularly instrumentation, which is to be tested in FELIX.

The code EDDYNET2D has been modified to calculate approximate values for the current density vector J at each mesh point from the line currents of the mesh.

The adiabatic temperature rise ΔT_{ad} in each time step Δt can be found from the current density by

$$\Delta T_{ad} = J^2 \rho_{el} \Delta t / c_p \rho_m \qquad (1)$$

where ρ_{el} is the electrical resistivity, c_p is the specific heat, and ρ_m is the mass density. Temperature rises accumulate as time progresses.

Heat diffuses along the plate, modifying the temperature found from Eq. 1. For a mesh with spacing Δx and Δy in the two dimensions, the temperature rise at an internal point ΔT_{dif}, incorporating diffusion, is given by

$$\Delta T_{dif} = \Delta T_{ad} + K \Delta t \, [T(x+\Delta x,y) + T(x-\Delta x,y) - 2\,T(x,y)]/(\Delta x)^2$$
$$+ K \Delta t \, [T(x,y+\Delta y) + T(x,y-\Delta y) - 2T(x,y)]/(\Delta y)^2 \qquad (2)$$

where K, the thermal diffusivity, is found from k, the thermal conductivity, by $K = k/\rho_m c_p$.

The values of parameters used in the calculation of temperature for the first FELIX experiment are given in Table 2. Calculations with a finer mesh (eight by eight instead of six by six) and calculations with a coarse time step (1 ms instead of 0.2 ms) gave results which differed from those in the figures below by only a few percent.

Contour plots of temperature rise on one quadrant of the plate are given in Figs. 10-13 for times of 10, 20, 40, and 160 ms, respectively. The pattern of temperature is similar at all times, with highest temperatures occurring along the edges of the plate, intermediate temperatures in the interior and at

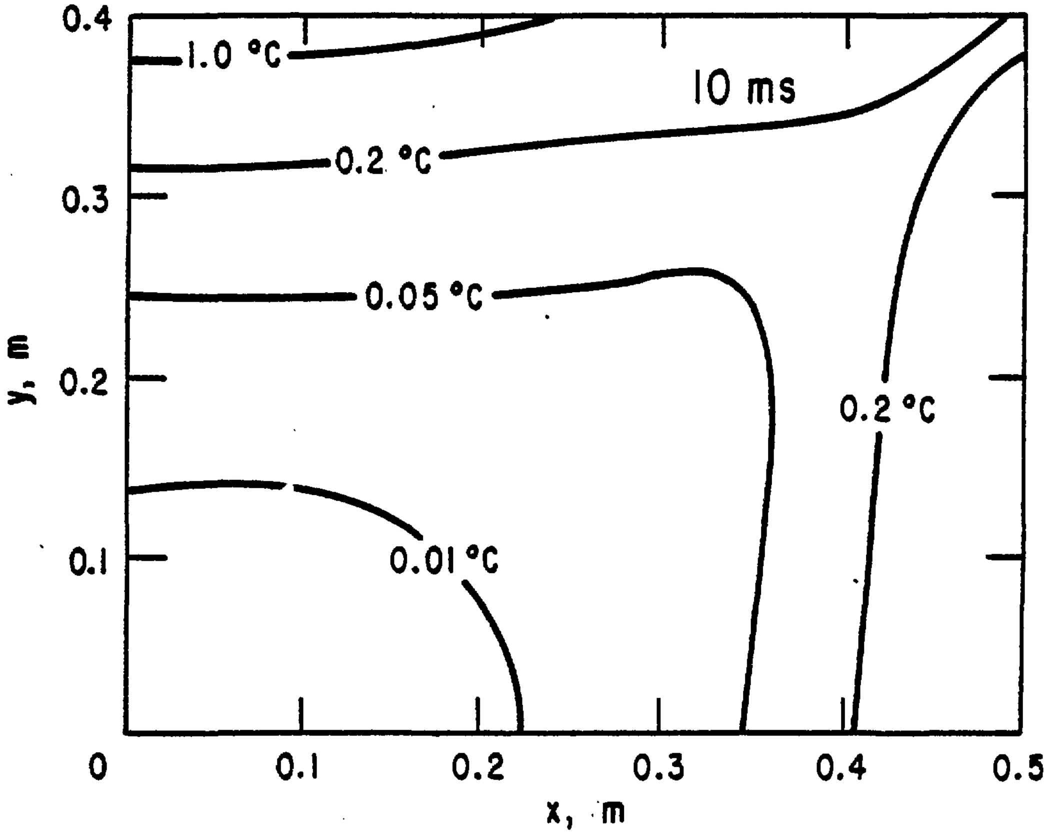

Fig. 10
Temperature Distribution over One Quadrant of Plate at 10 ms

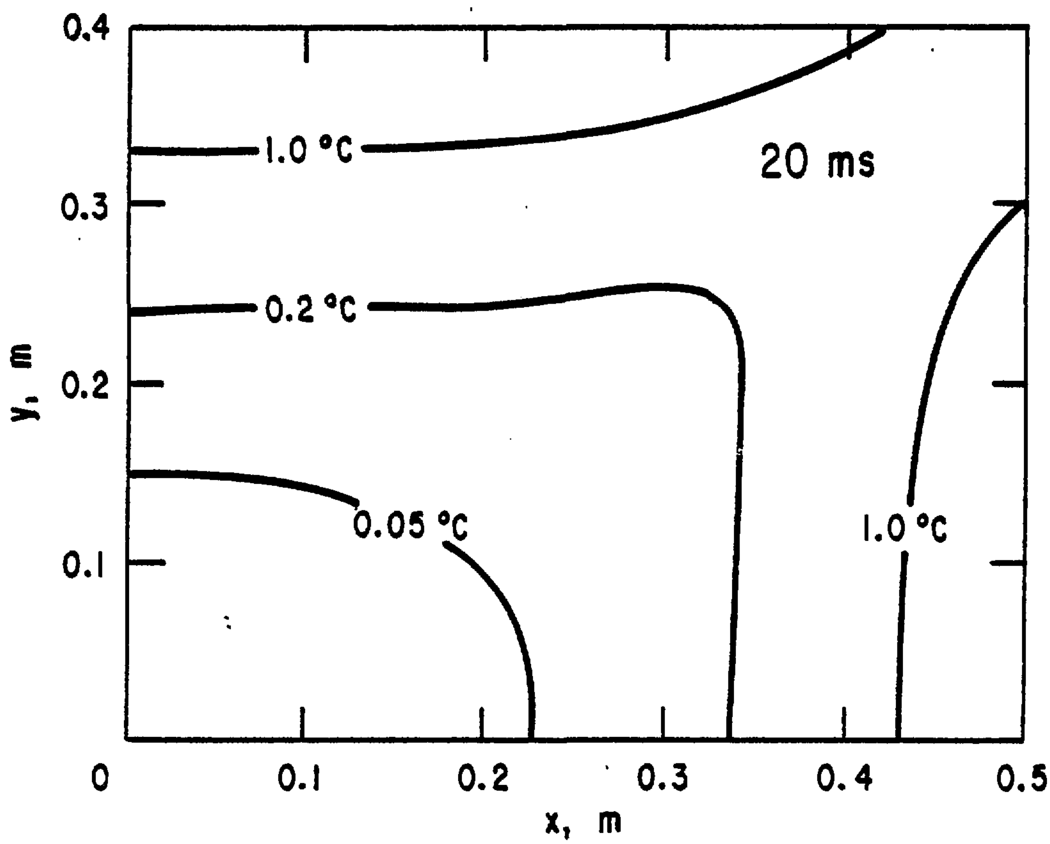

Fig. 11
Temperature Distribution Over One Quadrant of Plate at 20 ms

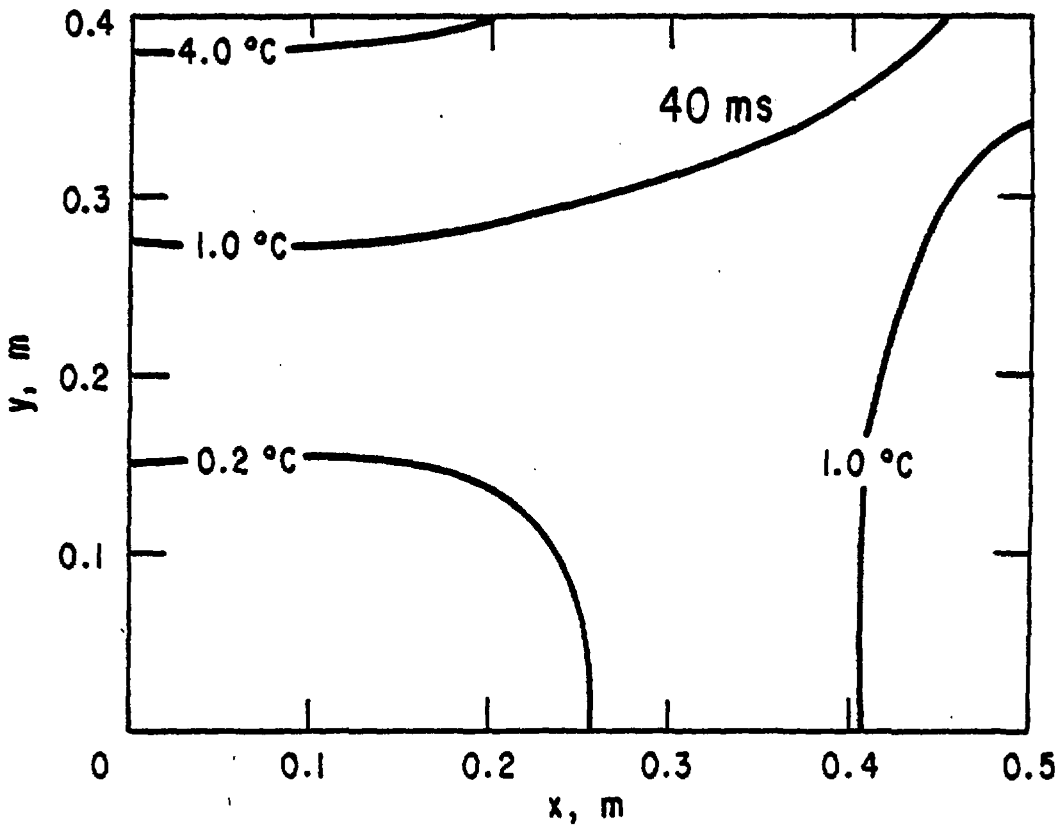

Fig. 12
Temperature Distribution Over One Quadrant of Plate at 40 ms

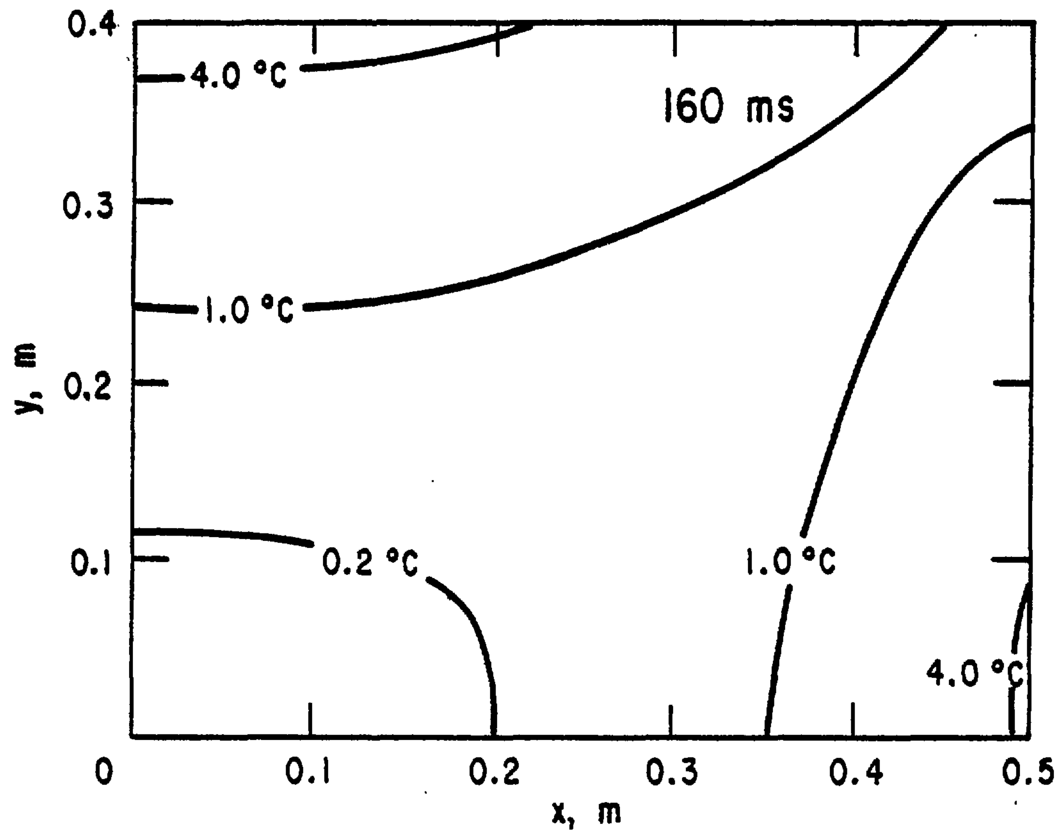

Fig. 13
Temperature Distribution Over One Quadrant of Plate at 160 ms

the corners, and lowest temperatures in the center. At all times, the highest temperature is in the center of the long edge ($x = 0$, $y = \pm 0.4$ m).

Table 2 Parameters Used in Calculating Temperature Rise In Aluminum Plate

Parameter	Symbol	Value
Dipole Field	B_d	0.5 T exp (-t/10 ms)
Electrical Resistivity	ρ_{el}	2.8 μΩ ·cm
Mass Density	ρ_m	2.7 g/cm^3
Specific Heat	c_p	0.9084 J/g°C
$\rho_{el}/c_p\rho_m$		1.1416×10^{-14} °C · m^4/A^2 · s
Time Step	Δt	0.2 ms
x Mesh Size	Δx	0.1 m
y Mesh Size	Δy	0.08 m
Thermal Conductivity	k	2.05 W/°C ·cm
Thermal Diffusivity	K	8.358×10^{-5} m^2/s
$K\ \Delta t/\Delta x^2$		1.7×10^{-6}
$K\ \Delta t/\Delta y^2$		2.6×10^{-6}

The greatest temperature rise was 5.1°C, which occurred at time 140 ms. Thermal diffusion within the plate turned out to be a small effect; after 0.2 s, ΔT_{ad} = 5.11°C, and ΔT_{dif} = 5.09°C at the center of the long edge; ΔT_{ad} = 0.384°C, ΔT_{diff} = 0.388°C at the corners; these differences (-0.3% and +1.0%, respectively) are negligible.

The range of temperature rises, up to 5°C, and the time scale, tens of ms, are convenient for measurement. However, at a repetition rate of one pulse per minute, the plate may have to be cooled actively, perhaps by air fans, between pulses to prevent an overall heating which could affect the calibration of other instrumentation, *e.g.* strain gauges.

4. INSTRUMENTATION

The instrumentation system for FELIX will be required to monitor various physical and electrical properties of the test articles. By far the most severe problem to be dealt with is the presence of an intense and fast changing magnetic field around the article. The most convenient and established methods for making these measurements involve converting the changes into electrical signals, *via* either resistance, voltage, or current. The nature of the changing magnetic field is such that for a total wire loop area of only one square centimeter there will be an error voltage of about 5 mV. Depending on the sensor being considered, this represents a signal-to-noise ratio of from 0.001 to 10. Solutions to these problems are being sought in three basic ways: First, by the use of the classic sensor with some form of signal protection or error compensation. Second, by the use of a special sensor developed to overcome the hostile environment so that its electrical signal can be made immune to that environment. Third, by the use of sensors that do not use electrical signals at or near the test area. In this last category are gross effects that can be optically scanned from a "safe" distance.

4.1 Strain Measurements

While the sensor studies for FELIX have not been limited to strain devices, the results so far will serve to illustrate the above points. Only conceptual ideas will be presented, since not all sensitivity and output signal levels are yet known.

4.1.1 Classic Strain Devices. The classic resistive strain gauge consists of a zig-zag pattern of thin wire bonded to the test surface and allowed to deform with it. The change in resistance is sensed in a bridge circuit and the correspondence with actual strain easily found. A common technique used to compensate for temperature effects may be usable in FELIX. It involves the use of a "dummy" gauge kept at the same temperature as the primary gauge, but not under strain. The "dummy" gauge is then made part of the bridge circuit in such a way that the temperature effects are equal but opposite and thus cancel. Since the FELIX tests will be at room temperature and will involve only small temperature changes, it might be possible to employ a "dummy" gauge subject to the same magnetic field changes and then cancel the errors in the bridge circuit.

Another approach under consideration is to sandwich two gauges of the same pattern and make the connections at one end so as to cancel the effective loop area while at the same time making the loop formed by the lead wires as small as possible. This approach, however, does not eliminate the error signal picked up by the lead wires themselves.

A Japanese-made strain gauge employing a unique wire pattern advertised to be "noninductive" may be available; if its gauge pattern is found to be somewhat immune to a magnetic environment, it may offer a partial solution. Semiconductor strain gauges use the same basic principle, but deform a small semiconductor crystal and obtain much larger gauge factors than the wire-pattern units. They have the same drawback with the lead wires and connecting loops. Piezoelectric-based strain devices may offer the same advantage with respect to signal level, but would have the same lead-wire problems.

4.1.2 Alternating-Current (ac) Excitation Devices. Strain-sensitive devices which use ac signals have been developed based on capacitive and inductive effects. Since typical excitation frequencies are in the megahertz region, it should be a straightforward task to filter out the transient magnetic error signals if they are sensitive enough. The coaxial capacitive strain gauge was developed by Boeing Corporation, apparently for very high-temperature applications. As the central part of the coaxial structure moves with respect to the outer part, the two capacitor values are changed in opposite ways. The high-frequency ac signals are then used to produce motion-dependent output signals. This structure is rather fragile; and since its constituent parts are metallic, the eddy currents may produce forces to upset its operation.

Strain gauges have been produced based on the inductive proximity detector, and, since they also use ac excitation, they should have the same signal-processing advantage as the capacitive devices. Since such devices make use of a magnetic field effect, they may be overloaded or burned out by the environmental field.

4.1.3 Nonelectric Devices. It has been stated that fiber-optic transducer concepts can be employed to monitor virtually any kind of input, and if development costs are not too high, a fiber-optic device would be the solution to many sensor problems. In a fiber-optic transducer, a glass fiber brings an optical signal to the sensor area, modifies the signal's amplitude, phase or other property, returns the result over the same or different fiber, and then extracts the information. A sensor which could produce or modify a property of a local light source could use a fiber-optic link to the same advantage. Optical signals moving over glass fibers would be immune to the FELIX magnetic fields, as well as to any electrical noise present from the main power supply systems. Since the attenuation of optical signals with distance is very small, this method would allow placement of the remaining signal and data-processing equipment at a safe, noise-free distance from the test area. Although most of these devices are still in the development stage, the following examples will illustrate the principles.

In the first example, a pair of "diffraction" patterns develops at the interface between the input and output fibers. The pitch of the grating can be made as small as 10 µm, so that a relative motion of 5 µm will produce a 0 to 100% change in transmission. The fibers would have to be mounted so as to produce this relative motion of the interface with strain.

The second example employs the "microbend" method. In this case, the fiber is passed between two meshed corrugated surfaces so that the bending is varied according to the relative position of the two sides. As the bending is increased, more light escapes from the core and is radiated away, decreasing the light intensity of the core beam. Signal processing would be the same as that above. There may be other methods based on changing a light-processing property such as reflection, refraction, or transmission of a second material, through which light passes, in proportion to an applied stress or deformation; a complete strain gauge and signal-carrying system would result.

4.1.4 Gross Effect Systems. A method now in commercial use allows the visual observation of strain patterns and amplitudes by reflecting and observing polarized light. The test surface is first coated with a special "photoelastic" material. Polarized light is reflected from the surface and observed through a polarizing filter and the patterns observed and photographed. It would be a real advantage to use a video recording system to store the time-varying strain pattern, but, since the patterns are expected to develop within a single TV frame time, high-speed photography would have to be used.

Another method in commercial use is "Brittle-Coat," a thin layer lacquer coating which is seen microscopically to be a field of small bubbles. After the coating hardens, the object is strained and the bubbles break along lines of equal strain in such a way that both qualitative patterns and quantitative measurements can result. Two disadvantages of the method are that only the maximum strains are recorded and that the time-dependent information is lost. Assuming that only one test cycle is possible with this method, it also has a definite operational disadvantage, since all FELIX support and diagnostic systems would have to operate properly without warm-up or pretesting.

4.2 Other Instrumentation

FELIX also requires instrumentation other than strain gauges; in particular, temperature-measurement devices and problems associated with them are being studied. Thermographic imaging systems may be the only viable method of obtaining the time-related information because of the short time (0 - 50 ms) during the thermal gradients build up. Vendor-conducted demonstrations of this equipment are planned.

Other types of required sensors are also being sought and evaluated, with particular emphasis on nonelectrical (optical) devices. FELIX should also profit from the experience and plans of TFTR and other fusion research activities concerning sensors for pulsed-field applications. The experience of many ANL research divisions will also be utilized regarding sensing equipment and methods.

5. PLAN FOR COMPUTER CODE EVALUATION AND DEVELOPMENT

The selection of appropriate computer codes for the program will be guided by an understanding of the practical limitations on codes. First, the spatial resolution of codes will always be limited; to improve that resolution by a factor of two requires increasing the number of elements by a factor of $2^3 = 8$ and the size of the matrix in the code by a factor of $8^2 = 64$. Existing codes treat between a few hundred and a few thousand elements; this number will increase somewhat, but not by orders of magnitude, over the next few years.

Thus it follows that analysis by code will always be limited to one level of complexity; i.e., it will be possible to model a single detailed structure, or several simple structures, but not several detailed structures in a single analysis. An analysis of a blanket and shield system can treat, as a whole, the modules which comprise the system, but not the details of those modules. An analysis of a module can include the effect of piping, laminations, and module-to-module electrical connections; but the detailed analysis of a module-to-module connection, for example, would require separate treatment.

Based on these practical limitations, one concludes that the analysis will probably require a number of specialized codes and at least one general three-dimensional code. All of these codes must be verified and calibrated by experimental modeling.

A plan for computer code development will consist of the four parts described in Section 2.4. Figure 14 shows a schedule of how those four phases are correlated with facility construction, the experimental program, and distribution of experimental results.

The code-evaluation process begins with the identification of codes which are being used or which are under development. The first steps in the process

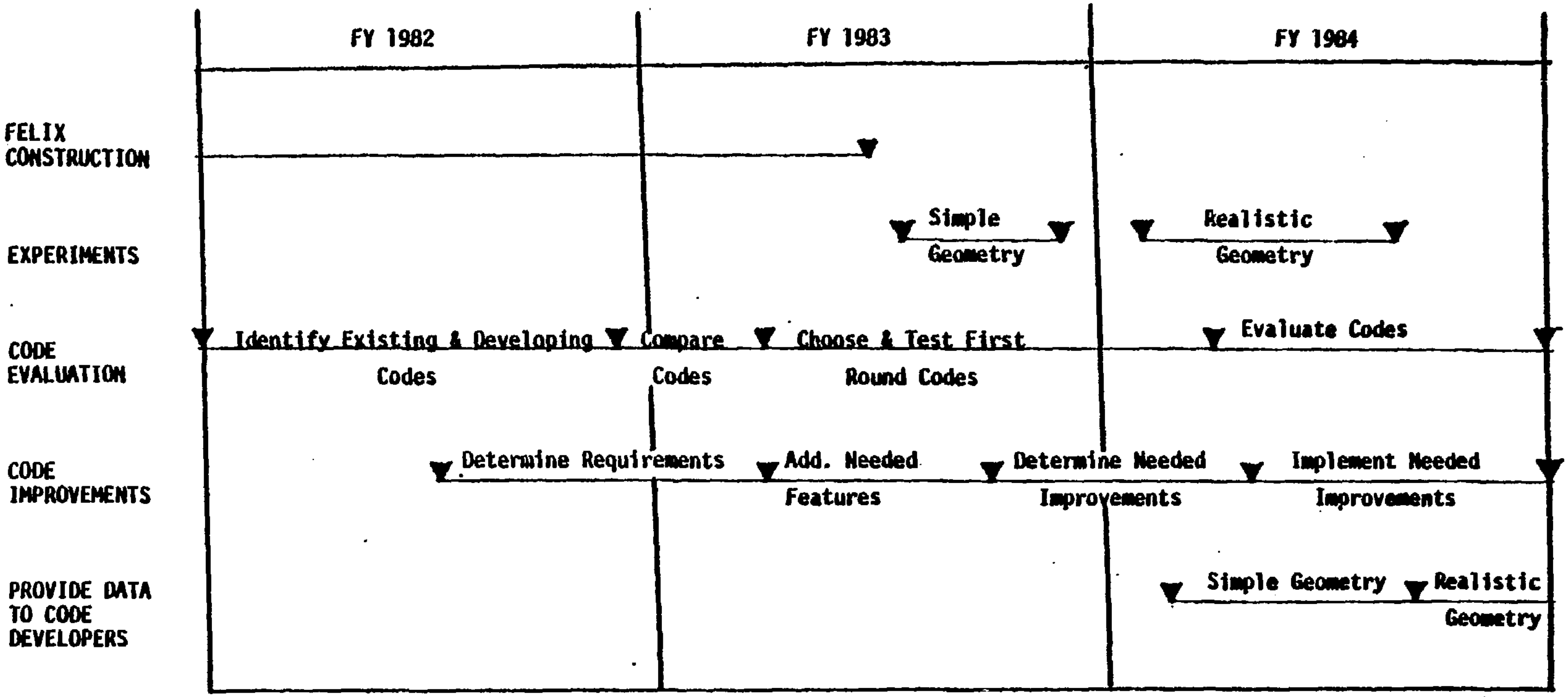

Fig. 14

COMPUTER CODE EVALUATION SCHEDULE

TPE III, PHASE I FY 1982-1984

were taken by informing the participants of COMPUMAG-Chicago about the TPE-III facility and program and by soliciting information about their codes. On the basis of written information and discussions with code developers and users, a small number of codes will be chosen, installed at ANL, and tested against the early experiments with simple geometries.

Meanwhile, the requirements for suitable codes will be determined, and the needed features will be added to the codes under consideration. After the codes are tested against the experiments, needed improvements will be noted and be developed either at ANL or by the codes' originators. The improved codes will then be tested against later experiments with geometries more closely matched to FW/B/S needs. The sensitive issue of interaction with code developers and users is discussed in Section 6.2.

6. OTHER CONSIDERATIONS

6.1 Personnel

L. Turner and W. Praeg are principal investigators.

6.1.1 Experiment Planning. Dr. L. Turner will be responsible for planning the experimental program and assuring that the results have technical significance to the magnetic fusion energy program.

Fraction of time spent on Phase I: 50%

6.1.2 Design, Assembly, and Operation of Test Stand. W. Praeg will be responsible for overseeing the design, construction, and checkout of the test facility.

Fraction of time spent on Phase I: 50%

6.1.3 Facility Operator. D. McGhee will be responsible for the day-to-day operations and experimental setups.

Fraction of time spent on Phase I: Initially 10%, increasing to 50%

6.1.4 <u>Other Key Individuals:</u>

- M. Knott will coordinate the choice, acquisition, installation, and operation of the instrumentation, control, and data-acquisition systems.
- R. Lari will participate in the electromagnetic design and computation of the facility and test pieces. He will also coordinate the identification, evaluation, testing and development of computer codes for electromagnetic analysis.
- R. Wehrle will carry out the mechanical design of test pieces and their support systems.
- Dr. K. Evans will participate in the design and planning of experiments, ensuring that they are relevant to the process of plasma disruption. He will also participate in the evaluation of experiments involving field penetration.

Biographical sketches appear in the ANL Expression of Interest in TPE-III.

6.2 <u>Involvement of Other Participants.</u>

Outside groups may be involved in three areas: guidance for the overall FELIX program, participation in the experimental program, and participation in the computational development and testing.

6.2.1 <u>Involvement in Program Guidance.</u> The following activities have provided input to the direction which TPE-III has taken.

- A FW/B/S eddy-current workshop held at ANL September 9, 1980.
- Close coordination with J. Murray of the FED Design Center to enable FELIX to keep up with the latest FW/B/S needs of FED.

- Close coordination with the U.S. INTOR team to enable FELIX to keep up with the needs of INTOR.
- Close cooperation with the mirror program and bumpy torus program activities.
- A community-wide review of the detailed design of the test facility held at ANL June 23, 1981. The review committee recommended that FELIX proceed as planned and suggested the priority list for improvements given in Section 2.3.
- Guidance from the FW/B/S Advisory Committee relative to the testing program and test stand.

6.2.2 Involvement in the Experimental Program. Professor F. Moon of Cornell University is serving as consultant to the experimental program. His principal contributions are in the areas of scaling laws and experimental techniques.

Suggestions for experiments to be performed at the facility are being solicited both informally and through journal papers describing the program. Groups who desire to carry out experiments at the facility will be welcomed. If this becomes more than an occasional occurrence, a community-wide panel will be established to evaluate proposals for experiments using the facility.

6.2.3 Involvement in Computational Development and Testing. Eddy-current computer codes are being sought throughout the electromagnetic-computation community both informally and formally (i.e., the program was called to the attention of the participants at the COMPUMAG-Chicago Conference on the Computation of Electromagnetic Fields in September 1981). Cooperation with the code developers and users could take three forms, listed here in order of increasing interaction:

- The results of the FELIX experiments will be available to any developer or user for use in verifying their codes.
- Upcoming experiments can be described to the developers and users who can use their codes to predict the results and even to suggest modifications of the experiments on the basis of their computations.
- The codes could be installed at ANL and used in the above ways. In this case, comparisons can be made among the codes.

6.3 Dissemination of Results.

Results will be published and otherwise distributed to the fusion community through the Management and Technical Coordination Center (MTCC). All results will be evaluated primarily for their impact on FW/B/S system designs in general, and on the FED design in particular. It is planned that the results will lead to discussions within the commmunity and to feedback for further experiments.

APPENDIX A

EXISTING EDDY CURRENT COMPUTER PROGRAMS

A.1 Programs Reported at COMPUMAG-Grenoble, September 1978

1. BUEDDY: C. S. Biddlecomb, Rutherford-Appleton Laboratory, England. This code used the Integral Equation Method to calculate eddy currents. The resulting equations are solved by an eigenvalue method. The 1D field applied to infinitely long 2D prisms of steel or conductor has been solved.

2. EDDYNET: L. R. Turner, R. J. Lari, Argonne National Laboratory. This code uses the Integral Equation Approach where a network of conducting line elements allows one to replace Maxwell's equation by Kirchhoff's circuit rules. It solves 1D fields applied to infinitely long (or thin) 2D prisms.

3. ECSTASY: P. Janecek, ASEA Co., Vasteros, Sweden. The program name is an acronym for Eddy Current and Skin Effect Two Dimensional Analysis SYstem. It uses a finite-element technique to calculate the vector potential at the vertices of a triangular mesh. The vector potential can be approximated by polynominals of degree 1 to 5. It solves 2D fields and 1D currents. A 200-triangle problem of degree 3 requires 64 K words of core.

4. FREDDY: J. H. McWhirter, Westinghouse R & D, Pittsburgh, R. C. MacCamy, Carnegie-Mellon University, Pittsburgh. This code uses a Fredholm integral equation method to solve 2D fields with 1D currents for constant permeable materials.

5. NO NAME: H. T. Yeh, Oak Ridge National Laboratory, Oak Ridge, Tennessee. This unnamed program uses the integral equation formulation to solve 1D fields and 2D currents in nonmagnetic materials.

A.2 Other Programs Reported in the Literature 1978 - 1980

1. NO NAME: Y. Suzuki, H. Ninomiya, Japan Atomic Energy Research Institute, Tokai, Japan, Y. Tanabe, Y. Sawada, I. Takano, Tokyo Shibaura Electric Co. Ltd, Yokohama, Japan. This unnamed program was reported at the IEEE 1978 Winter Meeting of the Nuclear Power Engineering Society. A finite element method was applied to the 3D fields of an axisymmetric test model of a tokamak. Up to 1945 pentahedron elements were used in 256 K words of core and 4900 cpu seconds, to calculate the eddy currents in the vacuum vessel. Good agreement was reported between the measured and calculated fields.

2. NO NAME: V. R. Christensen, D. Weissenburger, Plasma Physics Lab, Princeton University. A network mesh method has been reported in PPPL-1516 (April 1979) and PPPL-1517 for calculating eddy currents on a finite plane and a toroidal surface. The basic principle in this method lies in representing a conducting surface as a network comprised of a number of branches. Each branch has a resistance and a self-inductance, as well as mutuals to all other branches. The resulting branch resistance and inductance matrices are transformed into mesh matrices and a set of simultaneous differential equations is solved.

3. EDDYNET: L. R. Turner, R. J. Lari, Argonne National Laboratory. The set of programs in EDDYNET was rewritten using loop currents and a quadrilateral mesh and extended to 3D problems using a hexahedral

mesh. The EDDYNET2D code solves 1D fields and 2D currents in plane and curved surfaces. The EDDYNET3D code solves 3D fields and 3D currents for up to a 5 x 5 x 5 mesh in less than five minutes of cpu time, using 356 kbytes of core. This was reported at the April 1980 INTERMAG Conference.

4. TRIDIF: J. R. Freeman, Sandia Laboratory, Albuquerque, New Mexico. Solves the 2 D diffusion equation using a finite difference method on a triangular mesh. A fast, direct matrix-inversion method is used at each time step. Two-dimensional fields and 1D currents are solved in Cartesian or cylindrical coordinate geometry. Reported at the IEEE meeting in May 1980.

5. ONED, TWOD: Kuan-Ya Yuan, Frances C. Moon, and John F. Abel, Department of Structural Engineering and Department of Theoretical and Applied Mechanics, Cornell University, Ithaca, NY 14853. Report No. 80-5, Feb. 1, 1980, "Numerical Solutions for Coupled Magnetomechanics." These two programs calculate the local and nonlocal solutions of stream function, eddy current, temperature, and pressure and image solutions for ONED. Uniform magnetic fields or fields due to any number of magnetic dipoles can be applied.

A.3 Papers on Magnetodynamic Field Calculations to Appear in Proceedings of COMPUMAG-Chicago, September 1981

1. A Comparison of Integral and Differential Equation Solutions for Field Problems, J. Simkin, Rutherford and Appleton Laboratories, UK.

2. NMLMAP-A Two Dimensional Finite Element Program for the Transient or Static, Linear or Nonlinear Magnetic Field Problems, R. D. Pillsbury, Jr., Massachusetts Institute of Technology, USA.

3. The PE2D Package for Transient Eddy Current Analysis, A.G.A.M. Armstrong and C. S. Biddlecombe, Rutherford and Appleton Laboratories, UK.

4. Applications and Further Developments of the Eddy Current Program EDDYNET, L. R. Turner and R. J. Lari, Argonne National Laboratory, USA.

5. A Network Mesh Method to Calculate Eddy Currents on Conducting Surfaces, D. W. Weissenburger and U. R. Christensen, Princeton University, USA.

6. Eddy Current Calculations in 3 D Using the Finite Element Method, U. Jeske, Kernforschungszentrum, Karlsruhe, FRG.

7. A Fixed Fem-Biem Method to Solve 3-D Eddy Current Problems, A. Bossavit and J. C. Verite, Electricite de France, FRANCE.

8. Three-Dimensional Vector Potential Analysis for Machine Field Problems, M. V. K. Chari, A. Konrad, M. A. Palmo, and J. D'Angelo, General Electric Company, USA.

9. Eddy Current Calculations in Thin Conducting Plates Using a Finite Element-Stream Function Code, K-Y. Yuan, University of Wisconsin, J. F. Abel, and F. C. Moon, Cornell University, USA.

10. New Finite Element Techniques for Skin Effect Problems, A. Konrad, M.V.K. Chari, General Electric Company, USA and A. J. Csendes, McGill University, CANADA.

11. Computation of Three-Dimensional Eddy Currents in Thin Conductors, J. H. McWhirter, Westinghouse Electric Corporation, USA.

12. A Hybrid Finite Element-Boundary Integral Formulation of the Eddy Current Problems, S. J. Salon, Rensselaer Polytechnic Institute and J. M. Schneider, American Electric Power Company, USA.

13. A Boundary Integral Method for Eddy Current Flow Around Cracks in Thin Plates, M. A. Morjaria, S. Mukherjee and F. C. Moon, Cornell University, USA.

14. Methods of Analysis of Integral Equations Describing Skin-Effect in Conductors, W. Lipinski and P. Krason, Technical Univesity of Szczecin, POLAND.

15. The Solution of 3-Dimensional Induction Heating Problems Using an Integral Rotation Method, W. R. Hodgkins and J. F. Waddington, Electricity Council Research Centre, UK.

16. Finite Element Solution of 3-D Eddy Current Flow in Magnetically Linear Conductors at Power Frequencies, D. Rodger and J. F. Eastham, University of Bath, UK.

17. Solution of 3-Dimensional Eddy Current Problems: The T-Ω Method, T. W. Preston and A.B.J. Reece, G.E.C. Power Engineering Limited, UK.

18. Methods for Eddy Current Computation in Three Dimensions, C. S. Biddlecombe, E. A. Heighway, J. Simkin and C. W. Trowbridge, Rutherford-Appleton Laboratories, UK.

19. Finite Element Calculation of Eddy Currents and Skin Effects, J. R. Brauer, A. O. Smith Corporation, USA.

20. Transient Magnetic Field Calculations with TRIDIF, M. L. Hodgdon and J. R. Freeman, Sandia National Laboratories, USA.

21. A New Iterative Method for Eddy Current Problems, J. Poltz, E. Kuffel and R. Sikora, University of Manitoba, CANADA.

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25. Magnetic Vector Potential and Electric Scalar Potential in Three-Dimensional Eddy Current Problem, T. Morisue, Nippon Steel Corporation, JAPAN.

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APPENDIX B

SUGGESTED FORMAT FOR TEST PLANS AND TEST REPORTS

The following pages show the formats that have been suggested for test plans and test reports of individual experiments.

Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439

FUSION POWER PROGRAM

FIRST WALL BLANKET AND SHIELD
TEST PROGRAM ELEMENT-III
TEST PLAN

Document No. ________________

(Title of Test)

Date Issued: ________________

Prepared by: ____________________________________ Date ________________
Name Principal Investigator

Approved by: ____________________________________ Date ________________
Name Deputy Program Manager

Approved by: ____________________________________ Date ________________
Name Program Manager

1.0 INTRODUCTION

1.1 Scope

1.1.1 Scope of Work

A brief introduction outlining the overall purpose and the magnitude of the particular series of tests.

1.1.2 Scope of this Document

Briefly describes the purpose of the testing and the test article, and outlines testing sequences and test conditions.

1.2 Purpose

Gives a description of the background and the purpose of the test with applicable documents and appropriate reference(s) where applicable.

2.0 TEST OBJECTIVES

The specific test objectives of this series of tests are delineated.

3.0 TEST PIECE DESCRIPTION

3.1 Drawings

3.2 Specifications and Standards

3.3 Quality Assurance Guidelines

4.0 INSTRUMENTATION

Describes and specifies the parameters to be controlled or measured, the frequency of the measurements, and instruments to be used, the accuracy and the locations of the instruments. Typical measurements are temperatures, temperature distributions, strain, eddy currents, etc.

5.0 TEST PROCEDURE

Describes test conditions, number of tests, test sequences, calibration, startup and shutdown procedures, control parameters, test limits and procedures covering test termination or emergency shutdown.

6.0 TEST REQUIREMENTS

6.1 Pretest Data

Defines the test specimen characteristics required, such as physical dimensions, radiographs, weight, chemical or metallurgical analysis, etc.

6.2 Test Data

Describes the test data to be recorded, which will include but not be limited to the following:

- Test program title
- Date and time of entries
- Current and voltage measurements
- Magnetic field measurements
- Strain

6.3 Post-Test Data

Defines the test specimen characterizations required, such as physical dimensions, strain, x-rays, sectioning, and metallography.

7.0 TEST REPORTS

Specification of the post-test documentation (data summaries, test logs, analysis, etc.) in the form of a formal test report.

8.0 SCHEDULE

Test program milestones will be defined and a schedule for key activities provided.

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Argonne, Illinois 60439

FUSION POWER PROGRAM

FIRST WALL BLANKET AND SHIELD
TEST PROGRAM ELEMENT-III
TEST REPORT

Document No. ________________

(Title of Test Report)

Date Issued: ________________

Prepared by: ________________________________ Date ________________
Name Principal Investigator

Approved by: ________________________________ Date ________________
Name Deputy Program Manager

Approved by: ________________________________ Date ________________
Name Program Manager

1.0 **SUMMARY**

Short summary of tests and major conclusions.

2.0 **INTRODUCTION**

One paragraph introduction to the test report.

3.0 **APPLICABLE DOCUMENTS**

Lists applicable test plan, drawings, specifications, specific QA information, etc.

4.0 **TEST CONFIGURATION**

Describes the configurations. This can be very brief, by reference to the test plan. Any changes to the configuration described in the test plan should be given in detail.

5.0 **TEST PROCEDURES**

Describes the test procedures. This can be very brief, by reference to the test plan. Any changes to the procedures delineated in the test plan should be given in detail.

6.0 **RESULTS & DISCUSSION**

This section gives test results. It will probably include tables, graphs, etc. Results will be discussed and significant findings noted.

7.0 **CONCLUSIONS & RECOMMENDATIONS**

Detailed conclusions will be drawn from the tests and described in detail. Recommendations for additional tests, test variations, and revised test strategies will be given.