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PROGRAM PLAN FOR THE DOE OFFICE OF FUSION ENERGY FIRST WALL/BLANKET/SHIELD ENGINEERING TECHNOLOGY PROGRAM

Volume II - Detailed Technical Plan

Revision 2

August 1982

VOLUME II

This document is Part II of the plan for conducting selected aspects of the engineering testing required for magnetic fusion reactor First-Wall/Blanket/Shield (FWBS) components and systems. The purpose of this program is to furnish an established data base that contributes to a functional, reliable, maintainable, economically attractive, and environmentally acceptable commercial fusion reactor first wall, blanket, and shield system.

This program plan, which consists of two parts, updates the initial plan issued in November 1980 by the Department of Energy/Office of Fusion Energy (unnumbered report). Part I is a summary of activities, responsibilities, and program management including reporting and interfaces with other programs. Part II is a compilation in condensed form of the Detailed Technical Plans (DTP's) for Phase I (1982-1984) developed by the participants during Phase 0 of the program (July-December 1981).

The four sections which comprise Part II describe in detail the technical basis for each of the four Program Elements (PE's) of the FWBS Engineering Technology Program (ETP). Each PE is planned to be executed in a number of phases.

The purpose of the DTP's is to delineate detailed near-term research, development, and testing required to establish a FWBS engineering data base. Optimum testing strategies and construction of test facilities where needed are identified. The DTP's are based on guidelines given by Argonne National Laboratory which included the basic programmatic goals and the requirements for the types of tests and test conditions.

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Volume II

1.0 Program Element I

Major responsibility for Program Element I (PE-I) of the FWBS ETP aimed at the engineering development of magnetic confinement (MCF) fusion reactor first wall systems has been assigned to the Westinghouse Electric Corporation.

A first wall is defined as any mechanical configuration and arrangement of materials and structures that interact with the plasma, either confined or diverted. Such structures include:

- Heat Transport Panels
- Armor Configurations
- Limiters and Divertor Collectors.

PE-I focuses on the engineering development of first wall designs which typically consist of a first wall material (coated or uncoated) and a heat sink with either active of passive cooling. The interaction of the fusion plasma with the integrated first wall-heat sink presents unique and complex engineering issues and design uncertainties that must be resolved by experimental studies and engineering testing.

The objective of PE-I is to provide the first-wall engineering development that comprises test facility implementation, engineering testing, development of a generic thermal-hydraulic and thermomechanical engineering data base, analytical model development, data, correlations, and computer code validation. Use of an existing 50 kW, facused e-beam test facility (ESURF) and the implementation of a larger test facility (ASURF) based on the use of low voltage distributed e-beam guns is recommended. Both facilities have pressurized water coolant loops for heat rejection. A unique feature of ESURF is the capability of rastering the e-beam in two dimensions which permits significant flexibility in heat flux-target arera parameter variations. ASURF has a similar, but more limited, capability initially, with upgrade to 1 MW proposed. Subsequent upgrades to include a helium loop and liquid lithium loop are also proposed.

It is recommended that ESURF be used for separate effects, preliminary screening tests, using relatively simple, small scale test pieces. ASURF will be applied principally to multiple effects, intermediate to high cycle thermal fatigue tests on the more promising first wall concepts. The 1 MW upgrade is intended for testing large (in some cases full scale) test pieces where the size of the test piece is critical to the engineering issue(s) addressed.

The DTP addresses thirty-three major test/development elements and provides the related estimated costs and times required. The principal product of the DTP is the recommended test and development program strategies for PE-I. These consist of continous testing of first wall concepts in ESURF during calendar years 1982 and 1983 and special development tests in 1984. Operations in ASURF will begin in the Fall of 1982 and continue throughout FY 1985. The DTP is a working document which covers all types of first wall designs, subject to revisions as designs change and mature, and as test data become available. Implementation of the DTP should provide the following:

Two highly flexible first wall engineering test facilities that meet all of the test requirements for PE-I.

- Comprehensive testing of all types of first wall concepts, addressing the high priority thermal-hydraulic and thermomechanical issues.

- An evaluated engineering data base for generic first wall designs.

- Benchmarks for the validation of analytical tools for generic first wall designs.

The synergism between PE-I of the FWBS program and parallel DOE-OFE programs is illustrated in Figure 1.1. A considerable amount of interaction and feedback is anticipated between PE-I and the design and development of MCF devices as depicted in the figure. In connection with this relationship, a set of time windows for engineering data inputs to the various MCF devices was assumed, as shown in Table 1.1.

Table 1.1. Assumed Windows for Engineering Data Inputs to Various Magnetically Confined Fusion Devices

Devices(s)/Test Modules	Time-Frame Window
TFTR/TFTR upgrades, Doublet III, ISX-C, MFTF-B, EBT-P	1982-1985
FED, INTOR, TMNS	1984-1988
EBT-Q and first-wall test modules for FED, MFTF-B	1988-1991
DEMO	1992-1995

Table 1.2. Summary of Test Condition Goals for TPE-I First-Wall Thermal-Hydraulic and Thermomechanical Testing

Test Parameter	Condition A Heat Transport Panels	Condition B Limiter/Divertor Collector, Neutral Beam Strikes	Condition C Plasma Disruption Simulation
Surface Heat Flux, MW/m^2	$0.2 \rightarrow 1.0$	$3 \rightarrow 10$	$50 \rightarrow 300$
Surface Area of Test Piece, cm^2	$10^3 \rightarrow 10^4$	$10^2 \rightarrow 10^3$	$1 \rightarrow \leq 10$
Number of Repetitive Pulses[a]	$\geq 10^4$	$\geq 10^4$	Random[b]
Duration of Pulse, s	≥ 50	≥ 50	≤ 0.1
Test Environment	Vacuum[c]	Vacuum[c]	Vacuum[c]
Coolant (H_2O) Pressure, psi	$100 \rightarrow 2200$	$100 \rightarrow 2200$	$100 \rightarrow 2200$
Coolant Peak Temperature, °C	up to 300	up to 300	up to 300

[a]See Figure 1-4 for typical heat flux delivery characteristics
[b]Perhaps several per day.
[c]Base pressure < 10^{-4} torr.

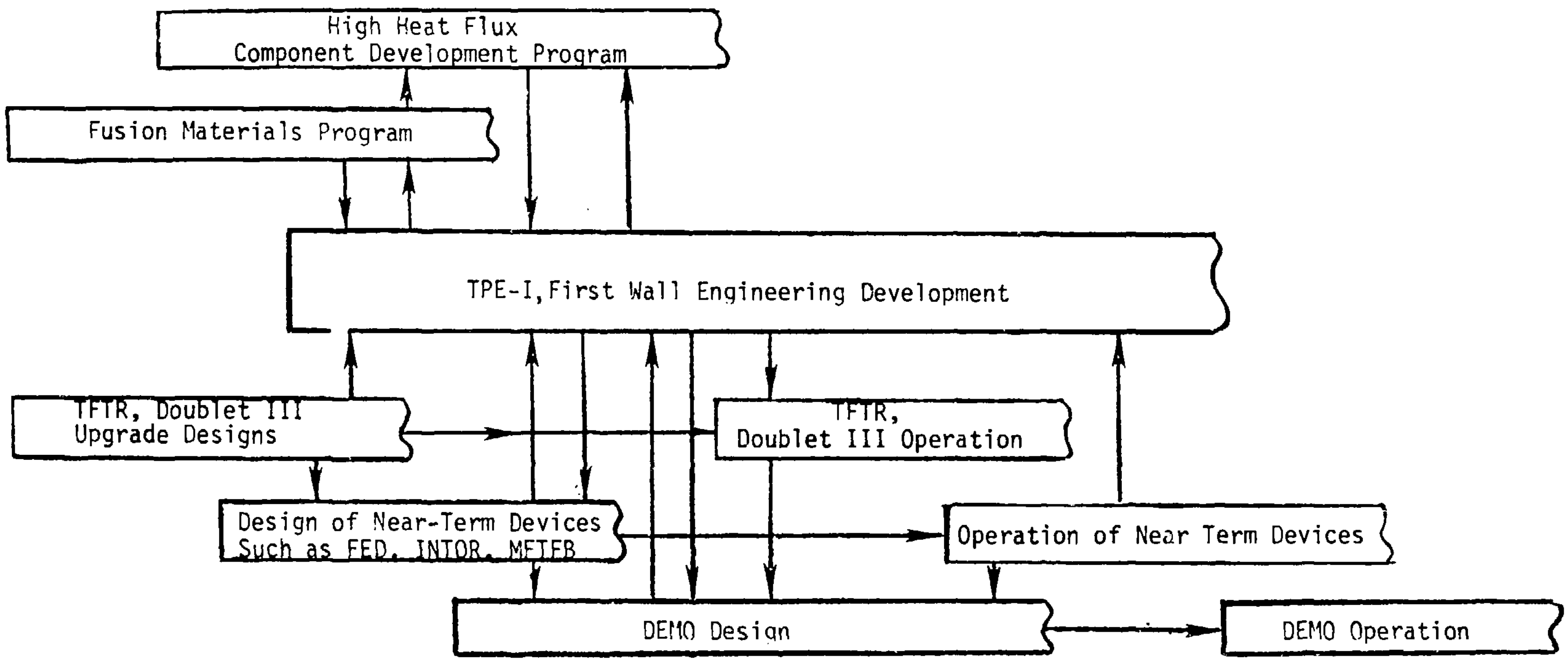

Fig. 1.1. Perspective of TPE-I of the first-wall/blanket/shield engineering test program.

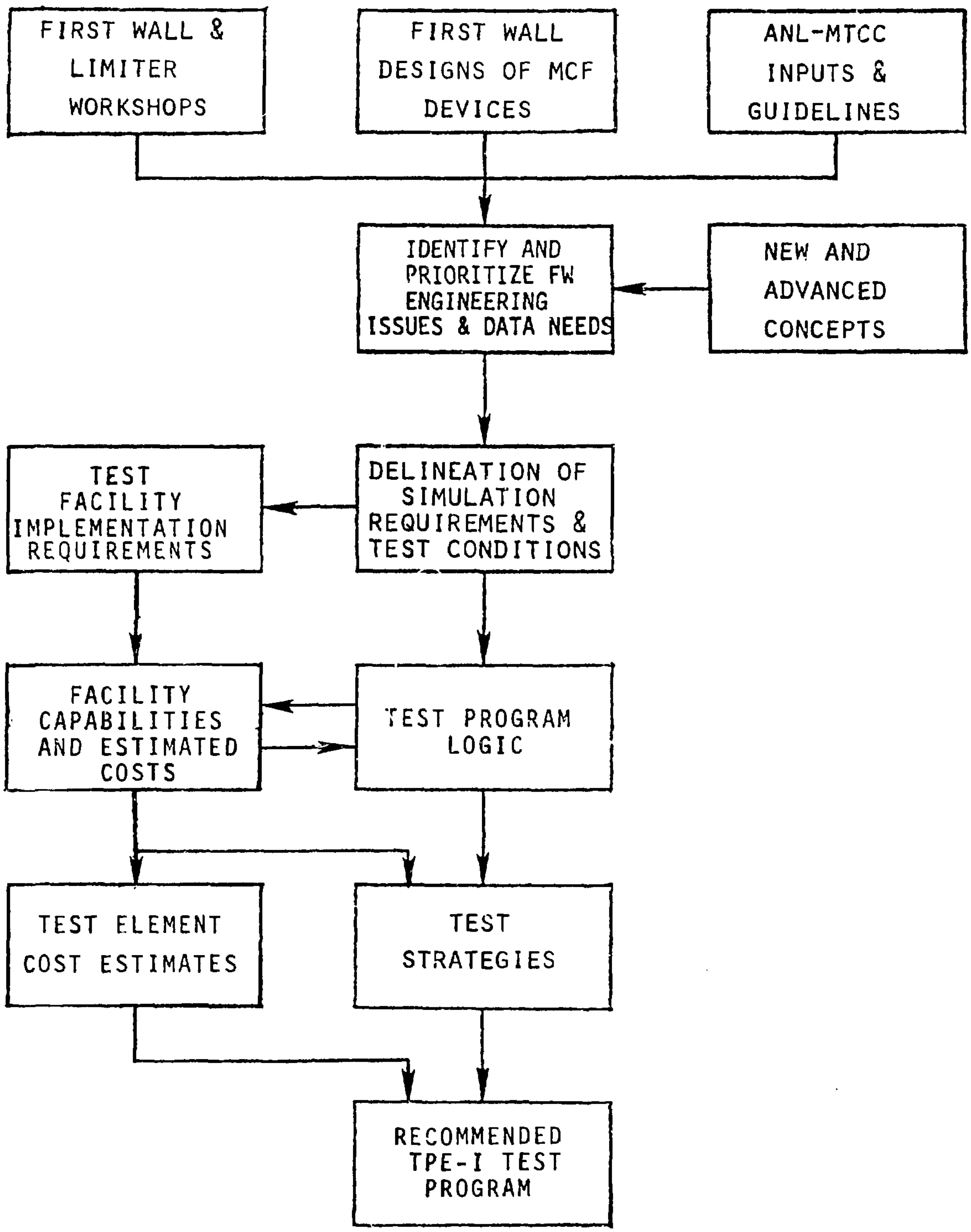

Fig. 1.2. Logic for the development of the detailed technical plan.

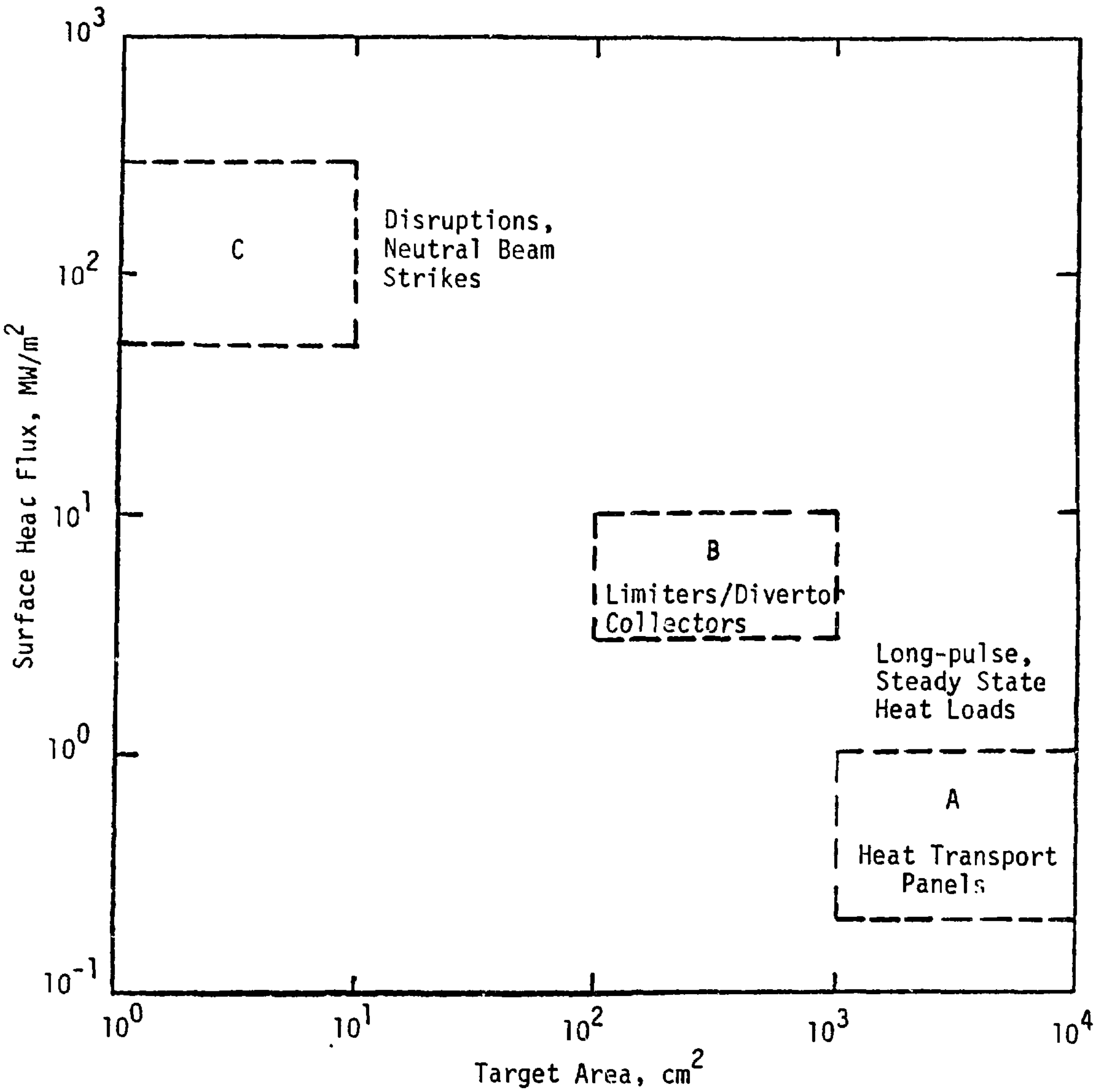

Fig. 1.3. Goals for first-wall test conditions (A, B, C)

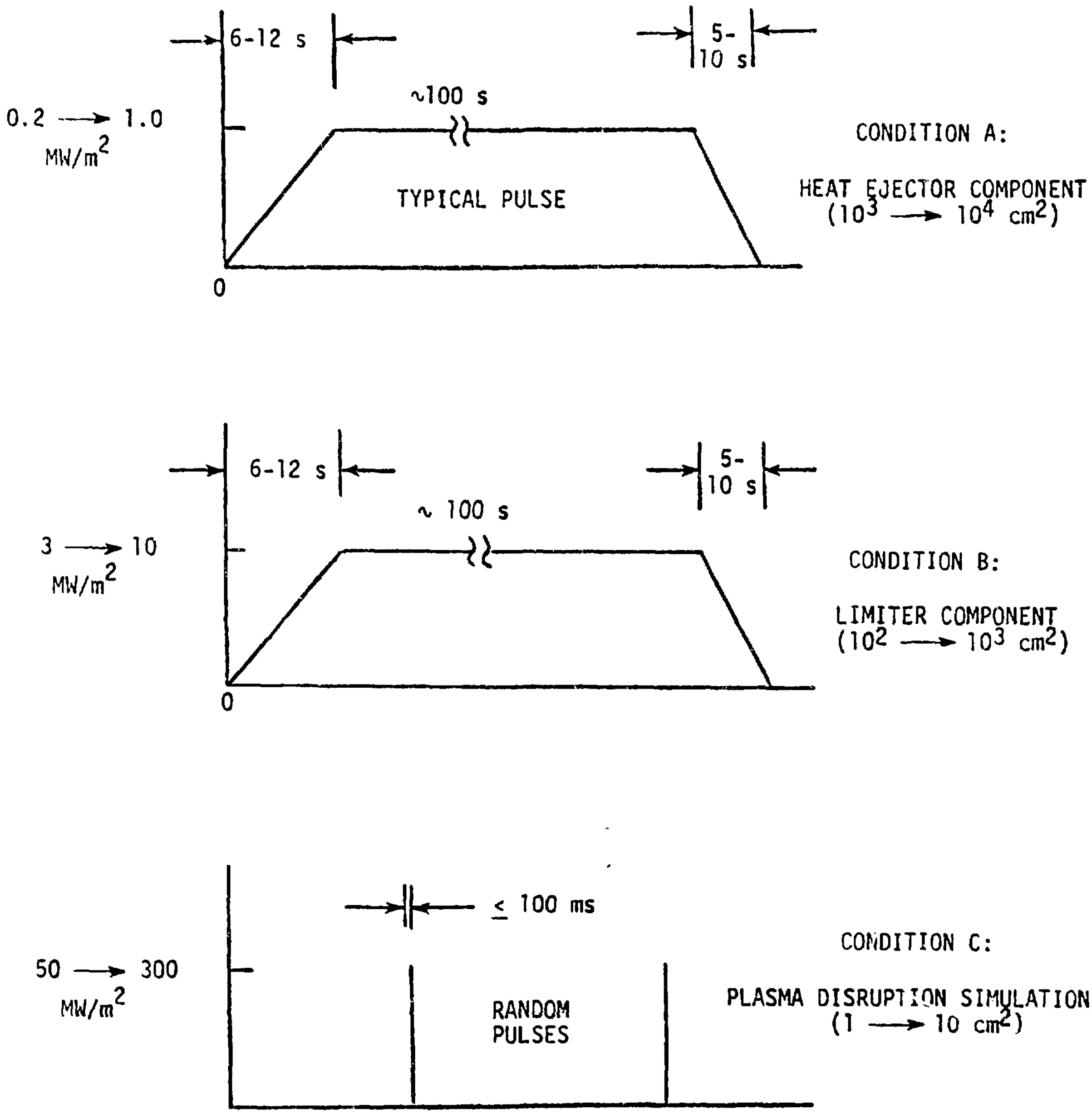

Fig. 1.4. First-wall heat flux test facility requirements.

The approach to the formulation of the DTP is illustrated in the logic diagram, Figure 1.2. Table 1.2 and Figure 1.3 show the goals for surface heat load and target areas, covering three specific sets of conditions, designated A, B, and C. Condition A is suitable for the testing of heat transport panels, condition B for limiters, divertor collectors and neutral beam shine-through simulations, and condition C is for plasma disruption and neutral beam strike simulations. Figure 1.4 gives the capabilities required for the time-dependent heat flux simulations.

1.2 First Wall Issues and Needs

A large number of engineering issues and R&D needs can be identified, based on existing first wall designs and concepts published in the literature. The issues are related to the characteristics of the component designs/concepts, the reactor operating conditions, and the environment that affects the first wall components. Consequently, an examination of these factors will provide a better understanding of the nature and the relative importance (priority) of the engineering issues. A wide variety of first wall design concepts has been considered and proposed for different fusion devices as summarized in Table 1.3.

1.2.1. First Wall Concepts

First wall designs typical of those commonly considered in many MCF devices typically consist of three major components: 1) outboard stainless steel heat ejection panels, 2) inborad, upper and lower wall graphite armor tiles and 3) pumped limiter panels. Consideration of the STARFIRE first wall design can provide some insight into the requirements of other steady state devices, such as the mirror reactors, and possibly a DFMO. Concepts that have been considered are shown in Table 1.3.

1.2.2 Priorities

Three levels of priorities, summarized in Table 1.4 were defined. Priority level 1 is associated with those issues that affect 1) the basic design feasibility of the concept, the go/no issues, 2) the life of the

Table 1.3. First-Wall Concepts and Fabrication/Joining/Attachment Techniques

First Wall System	Description of Basic Types of First Wall Concepts	Fabrication/Joining/Attachment Technique
I	Parallel, Large Diameter, Thick-Walled Stainless Steel Tubes	- Braze joined to common header
	Stainless Steel Flat Plate Joined To Ribbed Back Plate Forming Rectangular Coolant Channels	- Brazed - E-beam welded
	Stainless Steel Flat Plate Joined To Corrugated Back Plate, Forming Hemispherical Coolant Channels	- E-beam welded - Arc welded
II	Graphite Armor Tile, Mechanically Attached to Water-Cooled Stainless Steel Heat Sink	- Dove-tail attachment, dove-tail at the sides of the tile - Dove-tail attachment, dove-tail at the middle of the tile - Bolted attachment, graphite bolts - Bolted attachment, refractory metal alloy bolts
III	Armor Tile, Bonded to Water-Cooled Copper Heat Sink	- Graphite armor, brazed joint - Graphite armor, diffusion bonded - Tungsten armor, brazed joint - Explosive bonding
IV	Parallel, Small Diameter, Thin-Walled Stainless Steel Tube Panels, Pressurized Water Cooled	- Arc welded
	Parallel, Small Diameter, Thin-Walled Stainless Steel Tube Panels, Boiling Water Cooled	- Arc welded
	Parallel, Small Diameter, Thin-Walled Stainless Steel Tube Panels, Helium Cooled	- Arc welded
	Parallel, Small Diameter, Thin-Walled Stainless Steel Tube Panels, Liquid Lithium Cooled	- Arc welded
	Copper Plate With Small Rectangular Coolant Channels	-Brazed -Diffusion bonded

Table 1.4. Priorities of First-Wall Engineering Issues and Research and Development/Data Needs

Priority Level	Basic Characteristics of the Design/ Engineering Issues & Uncertainties
1	• Go/no go issue, affects the basic feasibility of the design/concept
	• Affects the component life; high uncertainties are involved
	• Need to be resolved before a reference concept can be selected among several alternatives
	• Generic to DEMO and commercial devices
2	• Major design/performance uncertainty
	• Need to be resolved to confirm the selection of the reference design/concept
	• Applicable to other fusion devices
	• Generic to near-term devices
3	• Needed to refine, optimize the design/performance
	• Associated with detailed design efforts

component, where a high degree of uncertainty is involved, and 3) where a selection of a reference design among several alternative concepts has yet to be resolved. Priority level 2 is principally associated with major design/performance uncertainties, while the basic feasibility of the design is not in question. Priority level 3 is associated with R&D required primarily to refine or optimize the design of the selected reference concept. All of the thermal-hydraulic and thermomechanical issues are involved in one or more of four basic engineering issues listed in Table 1.5. Some are closely related. First wall engineering issues, and their priorities are listed in Table 1.6.

1.3 Test Facilities

After consideration of the large number of different types of first walls components concepts, techniques for their manufacture, the wide range issues, and the simulation and test requirements, experimental facilities were evaluated and recommended, in the following sequence:

1) Utilization of an existing 50 kW, focused e-beam test facility (ESURF) for preliminary, concept screening tests.

2) Implementation of a 100 kW, distributed e-beam test facility (ASURF) for component life and multiple effects tests.

3) Upgrade of ASURF to simulate mechanical loads due to electromagnetic effects.

4) Upgrade of the 100 kW facility (ASURF) to 1 MW to test reference first wall designs where the engineering issues involved must be addressed by large or full-scale test pieces.

5) Upgrade of ASURF in the future to include other coolants (e.g., lithium, helium).

Table 1.5. Basic First-Wall Engineering Issues

	Priority
(1) Mechanical feasibility of first-wall structures and supports/attachments	1
(2) Life of first-wall structures and supports/attachments	1
(3) Predictability of thermomechanical responses	2
(4) Design margins/operating limits	2

Table 1.6. First-Wall Engineering Issues, Separate and Multiple Effects, and Their Properties

Engineering Issue/Separate Effects	Priority
1. Crack formation, deformation and mechanical feasibility due to long pulse cyclic heat loads.	
2. Crack formation and mechanical feasibility due to thermal shock loads (introduced by disruptions/neutral beam strikes).	
3. Thermal fatigue crack growth and fatigue life due to long pulse cyclic heat loads.	
4. Thermal fatigue crack growth and fatigue life due to simultaneous long pulse cyclic heat loads and disruption/neutral beam heat loads.	
5. Same as above but with simultaneous mechanical loads due to electro- magnetic effects.	
6. Simultaneous irradiation and thermal load effects.	
7. Simultaneous irradiation, thermomechanical and electro-magnetic effects.	
8. Erosion and rates of erosion due to surface melting/vaporization for metallic first wall materials.	
9. Erosion and rates of erosion due to sublimation for graphite first wall materials.	
10. Erosion and rates of erosion due to combined melting, vaporization/sublimation, physical and chemical sputtering.	
11. Redeposition of graphite.	
12. Graphite-steel interactions.	
13. Mechanical feasibility of panel structural support/attachments as a result of cyclic loads and dead weight stresses.	
14. Critical heat flux in asymmetrically heated coolant channels.	
15. Flow instability for parallel boiling two phase flow with non-uniform surface heat flux.	

Table 1.6 (Contd.)

	Engineering Issues/Separate Effects	Priority
16.	Life of first-wall systems cooled by high-pressure coolant-fatigue failure due to simultaneous mechanical (pressure and dead weight) and thermal stress loads.	2
17.	The validity of analytic model(s) and computer codes for the prediction of graphite erosion.	2
18.	The validity of analytic models and computer codes for the prediction of metallic material surface melt and vaporization phenomena.	2
19.	The validity of analytic models and computer codes for the prediction of disruption heat load effects.	2
20.	The validity of analytic models and computer codes for the prediction of boiling heat transfer under non-uniform and asymmetric heat flux conditions.	2
21.	The validity of analytic models and computer codes for the prediction of first-wall creep under simultaneous pressure loads and transient non-uniform heat loads (disruptions).	2

The characteristics of the heat source applications are summarized in Table 1.7. The heat source/test facilities were selected for the following principal reasons:

- They meet all of the basic PE-I test condition goals.

- The heat source test facilities are highly flexible, having the following capabilities:
  - can test all types of first wall designs/concepts
  - can address a host of critical engineering issues
  - can cover a wide range of test parameter space

- Their implementation is consistent with the program funding expectations.

The characteristics of the test facilities are summarized in the following sections.

1.4 ESURF, Electron Beam Surface Heating Facility

The Electron beam Surface heating Facility (ESURF) is an existing Westinghouse facility, operational since March, 1980 and first used to successfully test cathode prototypes for the Brookhaven National Laboratory negative ion source program. This was followed by divertor collector targets testing for MIT. ESURF has undergone a number of upgrades to attain its present capability; specifications are summarized in Table 1.8. The fully instrumented facility consists of a high power, 50 kW scanning electron beam which provides surface heating to targets located inside a vacuum chamber. The flexibility of this facility renders it highly suited to the small scale screening of a variety of first wall design concepts. Various concepts will be tested and compared to determine their relative design margins and mechanical feasibility as affected by different methods of fabrication. Here separate effects testing is adopted to address the high priority issues. Testing capabilities in terms of steady state operation and disruption simulation are illustrated in the performance map, Figure 1.5.

Table 1.7. Recommended Heat Source Test Facility Applications

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ESURF (50 kW heat source)

- Variable spatial and temporal heat load distributions and target areas
- Separate and multiple effects tests for preliminary, concept screening
- Operating limits/failure mode determinations, benchmarks for code validations
- Small scale test pieces
- Scaled down simulations of types of first wall designs
- Relatively inexpensive, short term tests
- Advanced instrumentation development
- Benchmarks for the validation of analytical tools

ASURF (100 kW heat source)

- Variable spatial and temporal heat load distributions and target areas
- Component life tests
- Simulation of multiple effects
- Intermediate to longer-term tests
- Simulations of all types of first wall designs
- High heat removal capability tests

ASURF UPGRADES (1 MW heat source)

- Multiple effects tests
- Large/full scale test pieces
- Selected reference designs for commercial applications
- Various coolants

Table 1.8. ESURF Specifications

Heat Source	Electron Beam; 150 kV and 5-330 ma
Maximum e-beam Power Output	50 kW
Maximum Scan:	20 cm x or y -- 28 cm x and 18 cm y
Scan Speed	1 cm/s to 1 cm/μs
Target Area	1 cm^2 to 500 cm^2
Peak Surface Heat Flux	∿ 300 MW/m^2 to < 1 MW/m^2
Rep Rate:	20 Hz to 20 kHz
Heat Sink Coolant	Water
Maximum Working Pressure:	400 psi* → 1014 psi**
Maximum Head:	700 ft. H_2O
Working Temperature:	300°F* → 500°F**
Maximum Temperature:	350°F → 600°F**
Maximum Flow Rate:	7 gpm (at 700 ft. head rise)* 30 gpm (at 550 ft. head rise)**
Pre-Heater Power	40 kW
Heat Removal	72 kW Air Controlled Heat Exchanger
Control	Texas Instrument Programmable Control System
Vacuum Tank Working Space	3 ft. Diameter x 4 ft. Long
Vacuum Pressure	$<10^{-4}$ torr

Pump Limited *Pump A -- **Pump B

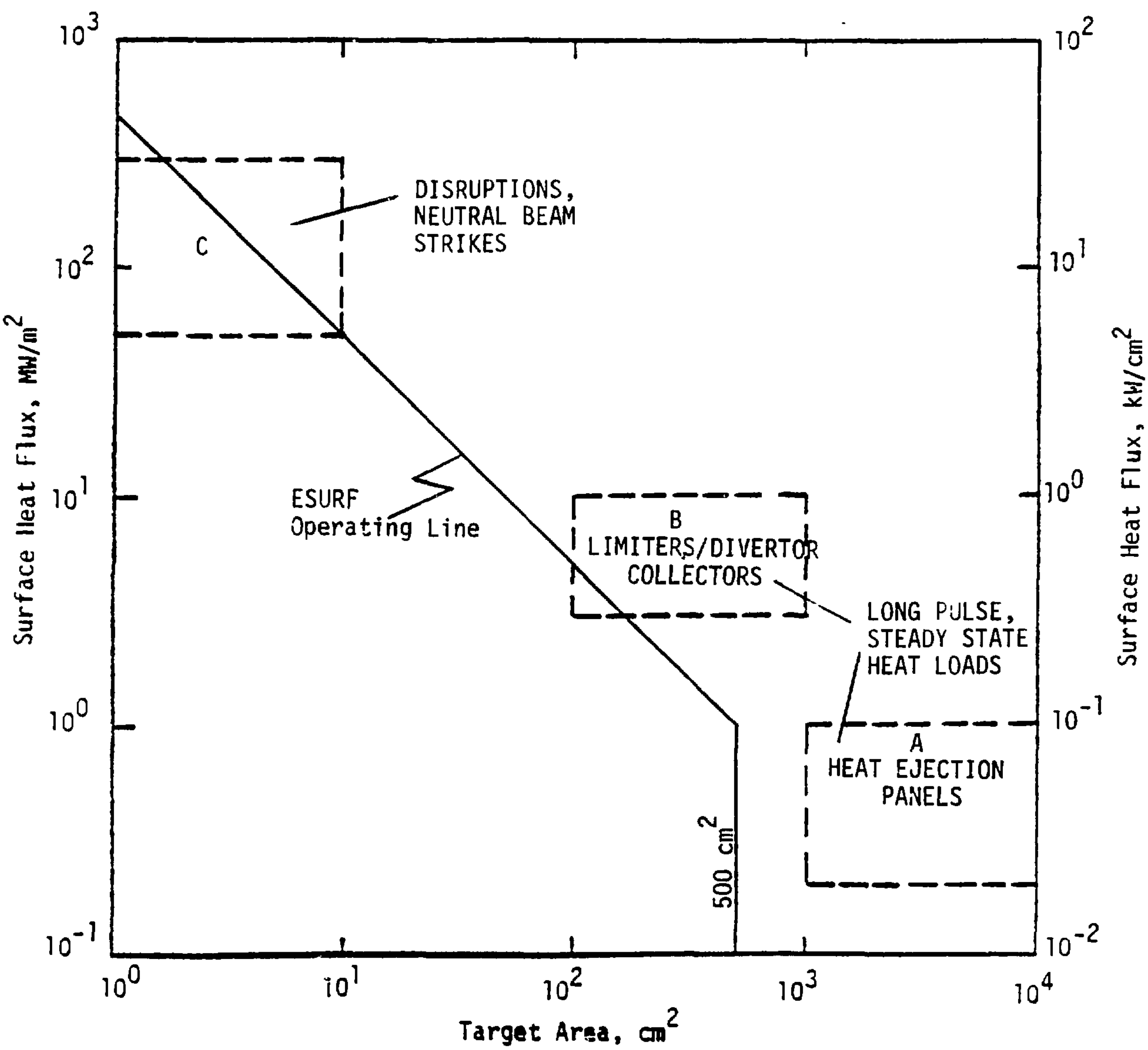

Fig. 1.5. A comparison of ESURF heat flux-target area capabilities with TPE-I test operation goals.

1.4.1 ESURF Data Acquisition and Control System (DACS)

The existing dedicated fusion data acquisition and control system at ESURF is based on a microprocessor/CAMAC (Computer Automated Measurement And Control, IEEE Standard 583-1975) system, considered to be the most flexible and efficient approach for this application. The approach has gained widespread use by the worldwide fusion research community (e.g., PLT Neutral beamline application).

The LSI-11/23 is the most advanced DEC (Digital Equipment Corporation) 16-bit microprocessor. This unit has complete software compatibility with the PDP 11/34 minicomputer and, therefore, can be expanded from its current 30 K word memory capacity/RT-11 operating system to a 128 K word memory capacity/RSX11 memory management operating system is required. Programs are developed under FORTRAN-IV using callable MACRO CAMAC handler routines.

1.5 ASURF and ASURF Modification

The Large Area SURface Heating Facility (ASURF) being constructed will incorporate an existing high pressure steam-water loop designated SWL-2, capable of rejecting up to 2 MWt. ASURF will consist of a 6 foot diameter by 8 foot long vacuum chamber and low-voltage, 100 kW distributed electron beam heat source systems. A number of upgrades are planned, to be conducted in stages as follows:

- Upgrade to a 1 MW heat source system - ASURF-1
- Mechanical simulations of electromagnetic effects
- Upgrade to accommodate a helium loop - ASURF-2
- Upgrade to accommodate a liquid lithium loop - ASURF-3.

Major differences between ASURF and ESURF are the larger target area, higher power, and longer heat source life attainable with the low voltage guns in ASURF. The facility is highly suited to the long term, intermediate cycle (10^3 to 10^4 cycles) and high cycle (10^4 to 10^5 cycles) thermal fatigue tests. Because of the less flexible target area, tests will be limited to first wall designs that have successfully passed the preliminary screening tests.

The specification for ASURF and the upgrades are summarized in Table 1.9. The planned heat flux-target capabilities are illustrated in Figure 1.6 which shows the basic capabilities of ASURF (solid lines) and ASURF upgrade (ASURF-1, dotted lines), and compares them with the reference test conditions A, B, and C. The reference heat load-target area requirements are well met by ASURF and are exceeded substantially by ASURF-1.

1.5.1 Long Pulse, "Steady State" Heat Flux Simulations

Low voltage, distributed electron beam systems were chosen for ASURF after a comprehensive comparison with ESURF. In addition to cost and schedule benefits, a low-voltage system has many major advantages:

One advantage, long cathode life, and hence high availability of the facility, provides the important capability for high cycle ($>10^4$ cycles) thermal fatigue tests. An important difference between ASURF and ESURF is that in ASURF the test pieces would be mounted vertically and the e-beams would be horizontal; whereas in ESURF, the e-beams are vertical and the target areas are mounted horizontally. Thus, ASURF permits orientation-sensitive issues such as the effect of dead weight stresses in the large panels to be tested.

1.5.2 Disruption Simulations

Because of the relatively long time between plasma disruption events and very high energy density, it is advantageous to use a capacitor discharge to simulate disruptions. By this technique, relatively high power, short time bursts of electron energy can be obtained. A wide range of disruption heat load-time simulations can be provided, depending on the power-time distribution required. The energy storage system for two types of power-time profiles were estimated; "square-wave*" and exponential decaying power. Cost estimates were made for systems that provide target areas of 10 cm^2 and 100 cm^2.

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*Approximated by minimizing the voltage drop in an inherent exponential decay through the use of condensers of large capacitance.

Table 1.9. Specifications for ASURF and ASURF Upgrades

	Facility			
	ASURF	ASURF-1	ASURF-2	ASURF-3
Total Heat Source Power Capability	100 kW	1 MW	1 MW	1 MW
Test Piece Target Area	1000 cm^2	1 m^2	1 m^2	1 m^2
Disruption Heat Flux, MW/m^2	≤ 300	≤ 300	≤ 300	≤ 300
Disruption Target Area, cm^2	10	10 or 100	10 or 100	10 or 100
Base Pressure, torr	$\sim 10^{-5}$	$\sim 10^{-5}$	$\sim 10^{-5}$	$\sim 10^{-5}$
Coolant	Water	Water	Helium	Lithium
Coolant Peak Pressure, psia	2200	2200	1000	200
Coolant Peak Temperature, °C	300	300	600	380
Coolant Flowrate	30 gpm	50 gpm	0.14 lb/s	100 gpm
Heat Rejection Capability	>100 kW	1 MW	1 MW	0.5 MW

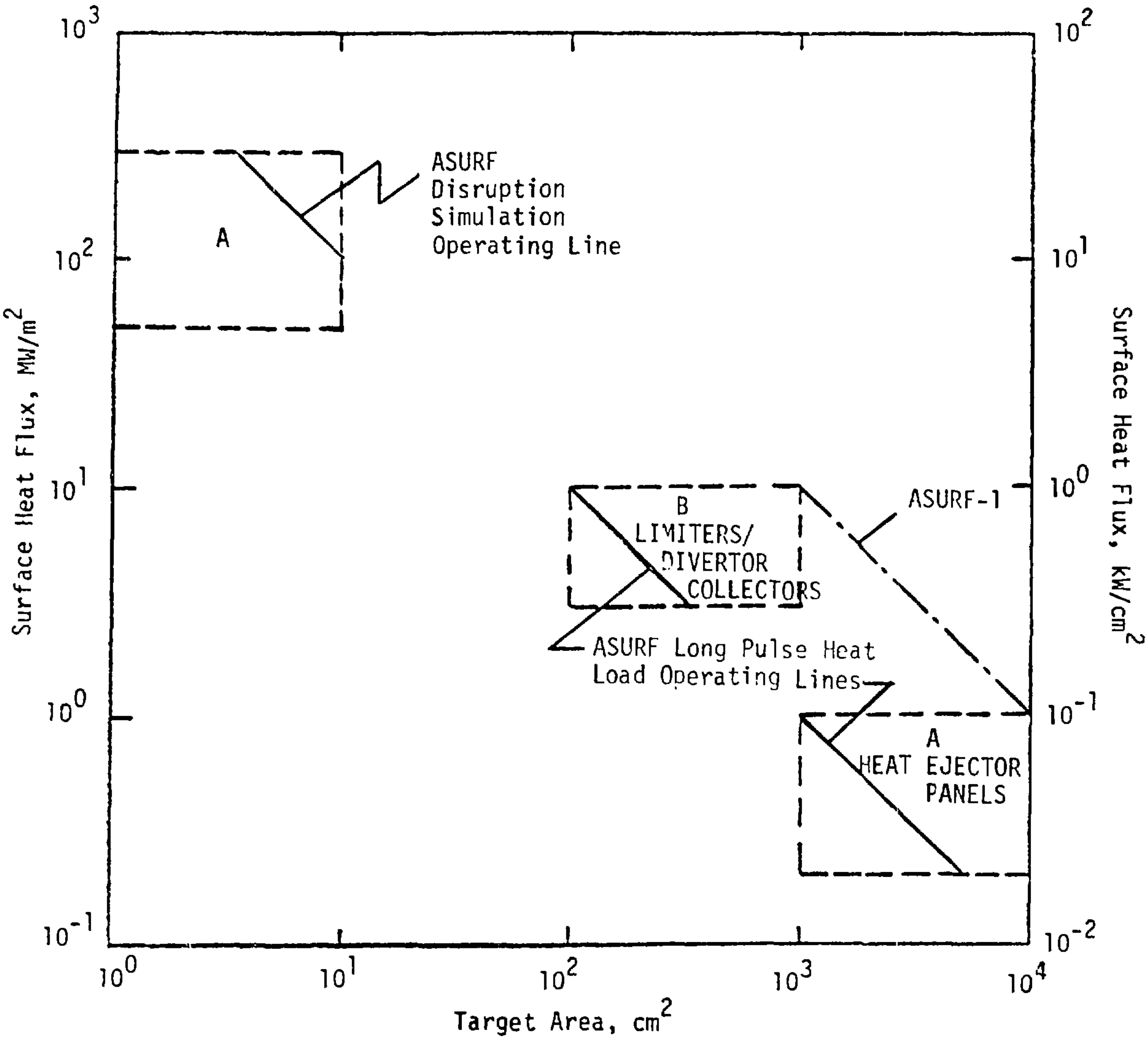


Fig. 1.6. ASURF heat flux - target area capabilities and comparison with TPE-I goals (Conditions A, B, C)

1.5.3 ASURF Control and Data Acquisition Systems

The ASURF control system, interlocks and instrumentation will be very nearly identical to ESURF except:

Data acquisition will be by the use of strip charts, digital readouts and visicorder initially, to be followed by a Digital Data Acquisition System (DDAS) and a CAMAC interface.

1.5.4 Electromagnetic Effects Simulation

Implementation of electromagnetic effects simulation by means of magnetic field coils, switching circuitry and associated instrumentation will require very detailed evaluation. Testing of this type appears to be feasible, but requires extensive development in many areaas. A cursory estimate of the cost of implementing such a simulation suggests that it would be prohibitive, given the preliminary PE-I budget guidelines. Consequently, an alternative, mechanical simulation method of the electromagnetic forces developed in the first wall during a plasma disruption was evaluated. The cost will be a great deal less than a coil structure required to develop the electromagnetically-induced forces directly. Furthermore, the mechanical force can be applied simultaneously with the application of surface heating, because there is no magnetic field to deflect the electron beam. There is considerable potential for interaction with PE III in this area.

1.5.5 ASURF-1, Upgrade to 1 MW

ASURF-1 is an upgrade of the baseline ASURF facility to include a 1 MW heat source. It is proposed that upgrading from 100 kW to 1 MW be accomplished by the design and fabrication of from 3 to 12 low-voltage guns in matrix arrangements. Commercial power supplies for the guns will be acquired. Special water cooled heat removal coils will be installed in the 6 feet diameter vacuum chamber when power levels are increased to 1 MW.

The 1 MW heat source and the large area capability are for testing concepts such as large, full scale/full length baseline stainless steel heat transport panel or limiter designs. Testing would be aimed at the study of multiple effects that include combined disruption and steady state heat loads, thermal and mechanical stress loads and high cycle effects (10^4 to 10^5 cycles). The mechanical loads will include pressure and dead weight stresses.

1.5.6 ASURF-2, Upgrade to Include a Helium Loop

ASURF-2 is a projected upgrade of ASURF-1 whereby the pressurized water loop is supplemented by a helium loop that can operate at a maximum prressure and temperature of 1000 psia and respectively. A helium subsystem consistent with the ASURF facility layout is feasible. The system design will permit operation in a once-through mode or in a recirculation mode. Operational times in excess of 2×10^5 seconds with a flowrate of 0.24 lb/s justify the additional costs associated with a helium recovery system. An analog data acquisition system will permit recording and evaluation of key parameters including coolant flow, test specimen temperatures, helium inlet and exit temperatures, and system pressures. This system will interface with the existing data acquisition system.

The system will be operated to maintain a helium flowrate sufficient to limit the coolant exit temperatures to a maximum of 1112° (600°C) and to operate with a test section pressure of 1,000 psia (6.88×10^3 kPa). Adequate safety devices will be incorporated. In principle, the helium loop could be operated at the same time as the high pressure water system to accommodate integral first wall/blanket/ module mockups that require both coolants.

1.5.7 ASURF-3, Upgrade to Include a Liquid Lithium Loop

The equipment required and the cost to implement a lithium heat removal system for dissipating up to 0.5 MWt was estimated, based on two pumped lithium systems operated at the Westinghouse Advance Reactors Division.

The lithium loop primary flow path might, for example consist of 2-inch Schd 40 piping, with secondary branches fabricated of 1/2-inch Schd 40 piping. All material would be selected so as to be compatible with lithium at the temperatures of interest. Existing, available systems components, such as a 100-GPM electromagnetic pump, magnetic flow meters and liquid metal valves would be employed where possible. The system would be designed to remove up to 0.5 MWt from the lithium to take advantage of an existing, liquid metal-to-air, multiple-pass, finned tube heat exchanger (from an inactive sodium test facility) if material compatibility is assured. Lithium purification would be achieved through the use of a hot trap, a cold trap and a magnetic trap.

The proposed lithium facility would employ control room space and control components currently available from the LMFBR-related sodium facilities. Methods of fabrication, construction and installation employed in the GPL-1 (200 GPM) facility would be used as a basis for commissioning the 100 GPM lithium facililty discussed here.

Many sodium components currently available could possibly be employed in the fabrication of the 0.5 MWt lithium facility. In addition, many procedures (i.e., fabrication, welding, etc.) and established techniques could also be directly applicable. The costs, therefore, would be concentrated primarily in the areas of engineering design, fabrication, installation and check-out. From the standpoint of thermal and heat sink simulations, liquid lithium can be replaced with liquid sodium. For this purpose, the GPL-1 sodium loop located in the GPL-1 building can be used directly, which can result in significant savings since no capital investments would be involved. In addition, test data on liquid metal cooled first walls can be obtained at an earlier data.

1.6 Instrumentation

The instrumentation required for each test may vary, depending on the specific objectives of the particular test. However, there are generic requirements, common to all tests, and special requirements, as follows:

1.6.1 Generic Instrumentation

The generic instrumentation will control and monitor the coolant conditions, vacuum pressure and power balances. The parameters to be

Table 1.10. Instrumentation Requirements

Parameter/Item to be Measured/Monitored	Instrument/Measurements
Coolant flowrate	Flowmeter
Coolant pressures	Pressure and differential pressure transducers
Coolant temperatures	Thermocouples
Vacuum pressure	Ion gauge
Heat source power output	Voltmeter and ampmeter
Power balance	Water flowrates and temperature drops for coolant flows through masks and plates
Test piece temperatures	Thermocouples
Surface temperature	Infrared camera
Test piece deflection	Linear variable differential trans-former (LVDT)
Surface strain	Strain gauges
Flow-induced vibrations	Accelerometers
Material vaporization rate	Quartz crystal sensor

controlled/monitored and the instruments required are summarized in Table 1.10. The actual number of instruments (thermocouples, strain gauges, etc.) required will depend on the type and size of the test piece involved and on the objectives of the test.

1.6.2 Special Instrumentation

There are a number of important experimental measurements specifically associated with surface strain and surface melt observations that are highly desirable but are expected to be difficult to obtain because of the high temperature, high surface heat flux conditions and the electron and x-ray environment of ESURF and ASURF. Accordingly, a survey and an evaluation of potential instrumentation concepts for these special applications was made. Four categories were evaluated, two for surface strain measurements and two for surface melt detection. The techniques considered are optical reflection, x-ray diffraction and the use of scribed grids. All will require substantial development cost, which includes testing in ESURF, development should therefore be deferred until results from testing in ESURF become available as they may provide a better guide to selection. Further study of this topic is warranted.

1.7 First Wall Engineering Development Logic and Test Strategy

The generic development logic for the various types of proposed first wall consists of screening alternative first wall design concepts by addressing the most critical design feasibility issues using relatively simple, small scale, low cost, short-term, separate effects tests. Depending upon the outcome, these will be followed by a series of increasingly more complicated, larger scale, longer-term, more costly, multiple effects tests, culminating in larger (or full scale) testing to address issues that cannot be adequately carried out using small scale facsimilies.

First wall strategies are based on the following:

Test sequences indicated by the first wall engineering development logic.

- Initiation of preliminary, concept screening tests using relatively simple, small scale test pieces in ESURF. The experiments are primarily short-term, separate effects tests.

- Continued small-scale testing in ESURF on the more attractive first wall designs to study multiple effects.

- Continuation of the development with larger scale, increasingly more complex, test articles of the more attractive design concepts with testing in ASURF, including multiple effects. The testing would be aimed at intermediate cycle (up to 10^4 cycles) and high cycle (10^4 to 10^5 cycles) thermal fatigue tests.

- Combined effects testing on selected first-wall concepts using large scale, full-size test articles where the size and scale are critical to the engineering issues to be resolved. Multiple effects would be included in these tests.

A representative test strategy for a typical first-wall concept is described in Figure 1.7. There are a number of major test-development elements (labeled A, B, C, etc.), where each one consisting of a series of experiments can be applied to a number of concepts.

Thirty-three candidate first-wall test/development elements, summarized in Table 1.11, are considered in the DTP. Twenty types of candidate test articles are described in Table 1.12. Three of the twenty (18, 19, 20) are not included in Table 1.11. They serve as potential replacements for the other test articles. Test article type 17, facsimile(s) of advanced high heat flux (1 MW/m^2 < 10 MW/m^2) panels is not described because an attractive, feasible concept is lacking at this time.

	A	B	C	D	E
DESCRIPTION	PRELIMINARY SCREENING TESTS	HIGH CYCLE THERMAL FATIGUE TESTS	PANEL SUPPORT AND DEAD WEIGHT STRESS TESTS	SIMULTANEOUS ELECTROMAGNETIC EFFECTS AND THERMAL LOAD TESTS	MULTIPLE EFFECTS TESTS
TEST FACILITY	ESURF	ASURF	ASURF	ASURF	ASURF-1
TEST PIECE SIZE (scale)	SMALL	INTERMEDIATE	INTERMEDIATE	INTERMEDIATE	LARGE
PURPOSE OF TEST AND IMPACT	- Separate and combined effects - Determine the structural integrity of the design - Determine the operating limits - Study surface melt and vaporization phenomena - Study low cycle thermal fatigue	- Combined effects - Determine thermal fatigue limits - Compare test results with those of panels with different joining techniques - Establish thermal fatigue data base - Compare and correlate the results with data from the small scale tests	- Multiple effects - Determine the mechanical integrity of first wall structural supports under combined thermal and simulated mechanical loads	- Combined multiple effects - Determine mechanical integrity under combined thermal stresses and mechanical loads simulating electromagnetic effects	- Multiple effects - Study the effect of simultaneous cyclic thermal stresses, dead weight stresses and disruption heat loads on the integrity and life of the assembly
EXPERIMENTAL MEASUREMENTS/DATA REQUIRED	- Temperature vs. time - Strain - Heat loads to failure - Physical changes	- Temperatures - Strain - Physical changes - Cycles to failure	- Temperatures - Strain - Physical changes - Cycles to failure	- Temperatures - Strain - Heat loads to failure - Physical changes	- Temperatures - Cycles to failure - Physical changes

Fig. 1.7. Typical test strategy.

Table 1.11. Matrix of Engineering Development Elements and Summary of the Estimated Costs and Times Required to Carry Out the Element

FIRST WALL TYPE	TEST/ DEVELOPMENT ELEMENT	TEST PIECE TYPE NO.	TEST FACILITY	DESCRIPTION OF THE ENGINEERING DEVELOPMENT ELEMENT			
				PRINCIPAL TEST PIECE MATERIAL	SUBSTRATE MATERIAL	COOLANT	MAJOR CHARACTERISTIC OF DEVELOPMENT ELEMENT
I	A	01	ESURF	S.S.		Water	System characterization/calibration
(Stainless	A	02	ESURF	S.S.		Water	Concept screening tests
steel heat	A	03	ESURF	S.S.		Water	Concept screening tests
ejector	A	05	ESURF	S.S.		Water	Concept screening tests
panel)	A	03	ESURF	S.S.		Water	Special instrumentation and benchmarks
	B	03	ASURF	S.S.		Water	Small scale, high cycle thermal fatigue tests
	C	14	ASURF	S.S.		Water	Intermediate scale, support and attachment tests
	D	03	ASURF	S.S.		Water	Combined electromagnetic & thermal effects tests
	E	15	ASURF-1	S.S.		Water	Large Scale, multiple effects tests
II	A	04	ESURF	Graphite	S.S.	Water	Small scale, preliminary screening tests
(Armor tile	A	06	ESURF	Graphite#	S.S.	Water	Small scale, preliminary screening tests
mechani-	A	07	ESURF	Graphite#	S.S.	Water	Small Scale, preliminary screening tests
cally	B	11	ASURF	Graphite	S.S.	Water	Intermediate scale-high cycle fatigue tests
attached)	C	04	ASURF	Graphite	S.S.	Water	Combined electromagnetic & thermal effects tests
	C	06	ASURF	Graphite	S.S.	Water	Combined electromagnetic & thermal effects tests
	C	07	ASURF	Graphite	S.S.	Water	Combined electromagnetic & thermal effects tests
	D						Analytical studies of graphite surface erosion
III	A	08	ESURF	Graphite	Copper	Water	Small scale, preliminary screening tests
(Actively	A	09	ESURF	Graphite	Copper	Water	Small scale, preliminary screening tests
cooled	A	10	ESURF	Graphite#	Copper	Water	Small scale, preliminary screening tests
limiter/	A	13	ESURF	Tungsten	Copper	Water	Small scale, preliminary screening tests
divertor	A	17	ESURF	Graphite	Copper	Water	Advanced concept, preliminary screening tests
collector)	B	12	ASURF	Graphite	Copper	Water	Intermediate scale-high cycle fatigue tests
	C	08	ASURF	Graphite	Copper	Water	Combined electromagnetic & thermal effects tests
	C	09	ASURF	Graphite	Copper	Water	Combined electromagnetic & thermal effects tests
	D	16	ASURF-1	Graphite	Copper	Water	Large scale, multiple effects tests
IV	A	01	ESURF	S.S.		Water+	Single tube heat transfer measurements
(Energy	A	02	ESURF	S.S.		Water+	Multiple tube boiling heat transfer studies
recovery	B						Analytical studies on boiling heat transfer
panels)	C	14	ASURF	S.S.		Water+	Single tube, high temp., high pressure & boiling heat transfer tests
	D	15	ASURF-1	S.S.		Water+	Large scale, multi-channel boiling-flow stability
	E	15	ASURF-2	S.S.		Helium	Combined multiple effects tests on large scale panels
	F	15	ASURF 3	S.S.		Lithium	Combined multiple effects tests on large scale panels

*Does not include the costs to implement and upgrade the facilities; based on 1982 dollars

#Coated Armor Tile

+Water at High Pressures and High Temperatures, including boiling heat transfer

Table 1.12. Candidate Test Articles for TPE-I

Test Article Type No.	Description of Representative Test Articles
01	Single stainless steel tube, variable wall thickness
02	Multiple stainless steel tubes; tube panel
03	Stainless steel flat plate panel bonded to a ribbed back plate
04	Single graphite armor tile, dovetail-attached to water-cooled stainless steel plate
05	Stainless steel flat plate panel with a corrugated backplate
06	Single graphite armor tile, bolted to water-cooled stainless steel plate
07	Coated single graphite armor tile, mechanically attached to water-cooled stainless steel plate
08	Single graphite armor, brazed to a water-cooled copper heat sink
09	Single graphite armor tile - diffusion bonded to a water-cooled copper heat sink
10	Coated single graphite armor tile - bonded to copper heat sink
11	Multiple graphite armor tile - mechanically attached to water-cooled stainless steel plate
12	Multiple graphite armor tile - bonded to water-cooled copper heat sink
13	Single refractory metal alloy tile - bonded to water-cooled heat sink
14	Long, single stainless steel tube with support/attachments to headers
15	Large-scale, multiple, parallel channel stainless steel panel with attachments to headers
16	Large scale graphite armor tile - bonded to water-cooled copper heat sink
17	Advanced high heat flux panel designs for first-wall panels, limiter/divertor collectors
18	Silicon carbide armor tile, mechanically attached to a heat sink substrate
19	Single refractory metal alloy heat transport tube
20	Refractory metal alloy heat transport tube panel

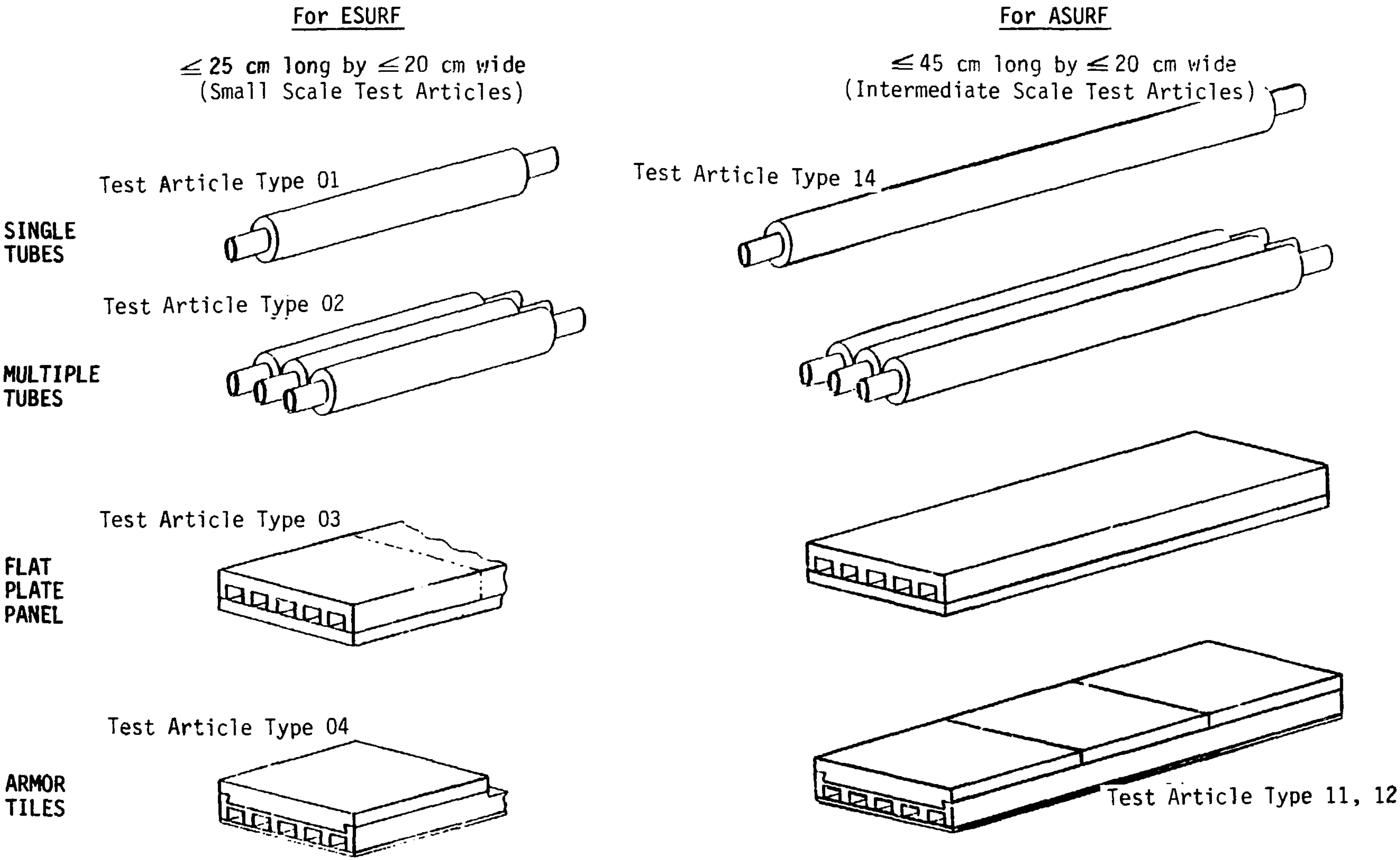


Fig. 1.8. Scales of test pieces for TPE-I.

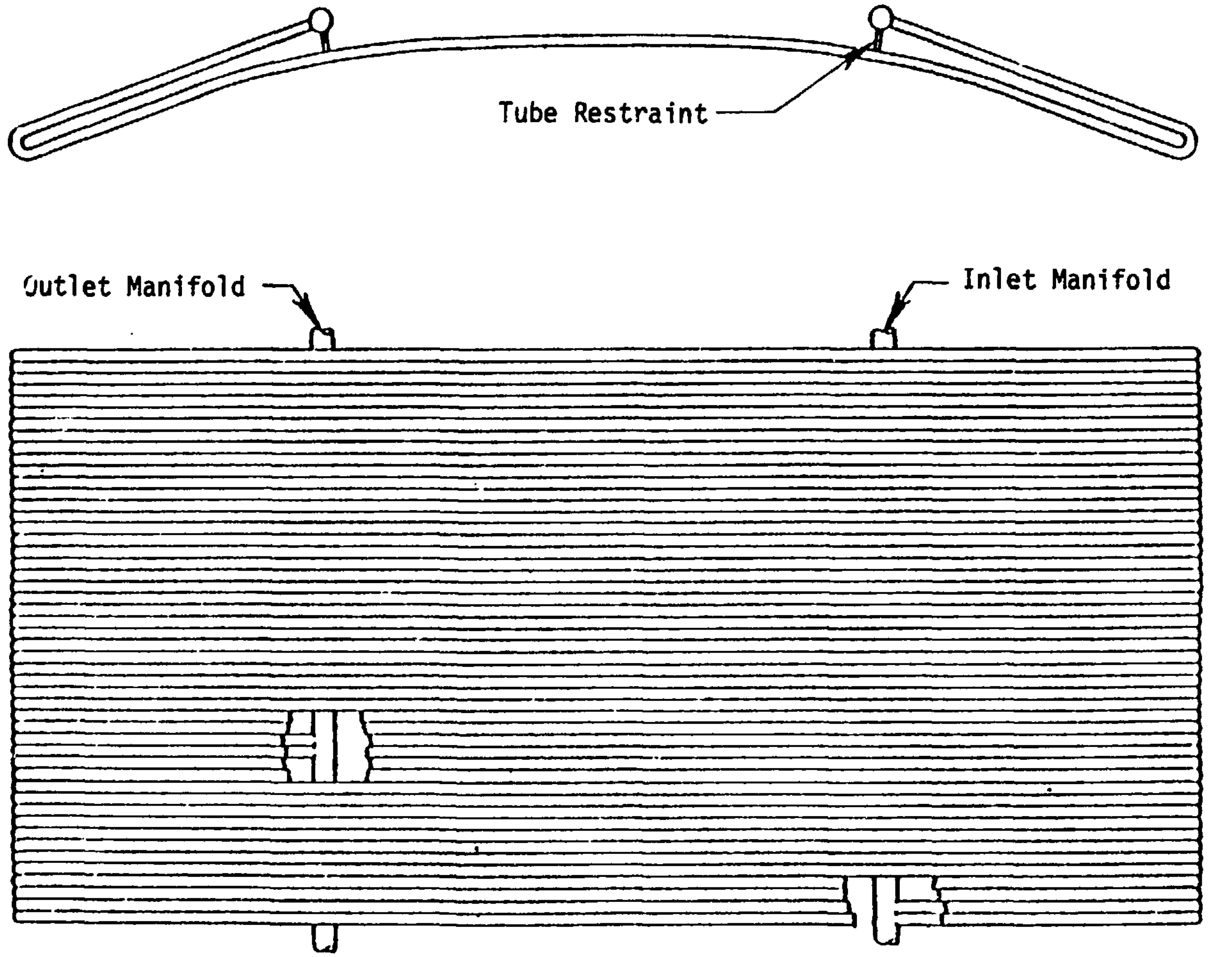


Fig. 1.9. Typical large-scale test article for ASURF upgrades $\leq$1.2 m long by $\leq$0.8 m wide (large/full-scale test articles of Type 15).

Test article types 01 through 10, 13, 17, 18, and 19 are typically small scale compatible with ESURF. Test article types 11, 12, 14, and 20 are typically intermediate scale test articles compatible with the 100-kW ASURF facility. Test article types 15 and 16 are large-scale test articles intended for the upgraded ASURF facilities. The scales of the test articles are illustrated in Figures 1.8 and 1.9.

Data evaluation, data analysis, and correlation are integral to each test element. The specific analysis to be performed, however, will depend largely on the type of test articles, the test conditions, and the objectives of the test. In general, any thermal, mechanical, and structural analysis that may be performed will use existing computer codes, where appropriate. New code development is not envisioned in the present scope of PE-I.

Modeling of the thermal-hydraulic and thermomechanical phenomena and analyses using existing analytical tools will be performed in attempts to correlate the data. In particular, theoretical analysis and the development of any new correlations are planned only as separate, development elements because of the significant cost and efforts involved. An example of such an element is the study of non-uniform, asymmetric boiling heat transfer and two phase flow.

There are three relatively complex phenomena that can be encountered on first wall components which are not well understood, namely:

- Surface melt and vaporization
- Sublimation and chemical sputtering
- Boiling heat transfer with non-uniform, asymmetrically heated walls.

While tools have been developed recently for the analysis of the first two phenomena, an analytical tool for the prediction of boiling under non-uniform, asymmetric heating is either unavailable or inadequate. Therefore, attempts to correlate the data obtained on such phenomena will require analytical modeling and possibly code development.

Table 1.13. TPE-I Facility Implementation Schedule and Milestones

ACTIVITY/TEST FACILITY DESCRIPTIONS	FISCAL YEAR 80	81	82	83	84	85	86	87	MILESTONE DATE
CY	80	81	82	83	84	85	86	87	
PHASE	0	1		2		3			
ASURF, 100 kW HEAT SOURCE AND 2200 psia WATER									JUNE, 1982
ASURF, 3 kJ DISRUPTION SIMULATION									APRIL, 1983
ASURF WITH MECHANICAL SIMULATION OF ELECTROMAGNETIC EFFECTS									FEBRUARY, 1984
ASÚRF WITH 1 MW CAPABILITY (ASURF 1)									AUGUST, 1984
ASURF WITH HELIUM LOOP (ASURF 2)									APRIL, 1985
ASURF WITH LIQUID LITHIUM LOOP (ASURF 3)									AUGUST, 1985

Table 1.14

Summary of Plans for Testing in ESURF and ASURF

Test Facility	Test Series Number	No. of Test Series	Test Piece Description	Test Parameters* — Water: Inlet T, °C	Water: Inlet P, psia	Water: Flow Rate gpm	Steady State: Heat Flux MW/m^2	Steady State: Duration (s)	Steady State: No. of Cycles	Disruption Heat Loads: Heat Flux MW/m^2	Disruption Heat Loads: Duration (ms)	Calendar Year
ESURF	0102	1	Single Stainless Steel Tube, Thin-Walled	60-220	100-1000	2-17	0.2-5	60	1			82
ESURF	0301	1	Stainless Steel Flat Plate Panel, Thick Wall	60	100	≤15	0.35-1.0	60	1-20	24-300	5-100	82
ESURF	0302	1	Stainless Steel Flat Plate Panel, Thin Wall	60	100	<15	0.35-1.0	60	1-20	24-300	5-100	82
ESURF	0401	1	Graphite Armor Tile, Mechanical Attachment	60	100	<15	0.2-1.0	60	1-30	24-300	5-100	83
ESURF	0501	1	Graphite Armor Tile, Bonded to Copper Heat Sink	60	100	<15	1.0-10	10-100	1-30	24-300	2-100	83
ESURF	0601	1	Advanced Limiter/Divertor Collector		TBD			TBD		TBD		84
ASURF	0201	1	Stainless Steel Three Tube Panel	60-300	100-1000	2-15	0.35-1	60	1-5000	-	-	82
ASURF	0302	1	Stainless Steel Flat Plate Panel, Thin Wall	60-300	100-1000	5-30	0.20-1.0	60	1-5000	-	-	83
ASURF	0401/ 0402 or 0501/ 0502	1	Graphite Armor Tile, Mechanical or Bonded Attachment	60-300	100-1000	15	0.20-1.0	60	10^2-5000	24-300	2-100	83
ASURF	1501	1	Advanced Flat Plate Panel, Thin Walled		TBD			TBD		TBD		84
ASURF	1701	1	Large/Full Scale Stainless Steel Panel and Attachments	<300	<2000	<50		TBD		TBD		84, 85

*The test parameters may be changed as results of preceeding tests become available.

Table 1.15. TPE-I Overall Test Program Schedule

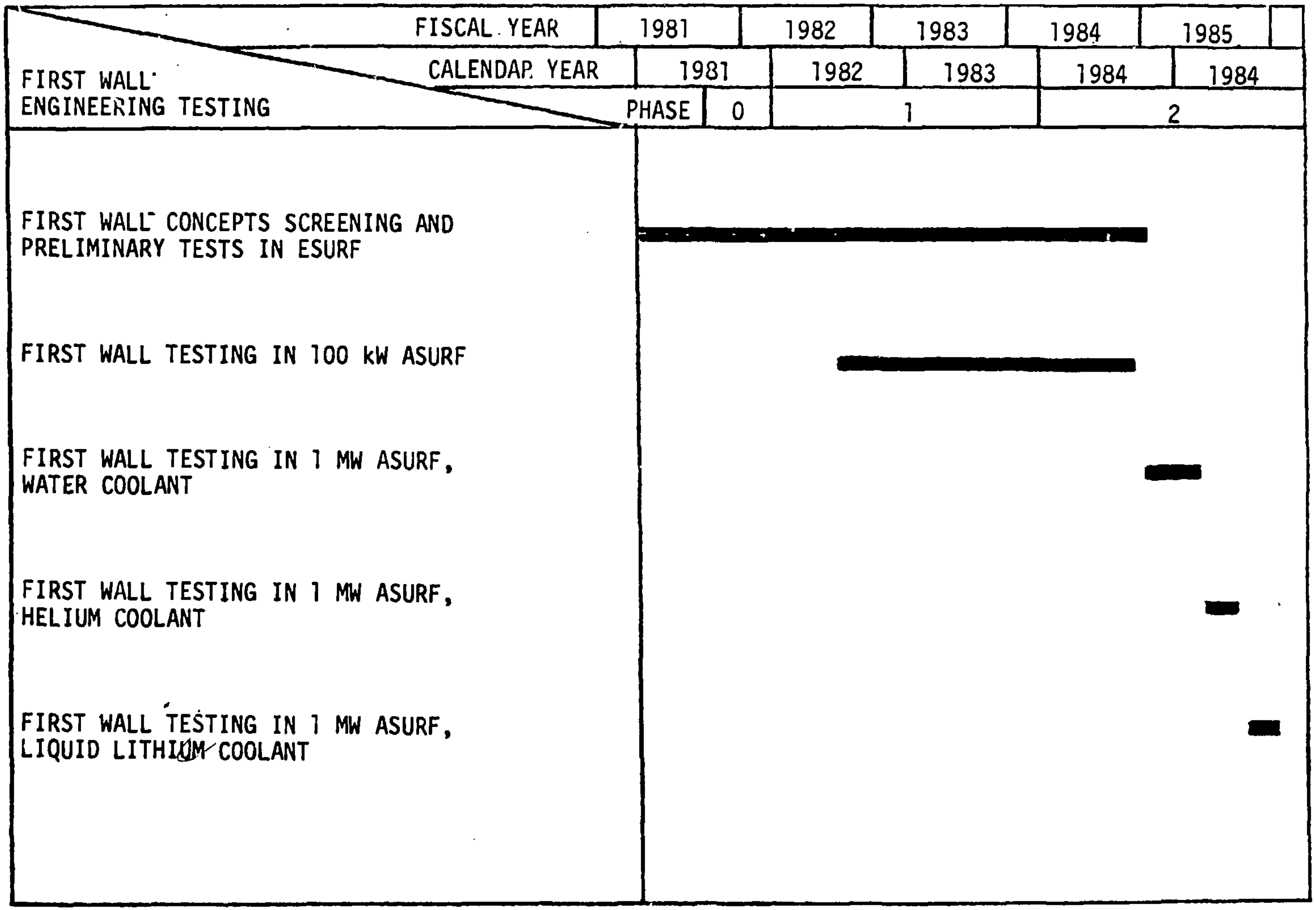
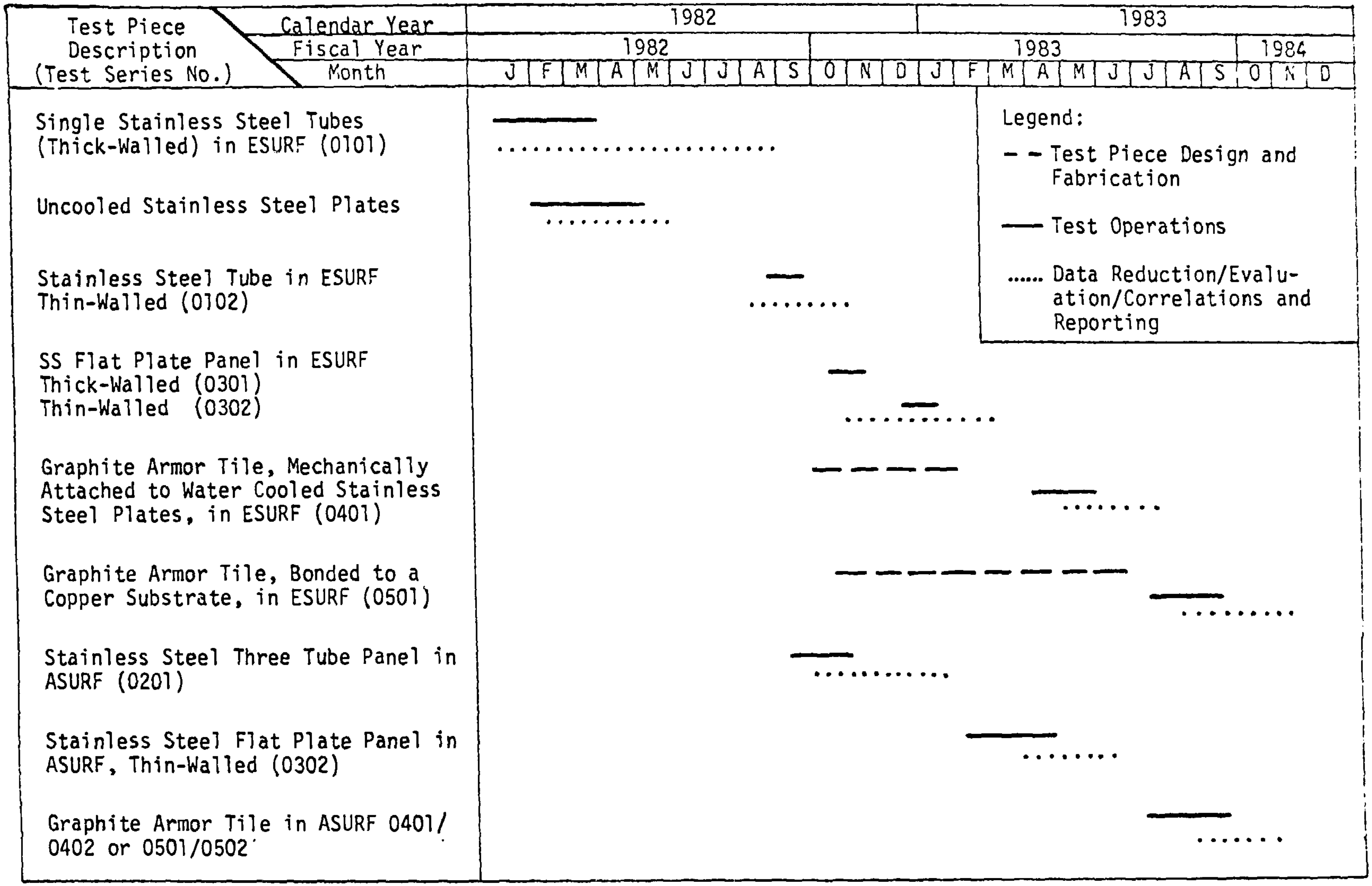


Figure 1. Phase 1 Schedule for the Design, Fabrication and Testing of Facsimiles of First Wall Components



In general, correlations of the data imply predictive analysis/calculation of measured parameters. Consequently, any analyses to be performed for a given test element must be carefully planned along with the experimental measurements to be made.

1.8 Recommended PE-I Test Program

In view of the need to develop four types of first walls and the fact that each type can have a number of alternative designs concepts, a given first wall concept cannot be fully tested and evaluated before starting testing of a second concept. A test program has therefore been formulated for the development of all four types of first wall, with the schedule based on the projected timetable for the availability of ASURF and ASURF upgrades as shown in Table 1.13. The recommended PE-I test program for Phase 1 is summarized in Table 1.14. The overall test program schedule for the first wall concepts is shown in Table 1.15 and in more detail in Table 1.16.

Phase 1 testing in ESURF is initially devoted to the preliminary screening of first wall design concepts proposed for various near-term devices. Later, in Phase 1 and Phase 2, advanced first wall concepts will be tested in ESURF. The more promising of the first wall systems will be subjected to more complex, simultaneous multiple effects testing in ASURF, where the combined effects are simulated mechanical loads (due to electromagnetic effects) and thermal loads (Phase 1 tests are limited to thermal loads).

ESURF is proposed for use in 1984 primarily for the development of special instrumentation, benchmarks for code validation, testing advances, and high heat flux first wall concepts. For the purpose of developing benchmarks, the test pieces should be instrumented to the maximum extent possible and, therefore, should include instrumentation for the measurement of surface strain.

Two types of testing will be conducted in ASURF: high cycle thermal fatigue tests of reference first wall systems (to take advantage of the long heater life) and large scale heat transport panel testing, where the scale of the test piece is of significant importance in combined effects tests. DTP development is based on the following:

- The specific sequence of facility implementation and upgrade steps.
- The reference sequence of development elements.
- The reference sequence of test pieces.
- The preliminary budget guidelines.

Any one of the above sequences can be altered as first wall design/development evolves and matures. For example, if later there is a greater need for testing with liquid lithium coolant, implementation of a liquid lithium loop may precede that of the helium loop. The test elements and the test pieces can be replaced/interchanged or alternative test sequences can be developed based on new budget guidelines or on factors such as a decision to accelerate the development of a specific first wall design. Alternative test strategies can then be developed based on the estimated time lines and costs developed for the individual test elements. The DTP is thus a living, working document, subject to changes and continued planning as first wall design and testing unfold.

2.0 Program Element II

2.1 Background

Program Element II (PE-II) of the First Wall/Blanket/Shield Engineering Test Program is being performed jointly by General Atomic Company (CA) and EG&G, Idaho, Inc. (EG&G), to develop the thermal-hydraulic and thermomechanical data base needed for the design and operation of blankets and shields for fusion reactors. Evaluation of blanket/shield thermal-hydraulic and thermomechanical data needs, investigation of various techniques to simulate fusion neutron bulk heating, development of testing strategies and the preparation of detailed test plans are addressed. Included are definition of and assignment of priorities to a set of data needs for proposed blanket and shield designs, evaluation of simulation techniques (both nuclear and non-nuclear) to be used in the testing phase to investigate the defined data needs, a survey of potential test facilities, and development of non-nuclear and nuclear strategies to define a testing program for investigating the data needs.

The following reports were consequently issued:

Veca, A. R., et al., "Data Needs Assessment Report," GAC-C16571, October 1981.

Deis, G. A., et al., "Evaluation of Alternative Methods of Simulating Asymmetric Bulk Heating in Fusion Reactor Blanket/Shield Components," EGG-FT-5603, October 1981.

Ware, A.G., Longhurst, G. R., "Test Program Element II Blanket Shield Thermal-hydraulic Thermomechanical Testing, Experimental Facilities Survey," EGG-FT-5626, December 1981.

Veca, A. R., et al., "Development of a Non-Nuclear Testing Strategy for TPE-II," GA-C16589, November 1981.

Deis, G. A., "Development of a Nuclear Test Strategy for Test Program Element II," EGG-FT-5651, November 1981.

Data needs can be divided into two broad categories, the first being basic concept design and evaluation data, and the second, design verification. They are of fundamental and primary importance respectively.

Basic concept design must be examined as it evolves to assure no detrimental effects. Design verification needs, on the other hand, are specific to particular concepts, dynamic, and generally change as progress is made. Testing of this nature should therefore be performed after concept selection, and be supported by analytical justification. Five basic blanket concepts and two basic shield concepts, shown in Table 2.1 have been identified.

Table 2.1 Blanket and Shield Concepts

Concept	Description
	Shields (Low Temperature, Nonbreeding)
I	Stainless steel structure with integral water cooling
II	Composite shield materials with internal cooling channels
	Blankets (High Temperature, Tritium Breeding)
I	Solid breeder in low pressure canister with integral cooling channels
II	Clad solid breeder in pressurized, coolant-filled module
III	Stagnant liquid metal breeder with integral cooling channels
IV	Flowing liquid metal breeder
V	Mobile solid breeder

The data needs for the shield concepts were found to be in the second category, so should be addressed later as designs mature. The data needs for blankets were found to be in the first category and must therefore be addressed as soon as possible in order to focus the direction and selection of designs. Priorities were accordingly developed identifying certain blanket types, specifically Type I, the low pressure solid breeder canister with coolant tubes, and Type II, the clad solid breeder in a high pressure module, which must be addressed as soon as possible. The basic thermal-hydraulic and thermomechanical data requirements for the solid breeder concepts are listed in Table 2.2. Investigation of these issues will be very helpful in selecting breeder materials and configurations (granules, packed beds or sintered pellets), operating temperature windows, and general design configurations for the blanket.

Table 2.2 Data Needs

THERMAL-HYDRAULIC DATA;

- Contact Resistance
  Heat Transfer Behavior Changes
  - Temperature
  - Time
- Effective Thermal Conductivity
- Purge Flow Distribution

THERMOMECHANICAL DATA:

- Thermal Ratcheting

From the evaluation of non-nuclear bulk heating simulation techniques, two material properties, electrical and thermal conductivities, are significant in determining which simulations can be useful in a given material. Usually a good electrical conductor is also a good heat conductor, so that the simulation approaches can be assigned priorities for each type of experiment in terms of whether the experiment involves conductors, nonconductors, or both. In the case of thermal-hydraulic (TH) tests, the distinction refers to the material which contains the fluid, since that is the material which is actually heated. In thermomechanical (TM) tests, the bulk materials involved are considered. For non-nuclear TH tests, discrete-source electrical resistance heating simulation is the most effective regardless of the containment material, mainly because of its flexibility and well-developed technology. Other choices for TH testing include direct resistance heating for experiments with conductive container materials and discrete source heating for experiments involving nonconductive materials and liquid metals.

For non-nuclear TM tests on conductive materials, direct resistance heating is the first choice. It has the advantage of providing bulk heat, while allowing some flexibility in generating spatial and temporal variations. Other primary choices for TM testing include microwave heating for tests on nonconducting materials and discrete source heating for tests which contain both conductors and nonconductors. For TH/TM experiments involving liquid metals, induction heating will be of low priority, due to the MHD forces generated.

2.2 Testing Strategies

Both the non-nuclear and nuclear testing strategies will consist of two phases consistent with the data need categories. The first phase is primarily concerned with addressing the critical issues identified for the various breeding blanket concepts. This encompasses very important predesign testing which will contribute to the evaluation and selection of various breeding blanket concepts. The second phase focuses on post-design component qualification. Critical components design will evolve during this time, currently estimated to begin approximately four years after the start of Phase 1.

2.2.1 Early Testing

All indications are that initial testing should be directed towards the investigation of the heat transfer characteristics of the solid breeder concepts. Critical go/no-go issues can be addressed at this early stage in the design to obtain information which is helpful in selection of the various concepts. This DTP is aimed at obtaining such basic information. Included are two single effect scoping tests to determine the heat transfer characteristics and the stability of the breeder blanket, and, an integral test to simulate all the non-nuclear aspects of the blanket. The heat transfer characteristics test is designed to investigate the effects of gaps and/or contact at the breeder/coolant tube interface. This information is essential to assure that temperature profiles in the breeder are maintained within acceptable levels so that there is an adequate tritium recovery rate and low tritium inventory, while preventing sintering and vapor phase mass transport of the solid breeder material.

The breeder bed stability test will investigate the effect of time at temperature. Sintering due to extended exposure at typical operating temperatures will affect tritium migration within the breeder and hence the tritium inventory. Mass transport of the breeder material constituents could affect the purge flow, heat transfer, and mechanical characteristics of the blanket.

The objective of the integral simulation test is to investigate the thermal-hydraulic and thermomechanical characteristics of a stainless steel cooling tube surrounded by solid-breeder material, a generic solid breeder blanket feature. This experiment addresses a number of issues simultaneously, including purge flow conditions, interface conductivity and thermal ratcheting. Accordingly, both the design and the interpretation of test results rely heavily upon the preceeding scoping tests.

2.3 Planned Tests

A somewhat detailed description of the tests mentioned in Paragraph 2.2.1 is given in this section.

2.3.1 Heat Transfer Scoping Test.

Successful operation of a breeder blanket demands that the heat generated by the fusion neutrons be removed in an efficient manner in order to avoid excessively high temperatures in the lithium compound. These high temperatures can cause sintering, affecting the physical and chemical stability of the blanket, and the tritium release rate from the blanket. Material interaction at the breeder/coolant tube interface can also result. Low temperatures can result in excessive tritium inventory.

The design of an efficient heat rejection system requires a thorough understanding of the heat transfer characteristics of the lithium compounds used as the tritium breeders. A similar understanding at the heat sink interfaces is required, as well as a knowledge of how these characteristics vary with temperature, nature of the materials, interfacial reaction layers, and contact pressure. This test will provide such information, which will also be needed for the design of the test article required later for the integral simulation test, and interpretation of the results. The following heat transfer characteristics will be studied:

- Effect of interfacial temperatures and gap size on the heat transfer coefficient between a Li_2O sample and a 316 stainless steel heat sink.

- Effect of interfacial pressure on the heat transfer coefficient between the sample and heat sink.

- Stability of the observed heat transfer characteristics.

2.3.1.1 Description of Experiment

The axial heat flow method is used to study the heat transfer characteristics. The experiment configuration is shown schematically in Fig. 2.1, using Li_2O as the lithium compound and 316 stainless steel as the heat sink. Two sets of experiments will be performed using Li_2O and $LiAlO_2$. The test conditions are given in Table 2.3.

A 316 stainless steel rod, 2.5 cm. in diameter, is heated at one end in a furnace to a predetermined temperature, to serve as the heat source. The heat flows axially through the Li_2O sample which is held in contact with the cooler end of the stainless steel rod (Fig. 2.2), and then across the interface between the sample and the heat sink. One end of the heat sink faces the sample, the other end is cooled with a clamp-on cooling coil. Insulation and heaters surround the various axial locations of the assembly to minimize radial heat loss. Sensing thermocouples are placed at different axial locations and radial positions to monitor the heat flow. The desired interfacial gap between the sample and the heat sink is obtained by sliding the heat sink and fixing its position by means of two sliding collars on

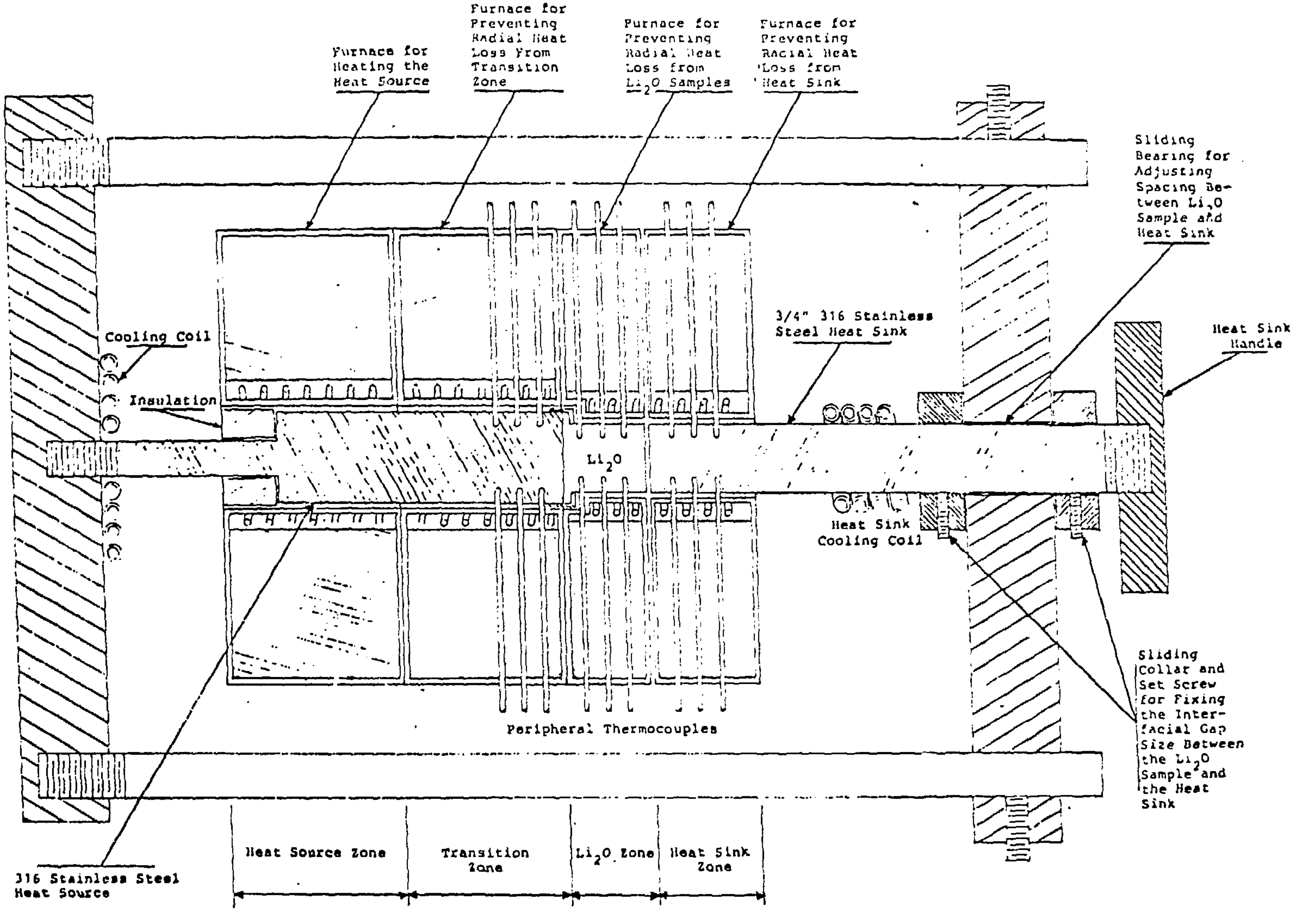


Fig. 2.1 Schematic Arrangement for Heat Transfer Characteristics Test.

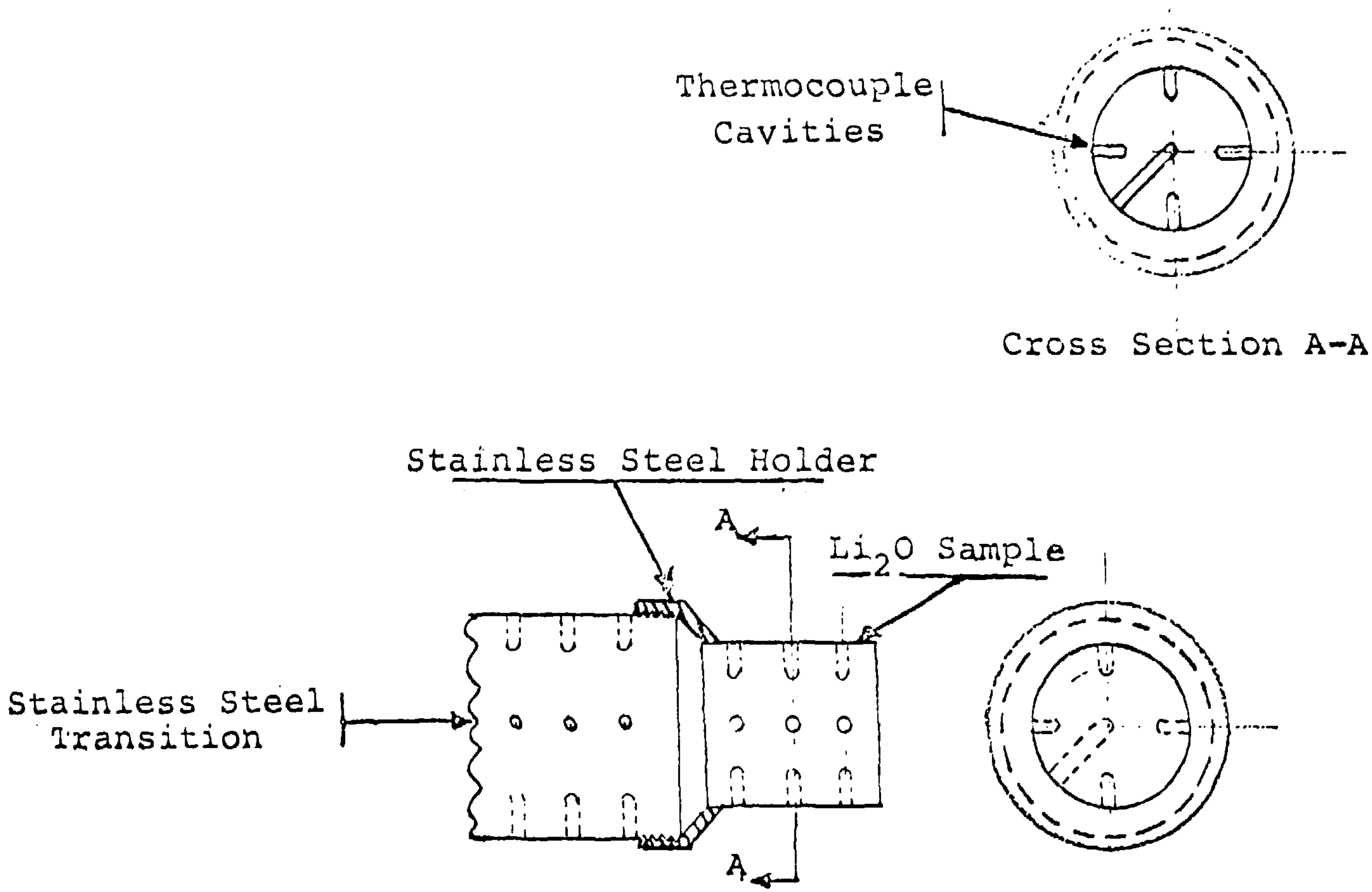


Fig. 2.2 Li_2O Sample.

opposite sides of the sliding bearing. The gap is filled with helium at 1 atmosphere pressure by situating the whole experimental arrangement in an enclosure through which helium of controlled moisture and oxygen content flows. Contamination of Li_2O by moisture and CO_2, and oxidation of the heat sink is thus prevented.

The effect of interfacial pressure on heat transfer across the Li_2O heat sink interface is studied by standing the test fixture upright so that the heat sink rests on top of the Li_2O sample. Weights placed on the flat face of the heat sink handle produce the interfacial pressure desired. Various

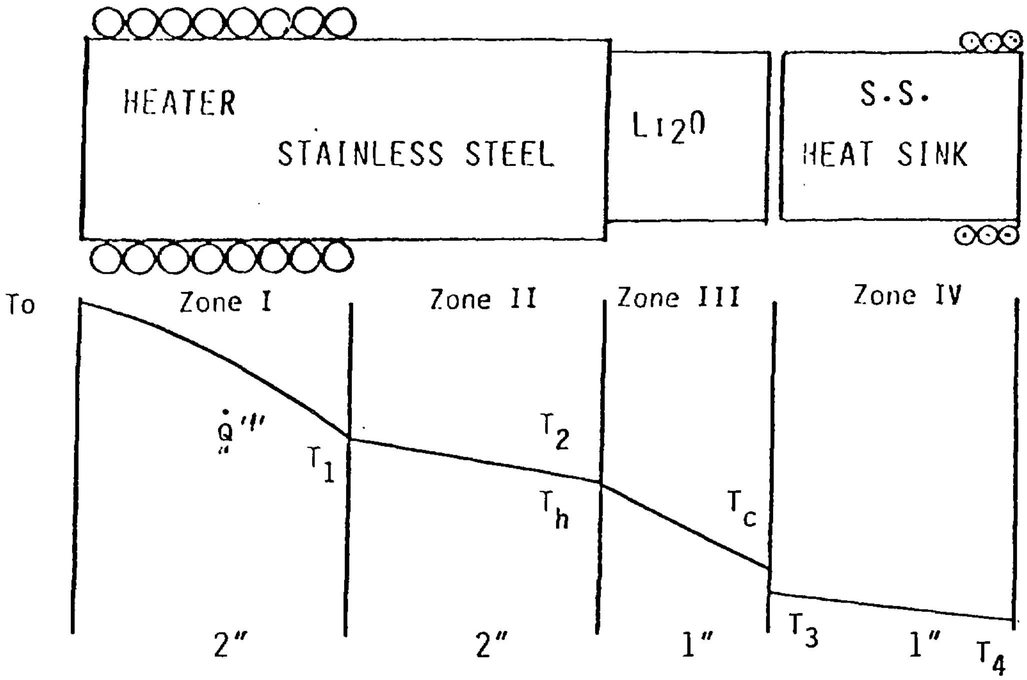
Table 2.3 Heat Transfer Scoping Test

Testing Conditions	
Breeder materials	Li_2O, $LiAlO_2$
Breeder temperature range, °C	300 to 800
Breeder/coolant tube gap temperature, °C	100 to 500
Gap range, mm	0 to 1.0
Gap contact pressure, kPa	0 to 300

effects can be studied by changing the position and the magnitude of the heat input to the heat source and the rate of coolant flow in the cooling coil so that the temperature of the Li_2O sample and the interfacial temperatures across the heat sink gap are varied.

The detailed experimental design and test plans will be developed during the early stages of Phase I. The experimental studies will cover a temperature range 500° - 800°C for the Li_2O sample, 100° - 500°C at the surface of the heat sink facing the Li_2O sample, an interfacial gap size 0 - 1.0 mm and interface pressures 0 - 300 kPa. One-dimensional (1-D) heat transfer calculations were made to give an indication of the temperatures at different locations of the proposed experimental apparatus. A simplified 1-D schematic diagram of the experiment and results of the calculations are shown in Fig. 2.3. The model consists of the heater zone where the heat is transferred radially into the stainless steel and then conducted axially

TEMPERATURE DISTRIBUTIONS



ASSUMPTIONS: 1-D CONDUCTION HEAT TRANSFER

$T_2 = T_H$

$K_{Li_2O} = 3\ W/m \cdot K$

$K_{SS} = K_{SS}\ (TEMP)$

VOLUMETRIC HEAT GENERATION AT THE HEATER ZONE

RESULTS:

H (W/m^2K)	T_0	T_1	$T_2 = T_H$	T_c	T_3	T_4 (°C)
3000	680	630	516	116	100	20
300	831	781	667	267	100	20

Fig. 2.3 Heat Transfer Scoping Test

towards the heat sink. In addition to obtaining the previously mentioned primary characteristics for which the test was designed, additional heat transfer information, primarily the effect of the Li_2O temperature on the effective thermal conductivity of the pellet, can be readily obtained. This information will be evaluated and made available to other fusion programs, such as the materials program.

2.3.1.2 Li_2O Sample Fabrication

Li_2O cylindrical pellets, 80% dense, 2.5 cm diameter and 2.5 cm length will be prepared by cold pressing and sintering techniques developed for the TFTR LBM program, using high purity Li_2O powder. These pellets will be ground with a diamond wheel under xylene to insure that the top and bottom surfaces are parallel and the diameter is uniform. Cavities for accommodating 0.5 mm diameter sheath thermocouples will be drilled under xylene as shown in Fig. 2.2. The finished pellet will be outgassed in vacuum to remove organic solvents, H_2O and CO_2, and stored in a sealed container prior to incorporation into the experimental apparatus. Similarly, a second set of samples will be made of $LiAlO_2$.

2.3.1.3 Test Data Analysis

For each set of testing conditions (i.e., Li_2O temperature, interfacial temperature, gap size, and interfacial pressure), the steady state axial heat flux can be calculated from the temperature gradient in the heat sink and the thermal conductivity of the 316 stainless steel. The thermal conductivity of the Li_2O sample can be calculated from the heat flux and the temperature gradient in the Li_2O sample.

To calculate the heat transfer coefficient across the gap between the Li_2O sample and the heat sink, it is necessary to know the Li_2O and heat sink surface temperatures at the interfacial gap. These temperatures can be obtained by extrapolating the axial thermocouple readings as a function of position in the Li_2O and in the heat sink. The heat transfer coefficient is then calculated from the steady state axial heat flux, the Li_2O and heat sink surface temperatures, and the gap size.

The test data should yield the following information:

- Heat transfer coefficients across the Li_2O heat sink gap as a function of interfacial temperature, gap size, and interfacial pressure.

- The effective thermal conductivity of the Li_2O pellet as a function of temperature.

These results will be used for the design of the test article for the integral simulation test.

2.3.1.4 Post-Test Examinations

After completion of the measurements described above, the sample, stainless steel heat source and heat sink will be subjected to the following:

- The microstructure of the Li_2O sample will be examined for any change in density, grain size, or pore structure.

- The heat source surface in contact with the Li_2O sample will be inspected for any interaction between Li_2O and 316 stainless steel at the heat source temperature.

- The heat sink surface in contact with the Li_2O sample will be checked for any interaction between Li_2O and 316 stainless steel.

Findings will help explain any observed instabilities of the heat transfer characteristics and any discrepancies between the observed thermal conductivity and heat transfer coefficient data, information in the literature, or calculated values. They will also be useful in the design and interpretation of the results from the integral tests.

2.3.1.5 Schedule

The schedule shown in Fig. 2.4 assumes that testing for both materials currently being considered, Li_2O and $LiAlO_2$, will be done sequentially with no time lapses between steps. A natural break occurs after testing the first material. The second material testing could be delayed as required.

2.3.2 Breeder Bed Stability Scoping Experiment

Tritium generated from the lithium compound used as a breeder is swept out continuously with a helium purge gas. Change in the pore structure of the lithium compound by sintering and vapor transport of those components having high vapor prerssure, however, may change the impedance of the flow path and affect the tritium extraction process. Furthermore, any rapid thermal cycling of the blanket may develop cracks in the lithium-containing breeding compound due to differential thermal expansion. The fragments formed may lodge themselves in the gap between the breeding compound pellets and the container and cause damage during subsequent heatup. This scoping test will investigate these effects by performing a long term flow test and thermal cycling study of a blanket bed simulated with Li_2O pellets clad in 316 stainless steel at temperatures of interest ($\sim$400° to 850°C). A second test will be conducted using $LiAlO_2$ with essentially the same experimental procedure.

2.3.2.1 Description of Experiment

The detailed experimental design and test plans will be developed during the early stages of Phase I. The experimental arrangement is shown schematically in Fig. 2.5. Six Li_2O pellets (of nominal 80% theoretical density) 2.5 cm diameter and 2.5 cm length are packed into a 316 stainless steel tube of 0.4 cm wall thickness, with a diametrical clearance of

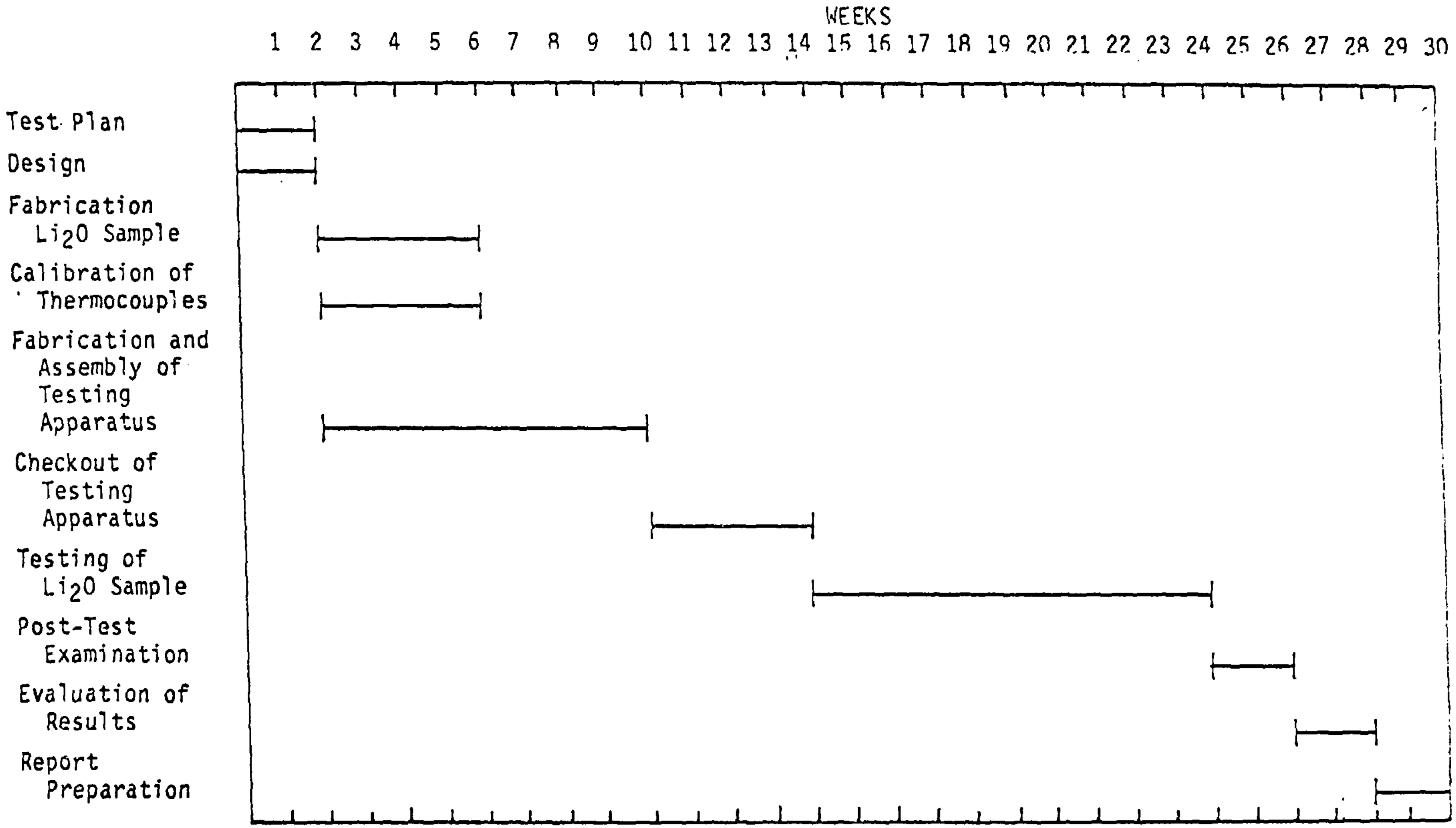


Fig. 2.4 Heat transfer scoping test schedule

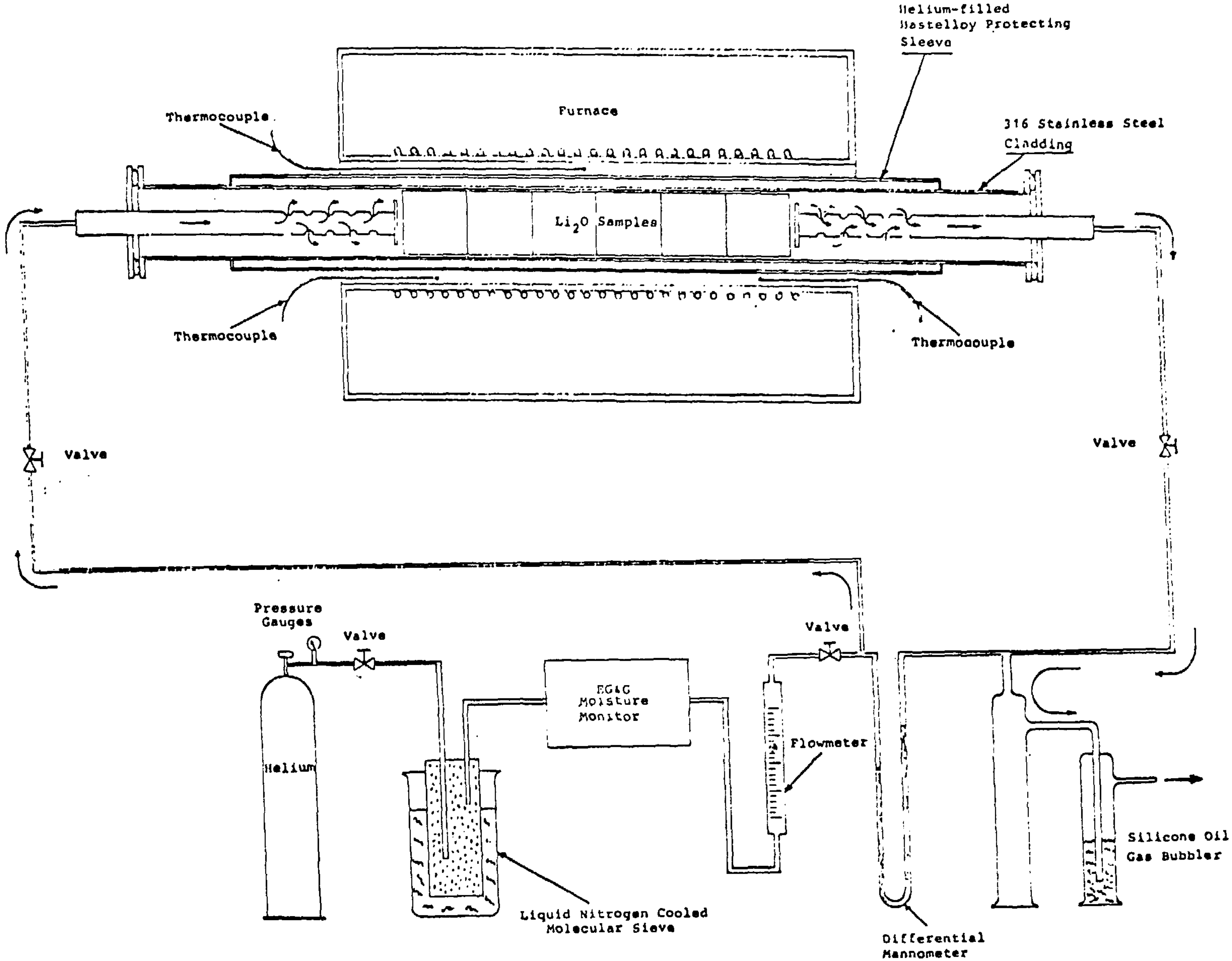


Fig. 2.5 Schematic Arrangement for Flow and Thermal Cycling Tests.

0.125 cm. To protect the stainless steel cladding from oxidation when the assembly is heated to high temperatures in air, it is surrounded by a Hastelloy jacket filled with helium at 1 atmosphere. The ends of the stainless steel tube are provided with copper-gasket sealed flanges with stainless steel tubing for the helium purge gas entrance and exit. The assembly is heated to the desired temperature in a furnace, with the temperature monitored by thermocouples to ensure that the Li_2O-loaded zone is kept within ± 15°C during the 1000 hr. test. The purge gas, flowing at a rate of 100 cc/min, will be 99.9% purity helium. Impurities such as H_2O and CO_2 will be removed using a liquid nitrogen cooled trap containing a molecular sieve.

The gas flow rate will be measured with a sapphire ball flowmeter and its moisture content will be measured with an EG&G moisture monitor. The exiting purge gas passes through a safety trap and a silicone oil bubbler prior to venting into the atmosphere. The pressure drop across the Li_2O-loaded zone is measured with a differential mercury manometer. The furnace is of the clam-shell type, allowing rapid cooling of the test assembly during the thermal cycling study by swinging the upper half of the furnace open.

The Li_2O test pellets will be similar to those described in paragraph 2.3.1.2, outgassed in vacuum to the highest temperature planned for the test, to remove impurities. $LiAlO_2$ pellets will be made using the same procedures.

Three tests of 1000 hr duration each are planned at temperatures of 600°, 800°, and 1000°C, respectively. Thermal cycling will be done manually from operating temperature to room temperature to determine its impact on the breeder bed stability. Ten cycles will be performed at each test temperature over 300 and 600 hr. periods. Two cycles per day (24 hr.) are planned for the final 100 hr. period. Table 2.4 summarizes the testing conditions.

Table 2.4 Breeder Bed Stability Scoping Test Testing Conditions

Breeder materials	Li_2O ($LiAlO_2$)
Breeder temperatures, °C	600, 800, 1000
Helium purge gas flow rate, cm^3/min	100
Number of temperature cycles	10

The proposed helium purge flow rate of 100 cc/min. through the Li_2O canister when normalized to the volume of Li_2O is equal to a flow rate of 0.021 cm^3/sec per cm^3 of Li_2O. This is similar to the STARFIRE design which has a value of 0.056 cm^3/sec per cm^3 of $LiAlO_2O$. Assuming a 15% diffusive flow area through the 80% dense Li_2O pellet, the corresponding helium flow velocity is 0.022 m/sec. This velocity will not have any convective heat transfer significance. The energy loss associated with heating the purge flow from 20° to 500°C was calculated at 0.29 watts, which is also negligible. Table 2.5 summarizes purge flow characteristics.

Table 2.5 Breeder Bed Stability Test

Purge Flow Characteristics

Helium flow rate	100 cm^3/min 0.021 cm^3/sec-cm^3
Helium velocity	0.022 m/sec
Convective heat transfer	Negligible
Power loss to purge flow	0.3 W

2.3.2.2 Post-Testing Examination

After completion of each test, the density of the Li_2O pellets will be determined by mercury porosimetry and the loss of materials due to transport in the purge gas flow will be determined by weighing the pellets. The macroscopic appearance and the microstructures of each pellet will be examined for any cracks and changes in grain size and pore structures. The stainless steel containment will be examined for any reaction with Li_2O in the hot zone and any condensation of materials in the cold zone. These results will be correlated with any change in differential flow pressure across the Li_2O zone during the flow test and the thermal cycling study.

2.3.2.3 Schedule

The schedule for the purge flow test is shown in Fig. 2.6; it assumes that testing at all three temperatures is performed sequentially with no time lapses between steps. Delaying the last temperature test can be done without significantly affecting the overall costs.

2.3.3 Integral Simulation Test

The Solid Breeder Blanket Concept Integral Simulation Test Series builds upon the information developed in the preceeding two scoping test series and provides non-nuclear integrated-effects data for a prototypal design, as discussed in the previously noted strategy reports by Veca and Deis. The particular configuration will, of course, be influenced by results from the earlier scoping tests, and by results from other experimental and design-development programs. The objective is to provide integrated-effects information on purge flow characteristics, effective thermal conductivity, temperature distributions, and the thermomechanical behavior of solid breeder materials, all in a prototypal environment. These needs all relate to Type I blanket concepts, which involve solid breeding materials in low-pressure modules with high-pressure coolant tubes embedded in the breeder, as typified by the INTOR and STARFIRE designs. Since all Type I blanket concepts involve the generic feature of a coolant tube surrounded by breeding material, the operating characteristics of this feature are extremely important.

The central concern in this test series is to examine a number of integrated effects under realistic conditions, in order to understand their inter-relationships and possible synergisms. The specific goal is to provide data on the following:

a) the effect of temperature and time on the effective thermal conductance of the breeder material
b) the effect of temperature and time on the purge flow conditions
c) bulk thermal ratcheting of the breeder material
d) thermal ratcheting at the material/tube interface
e) the effect of ratcheting on bulk breeder effective conductance
f) the effect of ratcheting on the interface conductance.

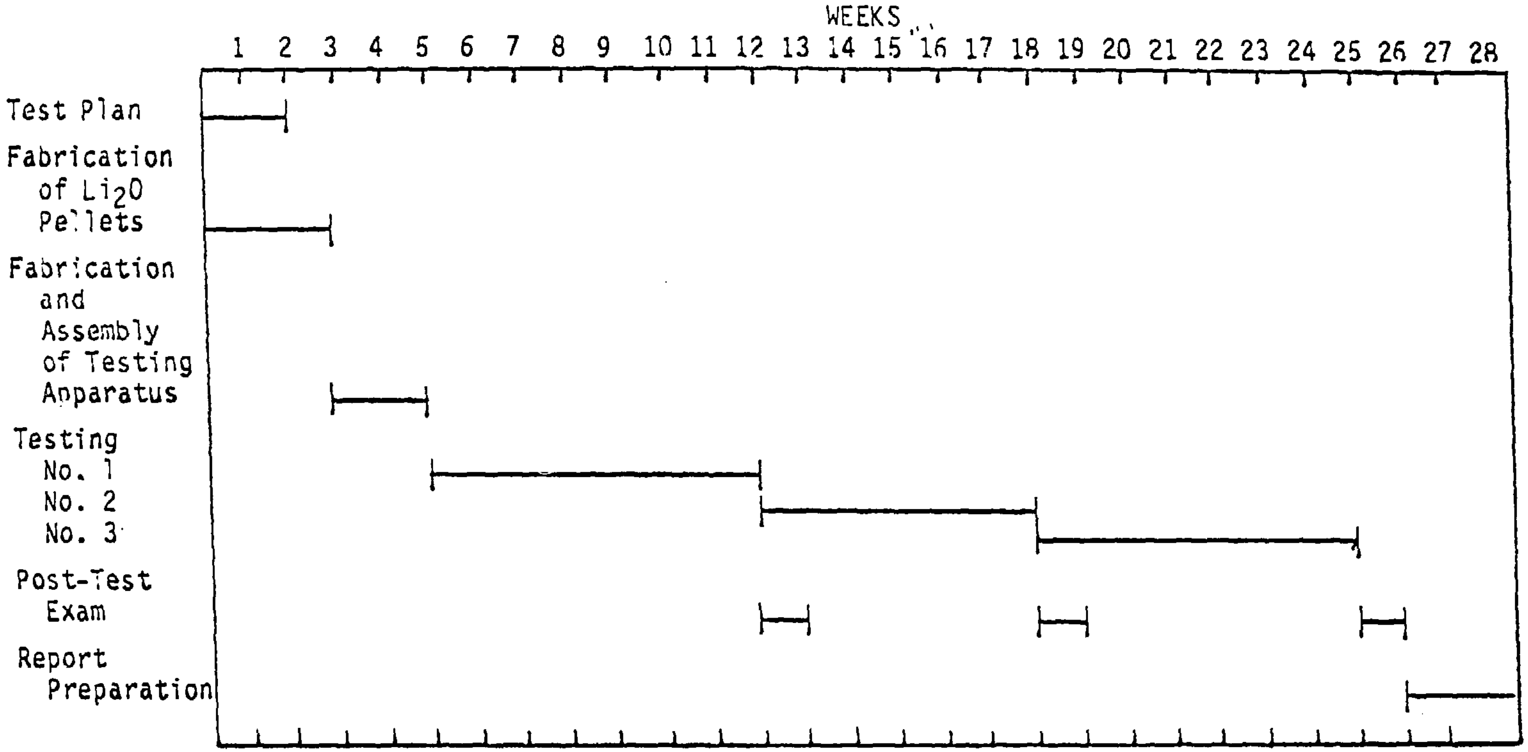


Fig. 2.6 / Breeder bed stability scoping test schedule

The data will be obtained from a realistic breeder/coolant tube test article operating at prototypal temperatures and heat fluxes, with a helium purge stream.

Because of the design of this experiment, significant information can also be provided on a number of other issues, including:

a) temperature/time dependence of breeder material sintering

b) material interactions at operating temperatures

c) breeder material transport (vaporization)

d) interface conductance

Although these are not primary goals of the experiments, the information can be obtained at little or no additional cost, and without compromising the goals listed previously.

2.3.3.1 Approach

The approach adopted in this experimental series is to employ a test article which simulates a unit cell of a Type I blanket concept. This unit cell consists of a stainless-steel coolant tube containing water coolant, surrounded by a cylinder of solid breeder material. The outer diameter of the breeder material is selected such that it represents an approximately adiabatic surface in an actual Type I blanket design. The internal design of the test article also simulates the actual design, employing prototypal coolant tube characteristics, gap dimensions, breeder material configurations, and purge flow configurations. The test article is subjected to an external heat flux, in a large vacuum furnace. This heat flux, which simulates the temperature profile resulting from nuclear heating, is selected to yield operating temperatures comparable to those expected in an actual blanket with nuclear heating. In one test, a cyclic heat flux is applied to simulate the heating history expected in tokamaks.

With this general approach, information on all five principle data needs can be obtained in an integrated-effects environment. Information on a number of other important, but secondary, issues, and on some synergistic effects will also result.

2.3.3.2 Planned Testing

Two individual tests, one addressing steady-state heating, and one addressing cyclic heating are planned. Both employ the test facililty and test article shown in Fig. 2.7. The facility, a large vacuum furnace, provides test space for a cylinder as large as 18 cm in diameter and 79 cm high. The proposed test article consists of a 5 cm diameter cylinder of Li_2O breeder material approximately 79 cm long, enclosed in an outer canister, with a central 1 cm diameter re-entrant water cooling tube. Provisions are made for a purge flow of helium gas around and through the breeder material.

Each test assembly is installed in the furnace, and support equipment and instrument leads connected. The furnace is evacuated and possibly backfilled with helium or argon. Water coolant and helium purge gas flow is established.

For the steady-state test, the power is increased slowly to maximum, perhaps over two hours, with all data measurements recorded. The maximum power level is initially determined analytically, based on information obtained during the scoping tests. Adjustments, based on observed test temperatures bring the temperatures within the desired range. For Li_2O, the maximum breeder material temperature will be approximately 850°C, which requires the application of approximately 5 kW of heat to the test article. Following the attainment of steady-state conditions at maximum power, the test is continued for at least 1000 hours, with detailed measurements being recorded every 12 hours throughout. Test shutdown will take place over several hours and be closely controlled and monitored.

For the cyclic heating test, the power is increased and decreased much more rapidly. The exact heating procedure to be followed has not yet been determined, but two possibilities have been identified. One possibility is to simply change the power as rapidly as possible without damaging the furnace heating elements. The other possibility would be to control the heating power in order to produce some desired temperature history on the outside of the breeder material. The advantage of the first approach is that it is easier to accomplish, but it will not simulate actual nuclear heating transient

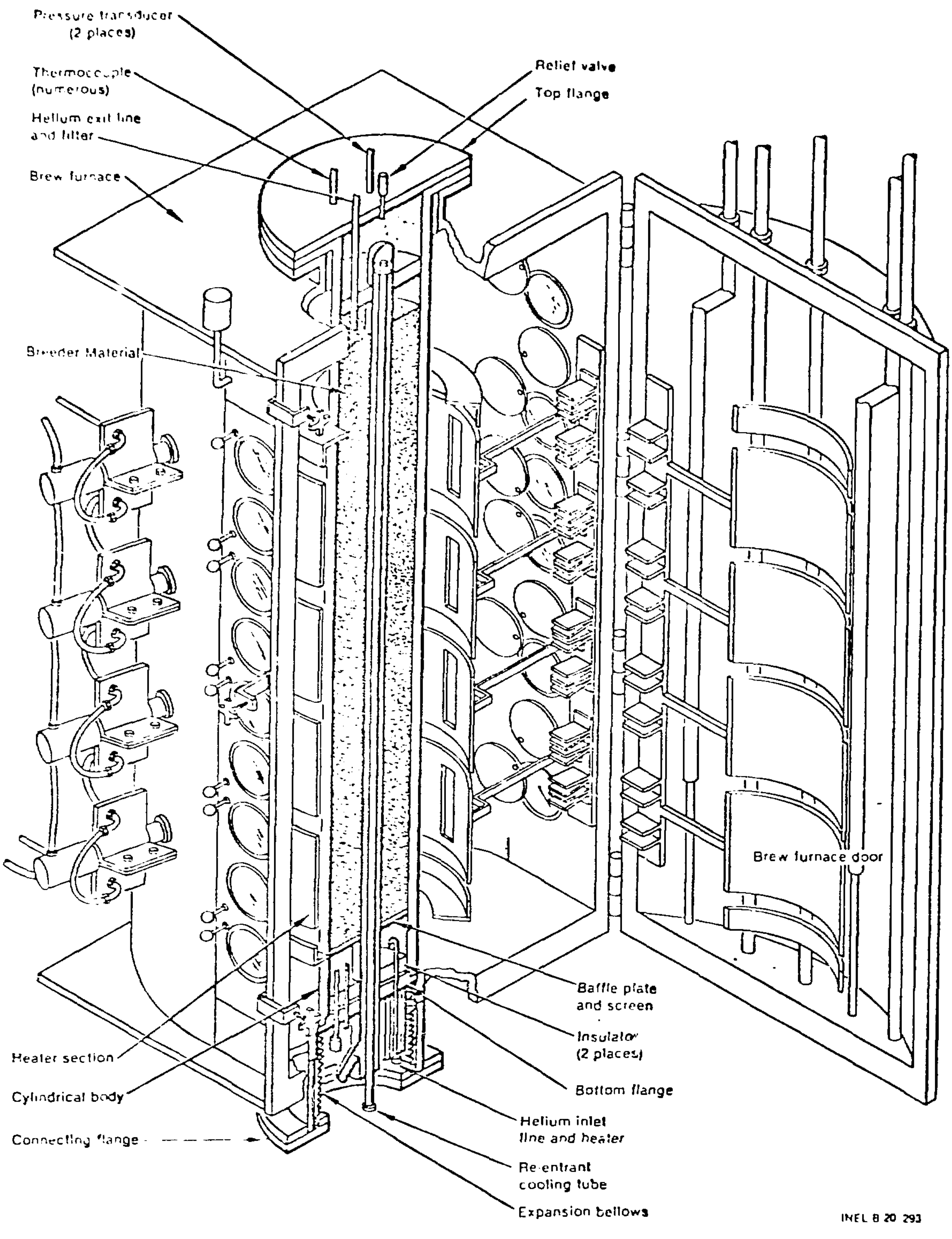


Fig. 2.7 Isometric view of Solid Breeder Blanket Concept Integral Simulation test, with test assembly shown sectioned and not to scale.

temperature profiles as well as the second approach. The disadvantage of the second approach is that it requires some form of closed-loop control, and is therefore more difficult to accomplish. A choice will be made following further analyses.

Regardless of which approach is employed, the major characteristics of the heating cycle are selected to simulate actual tokamak heating, and consist of a 100-200 sec full-power heating period, followed by a 25-50 sec zero-power dwell period. The cycle is applied to the test article, initially at ambient temperature, and detailed measurements are made every 30 sec until pseudo-steady state is attained (that is, when the maximum and minimum temperatures during the cycle do not change appreciably from cycle to cycle). After this time, data are taken approximately every 12 hours by making detailed measurements every 30 sec during one or several complete heating cycles. After approximately 1000 hours of pseudo-steady state operation, the heating is discontinued and detailed measurements are made every two minutes during the shutdown transient.

Following actual testing, the test assembly is allowed to cool completely to ambient temperature, after which the support systems and instrumentation systems are disconnected. The furnace is then vented to air, and the test canister is removed and taken to the appropriate facility for post-test examination. During this process, the breeder material is maintained in an inert atmosphere by isolating the purge system. Immediately following removal of one test article from the furnace, another can be installed and testing started, if desired.

2.3.3.3 Test Facility

The "Big Brew" facility, located at the Idaho National Engineering Laboratory (INEL) matches the testing requirements and is available for the FWBS ETP. The specifications are shown in Table 2.6. This large, high-temperature furnace has four separately controllable heat zones, each of which is 18 cm in diameter and 20 cm high. The usable working space inside the furnace is approximately 18 cm in diameter and 79 cm high. There are work access ports 20 cm in diameter at each end of the furnace and four viewing and instrument lead windows 7.6 cm in diameter at each zone. The chamber itself has a large hinged door that extends the entire length to allow easy access to internal components or test assemblies.

Table 2.6 Brew Facility Specifications

Heating Capability

Power: 530kW

Test Volume: 18 cm dia x 79 cm long

Equivalent Heat Flux: 120 W/cm^3

Engineering Data

Heating Element Size: 18 cm dia x 20 cm high

Maximum Temperature: 3000 C in vacuum, 2700 C in helium

Temperature Uniformity: 10 C

Heating Element Material: Tungsten mesh

Heat Shield Material: Tungsten sheet

Operating Vacuum: 5×10^{-5} Torr

Ultimate Vacuum: 1×10^{-6} Torr

Facility Requirements

Electrical: 530 kVA at 480V, 3 phase, 60 Hz

Water: 3.5 l/sec (54 gpm) at 25 C maximum and 0.3 MPa (50 psig) minimum

Air: 0.3 MPa (50 psig) minimum

Heating is by tungsten mesh. The maximum rated temperature of the furnace depends on the atmosphere in the test chamber, as follows:

a) 3000 C in vacuum (operating vacuum 5×10^{-5} torr)
b) 2500-2700 C in high-purity helium
c) 2000-2300 C in high-purity argon
d) 2000 C in hydrogen

The temperature uniformity of the heating elements is within 10 C.

Each of the heat zones is separately controllable. Controls are manual, or one or more zones may be tied to a single pre-programmed temperature cycle. Each heat zone is surrounded by separately controlled, water-cooled copper heat sinks just outside the heating elements, isolated from the heating elements by a five layer tungsten radiation shield.

The system has been checked up to a temperature of approximately 800 C, without encountering major problems. All utilities (power, air, and water) are connected.

2.3.3.4 Test System Description

The test system consists of the Brew furnace facility, the test assembly itself, the necessary test assembly support systems, and the instrumentation.

The test assembly (Fig. 2.8) is lowered into the Brew furnace from the top, using the facility crane. It consists of five parts, namely:

a) solid breeder bed
b) cylindrical body
c) top flange
d) bottom flange
e) cooling tube

A number of options for the breeder material composition and physical structure have been considered but there is no clear choice at present. The principal candidate materials were Li_2O and $LiAlO_2$. Each of these two materials can be used in a number of physical forms, including: packed (unsintered) powder, packed (pre-sintered) "minipellets", large pressed-and-sintered pellets, and large slip-cast shapes with bi-modal pore distribution. The last alternative (slip-cast shapes) was selected for the STARFIRE and DEMO studies, and therefore is considered the most "likely" of the various options. However, neither Li_2O nor $LiAlO_2$ are currently available in this form in sufficient quantity for this experiment. The other material forms can be fabricated now with little or no development effort, but are featured less prominently in blanket conceptual designs. The packed powder approach, the simplest to actually produce, is expected to be subject to rapid sintering at operating temperature. Similarly, a bed of packed minipellets is expected to experience extreme thermal ratcheting problems. Pressed-and-sintered pellets, although not subject to these particular problems, have not been produced in sizes larger than 2.5 cm diameter and 2.5 cm long. It is felt, however, that the existing technology can be extended to produce pellets

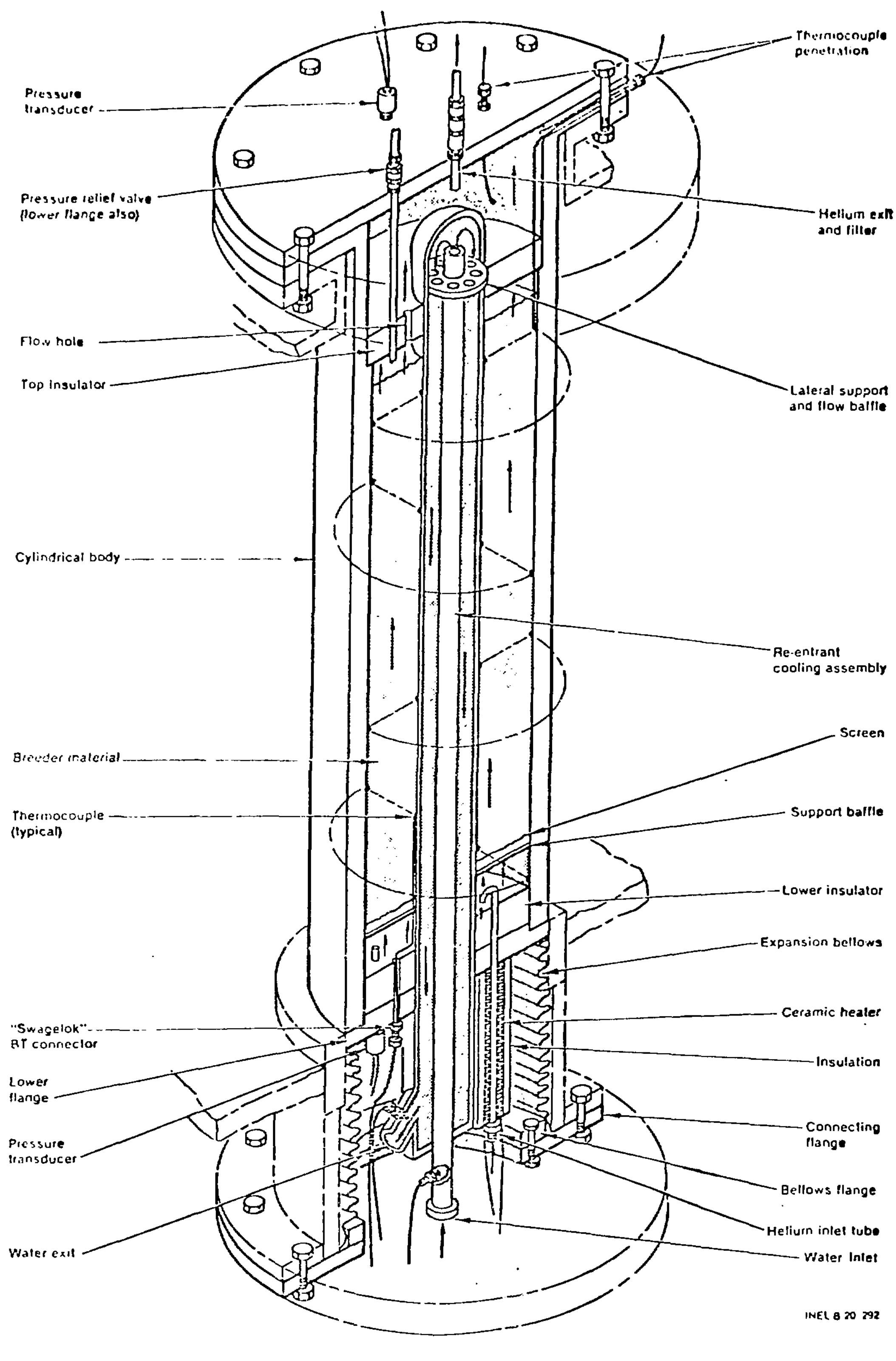


Fig. 2.8 Isometric cutaway view of the test assembly.

of 5.0 cm outer diameter, 2.5 cm long, with a 1 cm axial hole in the center, by a modest development effort.

This experiment is not strongly dependent upon a particular choice so Li_2O pressed and sintered pellets were selected, based on the experience of GA in this area.

Annular Li_2O pellets of 5.0 cm outer diameter, 1 cm inner diameter, and 2.5 cm length will be fabricated at 80% density by the techniques developed under the TFTR LBM program. They will be ground under xylene with a diamond wheel to uniform diameter and parallel end surfaces. The ground pellets will be outgassed in vacuum at the highest temperature planned for the test to remove impurities. About 40 such pellets are required for each test, in addition to 5-10 extra pellets for pre-test material characterization. The pellets are stacked, with the coolant tube in the center hole, inside the cylindrical body. The pellets rest on a lower baffle plate which supports the pellets vertically while allowing gas flow with little pressure drop.

The body of the test assembly is a Type 430 stainless steel tube, approximately 5 cm inner diameter and 120 cm long. Type 430 stainless steel (a no-nickel stainless steel) was selected on a preliminary basis, because of its predicted compatability with lithium compounds and acceptable mechanical properties up to approximately 900 C. A flange welded to the top end interfaces with the Brew furnace. A flanged bellows arrangement at the bottom end accommodated the difference in thermal expansion between the test assembly and the furnace. The flange seals are capable of withstanding elevated temperatures. An alumina-silica insulating disk located at each end will reduce axial heat loss and aid in attaining a uniform axial temperature profile across the breeder material. A perforated baffle plate located at the lower end of the pipe provides vertical support for the solid breeder pellets and allows gas transport with little pressure drop. Helium purge gas supplied to the bottom of the breeder material at approximately 20 psig exits at the top. Over pressure protection is provided. A stainless steel cooling tube extends upward to within 5 cm of the lower surface of the top flange. The water flows up the inner tube and down through an annulus between the inner and outer tubes; re-entrant design reduces the axial temperature gradient. Helium and water conditions are typical of reactors such as INTOR and STARFIRE.

2.3.3.5 Instrumentation

Commercially available instrumentation is used throughout. Eight thermocouples are attached to the inner surface of the cylindrical body itself, two in each heat zone for control and safety of the experiment, as well as to yield experimental data. Similarly, eight thermocouples are located on the outer surface of the central cooling tube for control of the cooling system and to yield experimental data. Finally, 16 thermocouples are placed in contact with the breeder material itself. These allow benchmarking of the effective breeder conductivity and the conductance of the interface between the structure and the breeder. It would be extremely desirable to include thermocouples within the breeder material itself, centered between the inner and outer surfaces to improve the measurements of effective conductivity and interface conductance. However, a cost-effective procedure has not been conceived for accomplishing this. An automatic data logger will be employed to record the detailed experimental data. In addition, strip-chart recorders will be used to maintain a continous record, in order to fully document any unanticipated events. The presence of an operator during operation of the Brew furnace does not warrant further sophistication.

2.3.3.6 Material Characterization

Pre and post-test examination will establish if any significant change has taken place in the breeder material condition during a test. Examinations will include measurements of density, porosity, and microstructural examination, all of which relate to sintering, plus determination of chemical changes. Measurements of all of these parameters will support the description of the processes taking place. The assumption is made that the materials are not too fragile for sectioning and that corners can be removed for a detailed analysis. Metallographic examinations will be made on the microstructures (porosity, grain size) of a cross section of the Li_2O pellet along the temperature gradient. Quantitative metallography will determine the porosity distribution along the temperature gradient. Attempts will be made to take core samples along the temperature profile to determine the apparent and true densities, and consequently, the open porosity fraction. Scanning electron microscopy will be employed to determine the morphology of the pores along the temperature gradient. A comparison with similar data obtained from characterization of the material before testing will be made.

2.3.3.7 Test Schedule

The schedule for conducting this series of tests is shown in Fig. 2.9. It is assumed that the tests are conducted sequentially, with time allowed between tests for analysis. This will allow modification of the test conditions for the second test, to make maximum use of each experiment.

2.3.4 Nuclear Test Planning

An additional activity to be conducted during the first two years of Phase I is initial planning for a fission-reactor-based test. As was pointed out in the Nuclear Test Strategy document, the near-term non-nuclear tests recommended in both the nuclear and non-nuclear strategies are identical. This circumstance allows the choice of whether or not to pursue nuclear testing to be made later in the program.

However, immediate planning for a nuclear test is important for two reasons. First, a planning effort of modest scale can produce significant information concerning possible test configurations, useable reactor facilities, and tentative costs and schedules. This information is vital in deciding when to initiate a nuclear test effort. The second reason that early planning is important is that nuclear tests will require more extensive planning and preparation than similar non-nuclear tests. Early planning can set the process in motion, effectively reducing the preparation time required when the actual nuclear test effort begins.

The particular type of nuclear test which will be investigated in the first years of Phase I will address Type I blanket thermal-hydraulics and thermomechanics issues. This test will be a natural extension of the test program and will feature a test article similar to that in the Integral

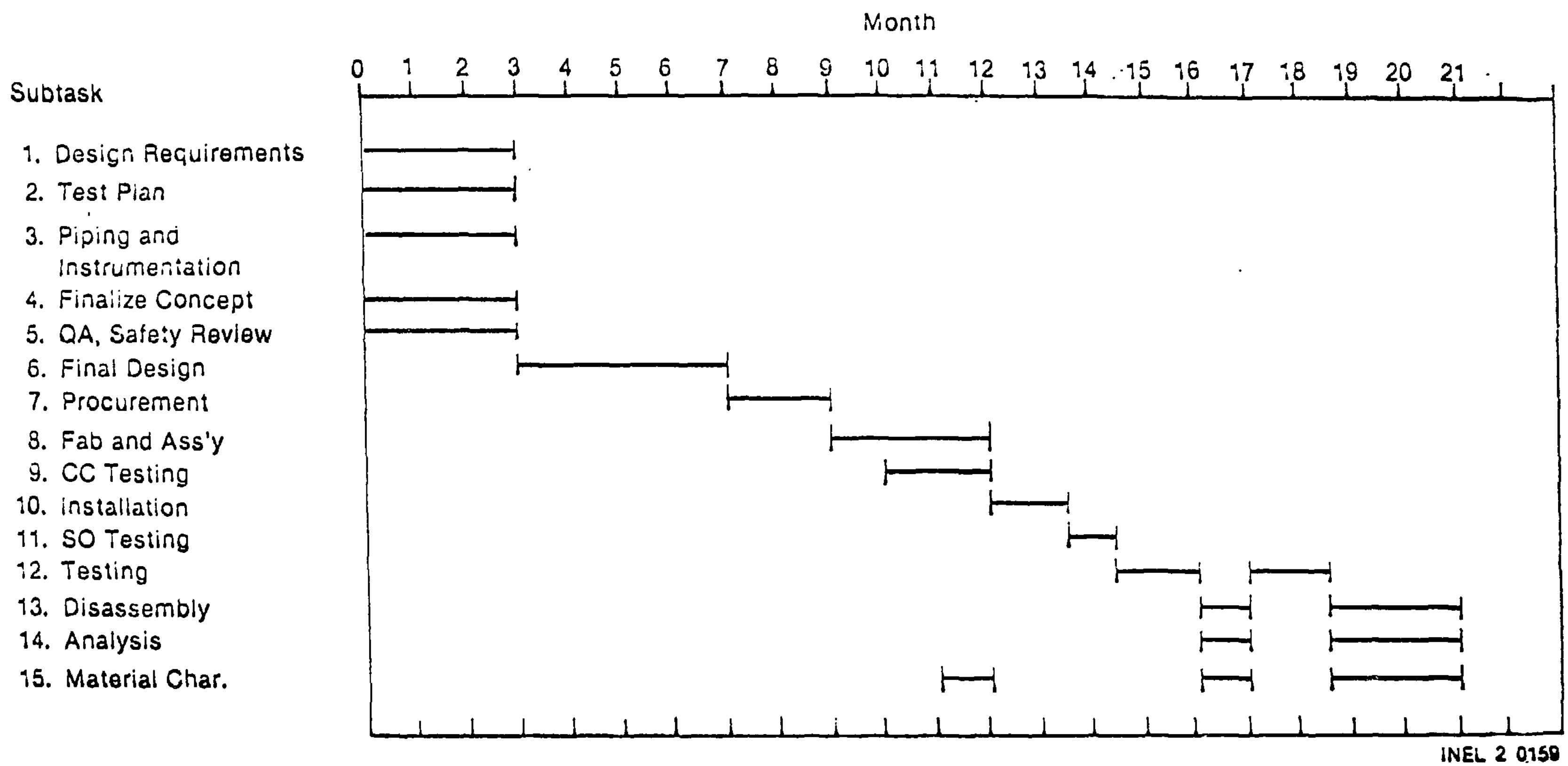


Fig. 2.9 Proposed schedule for the Solid Breeder Blanket Concept Integral Simulation Tests.

Simulation Test in general configuration; that is, a test piece which is a "unit cell" of a Type I blanket concept, including one or more coolant tubes surrounded by solid breeder material, with a helium purge system. However, in the nuclear test, true bulk heat will be provided by neutron/gamma radiation. This will allow significant improvement over non-nuclear experiments in the simulation of both thermal-hydraulic and thermomechanical effects. The specific goals of the experiment include investigations of the following:

a) Purge flow conditions

b) Heat transfer conditions

c) Thermal ratcheting effects

d) Tritium production and removal

Initial effort in this planning task will be to investigate candidate reactor facilities, and produce sketches of the configurational envelopes for each. Following this, a preliminary test program will be developed along with a pre-conceptual design of the test articles. If funding permits, preliminary schedules and cost estimates for the test program will also be made.

2.3.5 Future Plans

Three types of activities in the Post Phase I time frame are anticipated. The first of these is a continuation of concept verification testing with non-nuclear scoping and simulation tests, the second is the beginning of design verification testing and the third is initiation of fission-based nuclear testing.

2.3.5.1 Further Concept Evaluation Testing

A set of experiments aimed at investigating the basic data needs for blanket Types I through IV were defined in the Data Needs Assessment Report. These are summarized in Table 2.7. This testing builds on that described earlier for the solid breeder concepts, and also initiates scoping tests for other blanket types which use liquid metal breeders. The first Phase I test described previously for Blanket Type I includes only a narrow range of solid breeder materials. With additional funds, more material and material configuration options could be included. Additional materials and material configurations that could be investigated will depend upon the results of on-going activities such as the STARFIRE/DEMO study. Candidate materials include $LiAlO_2$ and Li_2SiO_3; configurations include packed beds of minipellets, microspheres, granules and powder as well as the Li_2O sintered pellets being pursued in the first series of tests. If the design studies show these alternatives to be attractive, additional series of tests would be performed.

Table 2.7 PE-II Phase I Non-nuclear Testing

	Blanket Design Concept			
	I	II	III	IV
Scoping Experiments	1	(a)	2	(b)
Flow Tests	2	2	(c)	3
Integrated Simulation Tests	1	2	3	4

Number denotes order of beginning the tests during the initial years of TPE-II Phase I.

(a) Same as, and already done by scoping tests for Blanket Type I.
(b) Same as, and already done by scoping tests for Blanket Type III.
(c) Same as, and already done by flow tests for Blanket Type II.

BLANKET CONCEPT:

Type I - Low pressure solid breeder canister with coolant tubes

Type II - Clad solid breeder in high pressure module

Type III - Liquid metal breeder with coolant tubes

Type IV - Flowing liquid metal breeder

Additional tests could also include integral simulation tests on various blanket designs, starting with the Type II pressurized canister concept. The previous Type I scoping test results will be equally applicable to Type II blankets. An experiment consisting of a cluster of close-packed cylindrical rods containing Li_2O or $LiAlO_2$ pellets for the packed bed used in the first experiment would allow an integrated simulation test of the Type II blanket concept. This test would integrate the effects of solid breeder thermal conductivity, solid/clad contact resistance and overall thermomechanical stability for Type II blankets.

The effect of a magnetic field upon the heat transfer properties of liquid metal breeder materials (lithium and lead-lithium) is of concern for Type III and IV blankets. MHD effects are expected to reduce the effective heat transfer rates of the liquid metal.

Because of budgetary limitations, it may not be possible to study these effects in the near future. However, a test program based on the following criteria would serve to clarify many important issues related to liquid metal blankets. Should such a program be implemented, test article dimensions, magnetic flux density, coolant flow rate, etc. will be selected so that ranges of the governing non-dimensional parameters simulate full scale conditions. These parameters include:

(a) in the absence of a magnetic field

Re (Reynolds number)	=	ud/μ
Nu (Nusselt number)	=	hd/k
Gr (Grashof number)	=	$g\beta\Delta Td^3/\nu^2$
Pr (Prandtl number)	=	$C_p\mu/k$
Pe (Peclet number)	=	$Re \cdot Pr$
ϕ' (Conductivity Ratio)	=	$2w\sigma_w/\sigma d\left[1 + \frac{4w\sigma_w R_c}{d^2}\right]$

(b) in the presence of a magnetic field

M (Hartmann number)	=	$Bd\sqrt{\sigma/\mu}$
N (Steward number)	=	M^2/Re
Ly (Lykoudis number)	=	$M^2/\sqrt{Gr}$

Both steady state and transient conditions will be addressed. The measure of performance will be local and bulk heat transfer, flow distribution and uniformity, and pressure drop.

For steady state conditions, the effect of magnetic flux density and alignment will be examined for:

- The transfer of heat into, through, and out of the liquid metal (both local and bulk heat transfer)

  and

- Flow distribution and pressure drop.

For transient conditons, bulk and local heat transfer and flow, will be examined as they are affected by:

- Abrupt increase in heat load.
- Flow interruption or cessation.
- Partial flow blockage.
- Flow induced vibration.
- Magnetic field interruption or cessation.

A related area of interest would be to study pressure drop reduction when using pipes having insulating walls ($\phi' = 0$). Establishment of ϕ', the wall/liquid metal conductivity ratio for a series of materials would be of interest to reactor designers.

A suitable facility would comprise a liquid metal heat loop, heat source and a direct current electromagnet for most tests; a superconducting magnet would be the best means to achieve proper Stewart numbers, i.e., high magnetic interaction parameter values of 10^4. In addition, essential componentsand sub-systems would include:

- liquid metal circulation system.
- separate cooling system (probably pressurized water) and heat sink.
- bulk and transient heat sources (non-nuclear).

Argonne National Laboratory facilities appropriate for such testing include FELIX (see Section III of this plan) and an existing split coil superconducting magnet which has a 4.0 T field in its working volume.

2.3.5.2 Design Verification Testing

The second possible activity of the Post Phase I time frame involves non-nuclear design verification experiments for FED, INTOR, or other near-term devices. The first of two phases would consist of testing individual components or small groups of components as designs evolve, followed by a full scale blanket/shield module test for final verification. In reviewing the FED/INTOR concepts (Data Needs Assessment Report) some generic test requirements for the shields were determined, namely:

1. Flow distribution/flow blockage.
2. Differential thermal expansion/ratcheting between the plates.
3. Coolant leakage into vacuum chamber.
4. Fabrication consideration.

The flow distribution/flow blockage tests are seen as simple investigation of the flow pattern in the FED/INTOR shield components such as headers, coolant passages, orifices, etc. The potential for differential thermal expansion/ratcheting between plates arises due to the current shield design which is a box type structure built from large steel plates bolted together with Al_2O_3 insulation in between. Direct resistance heating in the various plates can simulate a temperature gradient between the plates and investigate the differential expansion/ratcheting effect. The potential for coolant leakage into the vacuum chamber arises due to the current shield design in which the attachment of the first shield plate to the side plate consists of a large weld which must function both as a structure as well as a coolant seal weld. Concerns have arisen recently about weld embrittlement at low total fluences in fission reactor pressure vessels. As part of the overall shield design, the performance of the weld must be verified and the strength of the weld under design conditions but without neutron effects be assessed. This verification is principally a measurement of thermomechanical effects in the shield box structure. It appears that direct electrical resistance heating of the structure will allow straightforward simulation and measurement of these effects. Fabrication considerations are beyond the direct scope of PE-II but must be considered to assure that good design practices are followed.

The second phase of verification testing focuses on module verification to prove the designs. These tests are required to assure that the overall system performance is acceptable and the blanket/shield modules can perform safety and reliable in the reactor. For this reason both thermal-hydraulic and thermomechanical performance will be investigated. Accurate simulation techniques should be used to assure that not only the steady state but also cyclic/transient characteristics are investigated.

2.3.5.3 Fission-Based Nuclear Testing

The third area is in fission-based based nuclear testing in two roles. First, it may be valuable in simple scoping tests or multiple effects tests in which radiation is an important factor. This might involve, for instance, continuation of the solid-breeder experimental program discussed earlier to include testing of the unit cell/coolant tube test article in a fission reactor, and to examine the additional synergisms resulting from the presence of radiation. This type of testing must build upon earlier non-nuclear testing, and will involve test articles designed to fit into existing test reactors. This will probably be the first type of nuclear testing to be undertaken.

The other role of nuclear testing will be in B/S design verification testing, currently viewed as the more important one in the long term. Nuclear testing will provide the most realistic simulation of the fusion reactor environment and thus will be vital in final design verification. Typical tests of this type are envisioned to involve large test articles, such as complete, functional, full-scale blanket modules. Because of their size, some modification of an existing reactor will likely be necessary.

3.0 Program Element III

3.1 Background

Fusion experimental devices and reactors use magnetic fields for the confinement, control, and heating of plasmas. Of necessity, the first-wall/blanket/shield (FWBS) systems 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 currrently-operating fusion experiments; and considerable effort has gone into understanding the electromagnetic effects expected in experimental devices under construction. 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 will be subject to much larger electromagnetic effects, which must be understood during the design stage.

Thus, the decision was made to establish electromagnetic effects studies as Test Program Element-III (PE-III) of the FWBS ETP. Preliminary concepts for PE-III were supported at an informal workshop on experimental tests of electromagnetic effects in the FWBS Test Program, held at ANL in September 1980. Authorizaton was given by DOE in June 1981 for ANL to conduct PE-III in-house. Shortly afterward a design review held at ANL supported the design of the experimental program and the proposed test bed, now called FELIX (Fusion ELectromagnetic Induction EXperiment); recommendations were made for prompt definition of the experimental program and priorities were suggested for upgrades.

Since then, 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 coil winding is in progress. The magnitude of expected effects has been predicted using a computer simulation of proposed early experiments, and selection of instrumentation to measure those effects has begun.

The designers of a FWBS system can expect to gain the following from the PE-III program:

(1) Verified computer codes suitable for calculating FWBS electromagnetic effects.

(2) Reactor-relevant experimental data which can be used to verify other computer codes.

(3) A practical understanding of the segmenting requirements of the FWBS and of the electrical interfacing 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 elctromagnetic 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 magnetic fields.

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 studies, such as the consequences of holes and segmentation, and other geometrical complications, can be modeled using computer codes; others 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 FWBS system will certainly tax the eddy-current codes of the foreseeable future.

The facility presently being constructed meets all the experimental requirements. The concept is shown in Fig. 3.1 and a cross section in Fig. 3.2. Facility upgrades will be necessary in order to gain a multiplication of data as more is learned. Proposed upgrades are as follows:

3.2 Facility Upgrades

The facility will be upgraded in accordance with recommendations made by the panel convened on June 23, 1981, to review the FELIX design, and experiments planned. The time at which upgrading will be implemented will depend on the level of funding. Priorities are:

3.2.1 Plasma Disruption Simulation

First priority will be given to simulation of a plasma disruption 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.

3.2.2 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-eight increase in cross-product forces will be sufficiently large to enable, for example, destructive tests of

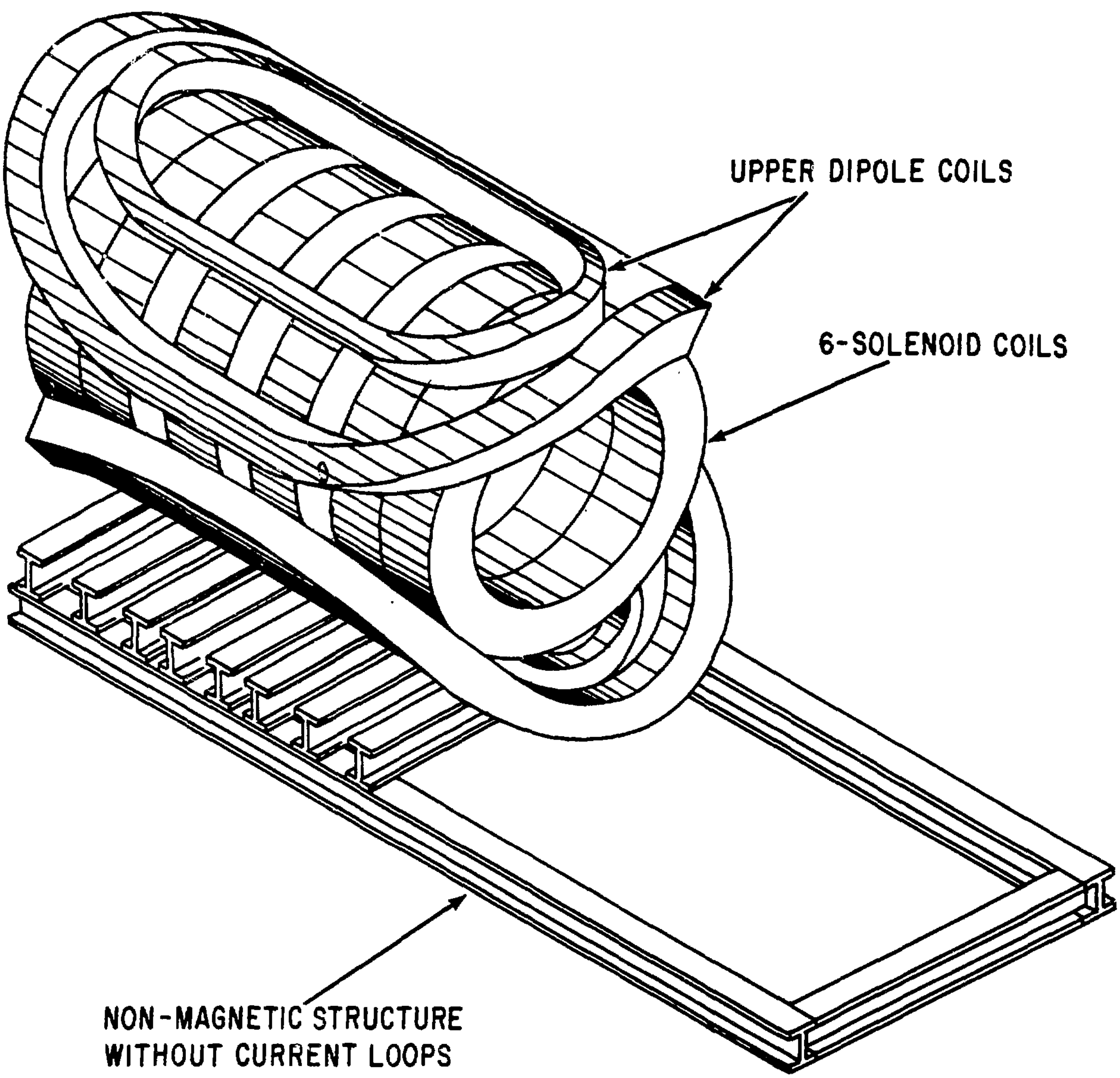


Fig. 3-1. FELIX test stand concept.

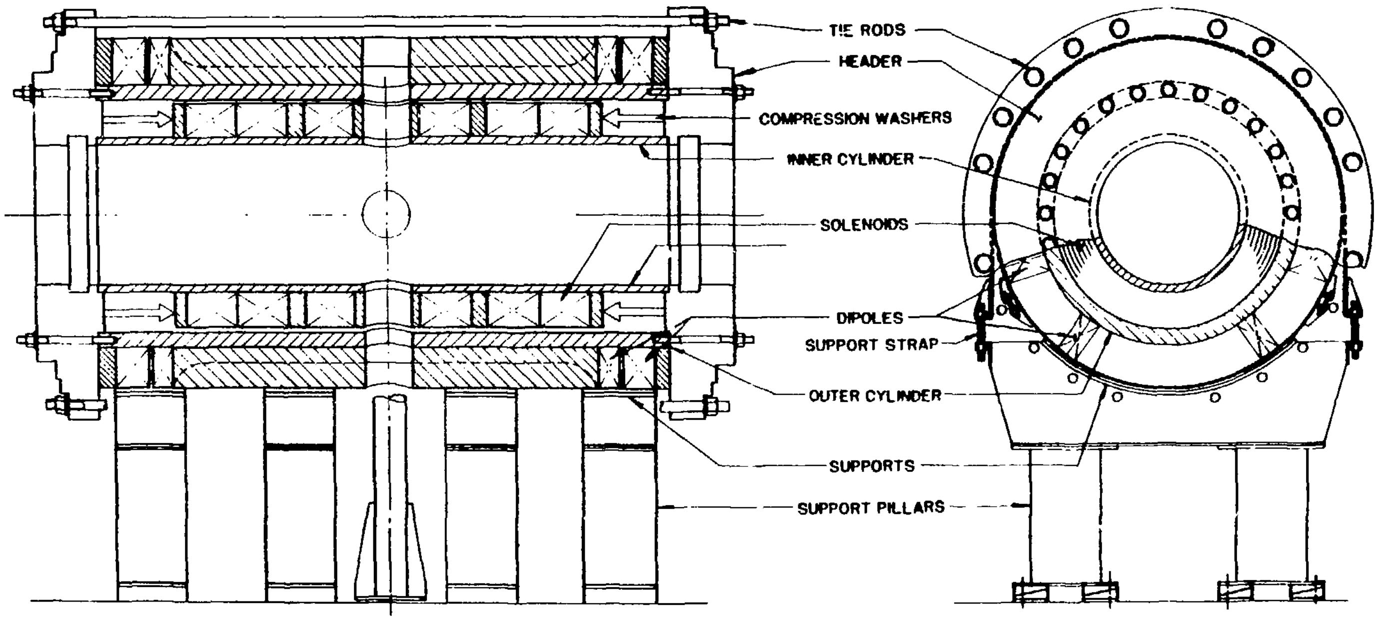


Fig. 3.2. Cross section and end views of facility.

prototypal components. (The solenoid tie rods, initially of stainless steel, will be changed at the time of implementation to Inconel, to withstand the increased stress levels.)

3.2.3 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 diffcult, however, to achieve good results in practice.)

3.3 Computational Needs

In addition to experimental tests, the development of computer codes is an integral part of PE-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 (1-D) current with two-dimensional (2-D) field, two-dimensional plane current with strictly one-dimensional field, two-dimensional shell current with perpendicular field, or truly three-dimensional (3-D) field and currents. They can also be characterized by the method of solution: finite elemen , 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.

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 avialable codes 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 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.

3.4 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 3.3.A shows the schedule for these experiments along with the schedule for the construction of the facility, instrumentation, and test-article support structure. (Ongoing facility construction is depicted in Fig. 3.3.B.)

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.

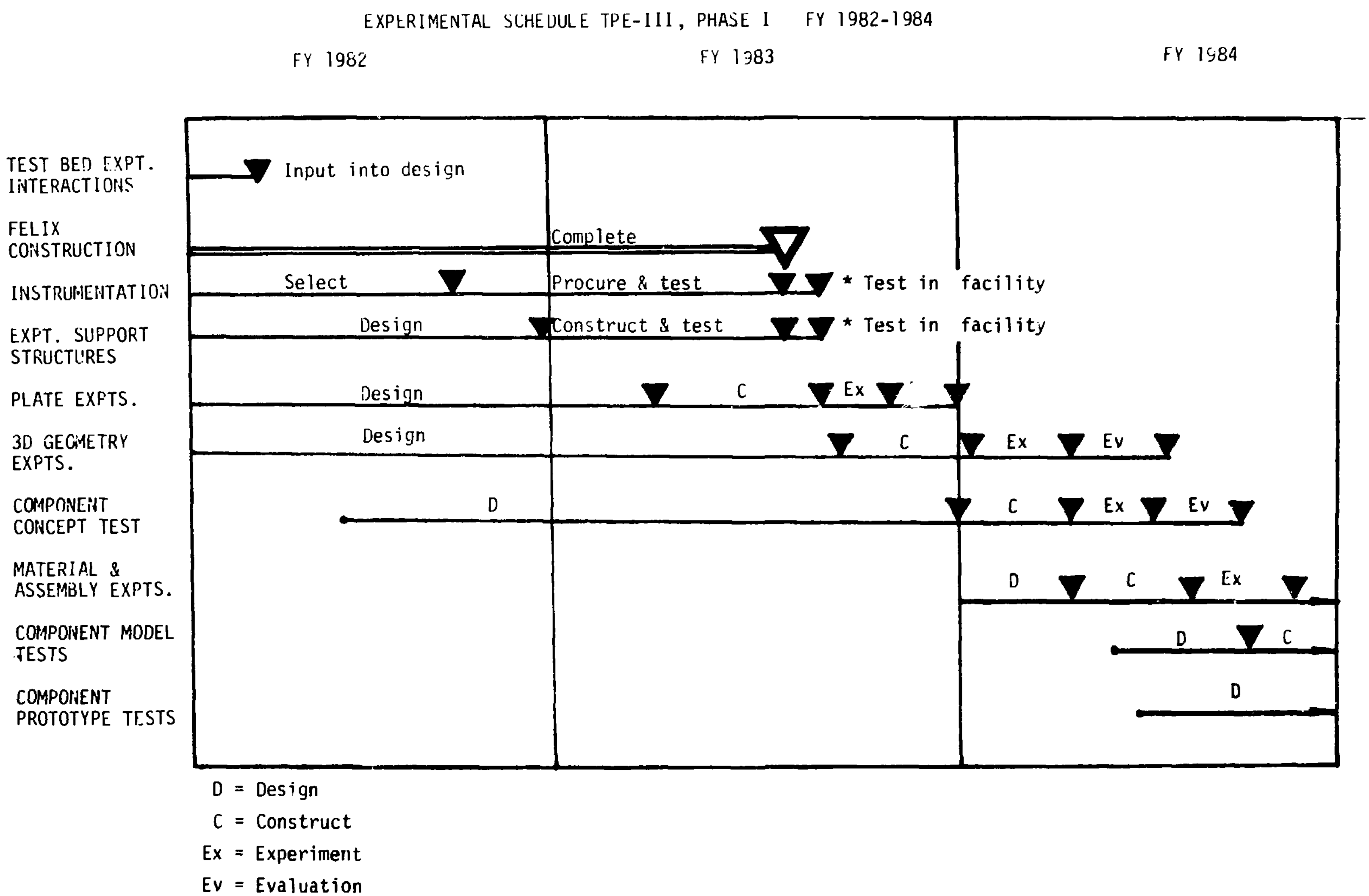


Fig. 3.3.A. Experimental schedule.

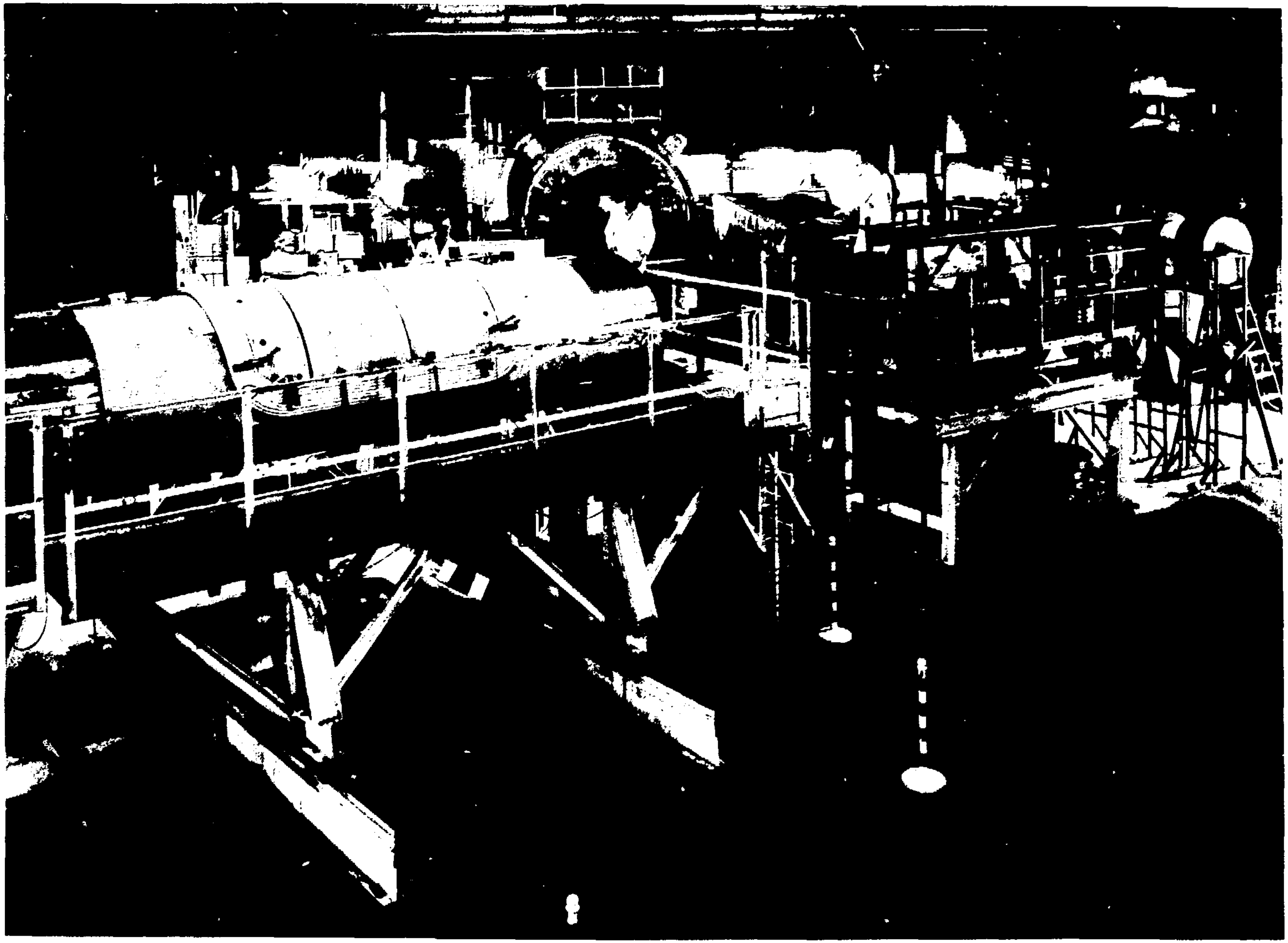


Fig. 3.3.B. FELIX Facility under construction.

3.4.1 Two-Dimensional Experiments

The first series of experiments to be performed when the facility is completed will be of about a two-month duraton 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. The objectives of the two-dimensional experiments will be:

- To study the 2-D eddy-curent 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 (3-D geometry in practice) can be modeled adequately by 2-D computer codes.
- To evaluate two-dimenisonal 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.

The test article is a rectangular aluminum plate 1 m × 0.8 m and 1 cm thick, held perpendicular to the dipole field with its long dimension parallel to the solenoid field. An 1100-aluminum alloy has been chosen as the test material, on the basis of its low resistivity of 2.8 $\mu\Omega \cdot cm$. 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. 3.4.).

As a preliminary step for later experiments on segmentation effects, the plate experiment will be repeated with the four quadrants of the plate electri-cally insulated from each other. Output from the two-dimensional experiments will include:

- A summary of 2-D experimental results.

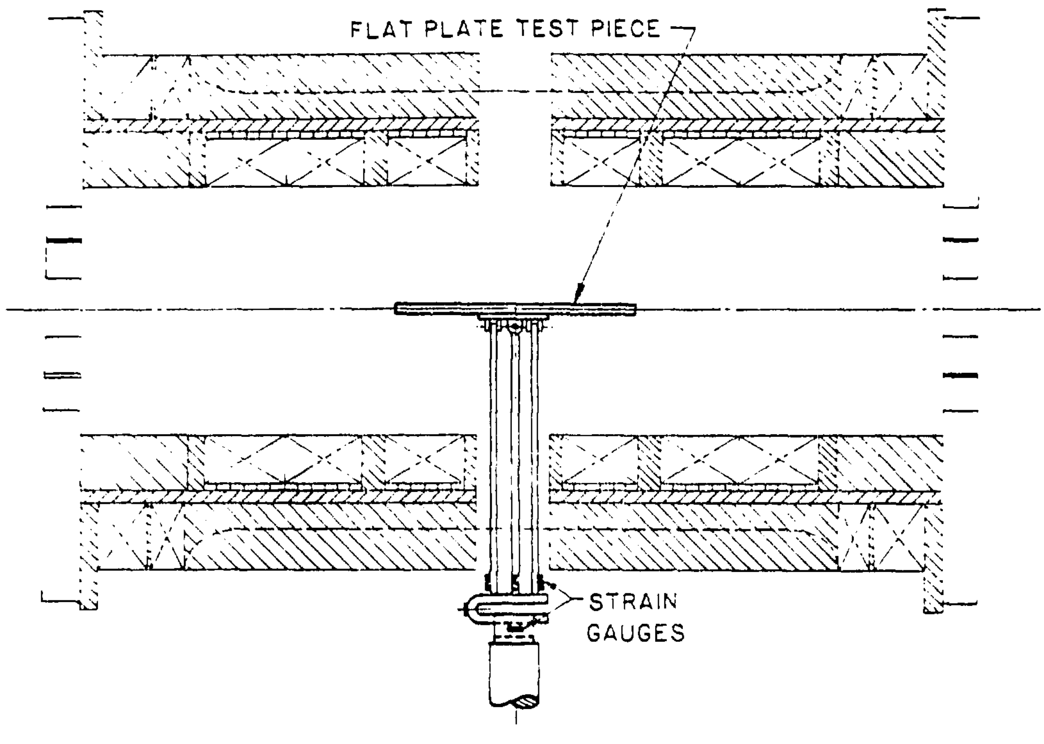


Fig. 3.4. Flat plate test articles positioned in test facility.

- A complete record of data for verifying codes.
- A small number of verified 2-D codes.

3.4.2 Three-Dimensional Experiments

Experiments, also about two months in duration, will deal with three-dimensional geometrical efects. Test articles will include the hollow conducting cylinder shown in Fig. 3.5 and stacked conducting bricks. The effects of segmentation and the separation between segments will be studied. The goals of the three-dimensional 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 3-D codes on the basis of their accuracy, efficiency, and convenience.

The 1100-aluminum alloy hollow cylinder depicted in Fig. 3.5 has two full-length slits located diametrically opposite one another. The cylinder, 120 cm long, 40 cm outside diameter, and 0.5 cm thick, can be rotated so that the slits are at any desired angular position.

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 comparison with code predictions. The output of the 3-D experiments is expected to include:

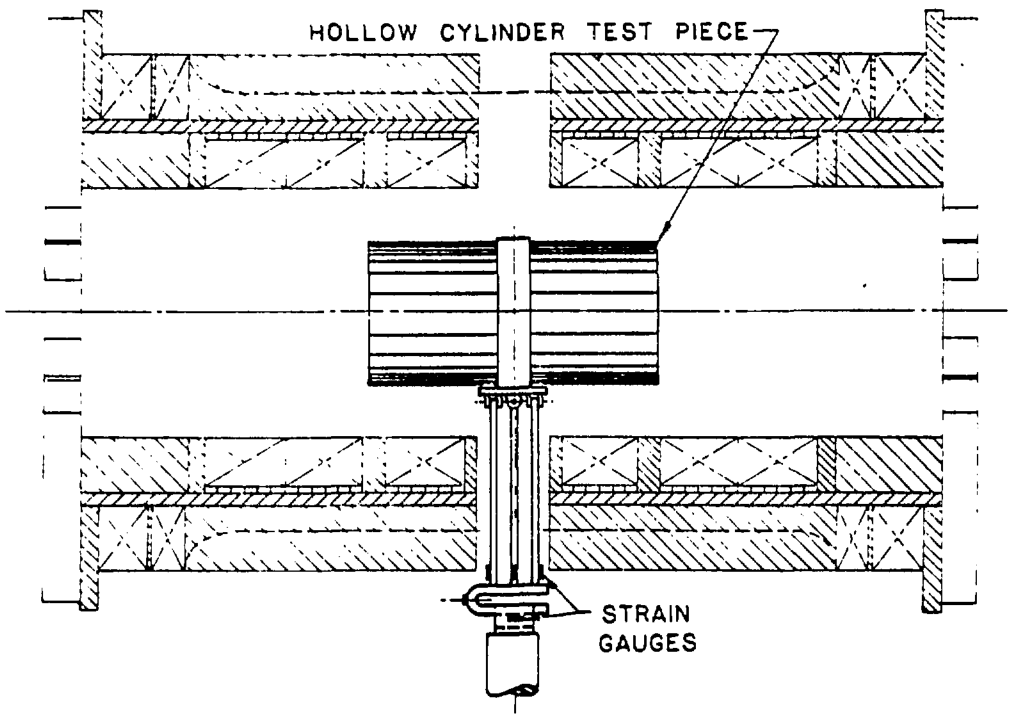


Fig. 3.5. Hollow conducting cylinder positioned in test facility.

- Detailed results on segmentation effects, with appropriate scaling rules.
- Experimental data sets appropriate for verifying 3-D computer codes.
- A small number of verified 3-D codes.

3.4.3 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 two-dimensional and three-dimensional 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 as a part of PE-IV and to provide information needed to make choices in the FED FWBS 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. The assembly effects experiments are expected to accomplish the following objectives:

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

At this time, it is impossible to know exactly what assembly effects experiments should be conducted. An example that incorporates several features of possible experiments is an electrical connnector between two first-wall or blanket modules, designed for remote assembly. Such connectors are being developed as part of PE-IV. Figure 3.6 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

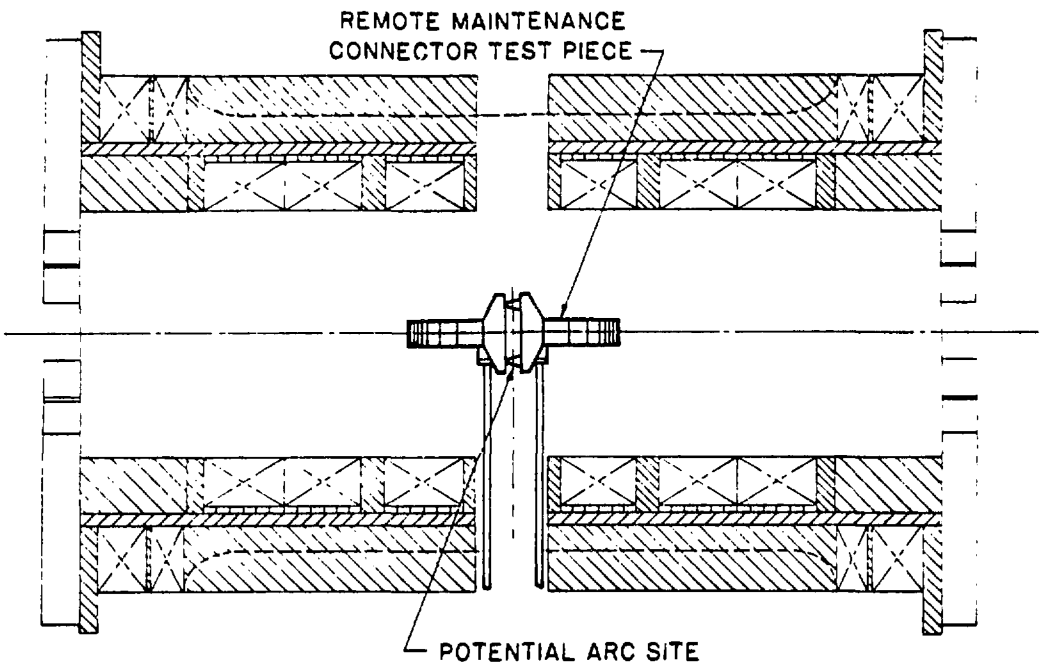


Fig. 3.6. Typical test article for assembly effects experiments.

simulate reactor conditions, the experiment should be carrired out in vacuum; a vacuum vessel designed for general use in FELIX experiments would be a useful addition to the facility.

It is anticipated that the output from the assembly-effects experiments will include:

- Value and variance of joint resistance.
- Stress dependence of joint resistance.
- Information needed to select an electrical connection suitable for remote assembly.

3.4.4 Component Concept Tests

The component concept tests will be the first to simulate actual FWBS components. The test articles will be geometrically similar to the component conceptual design they represent, but will be largely homogeneous in material and lack many 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. 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 restaint 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.)

Test articles might be scale models of various limiter concepts or various concepts for 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 articles will be homogenous in material and without bolted joints or other details. These tests should yield:

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

3.4.5 Material and Assembly-Effects Tests

These experiments are similar in concept to, but extensions of, those described in Section 3.3.4. 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 the effects of electromagnetic forces on a first-wall melt layer might also be studied. The objectives are similar to those for the earlier Assembly-Effects Tests (Section 3.4.3).

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 articles could include wall sections with bellows or dielectric breaks, clamping pieces, or a model of a packed-bed blanket module.

In addition, 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 selection 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. 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 response of a melt layer to electromagnetic forces.

Other experiments of interest would be an examination of the behavior, and in particular the electromagnetic behavior, of a melt layer of the first wall following aplasma disruption. Currently, this is 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.

3.4.6 Component Model Tests

In component model tests, the test articles will include some of the details and the material heterogeneity of actual component designs. These tests will identify electromagnetic effects associated with details which were not present in the component concept tests. (Section 3.4.4.) The goals of these tests will be:

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

If the test is to model a limiter, the model will include cooling tubes and coating. Thicknesses will be chosen so as to develop stress levels expected in the actual component. The tests will yield:

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

3.4.7 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, experimental blanket modules, and other components can be tested. The goal of these tests will be to verify successful operation of the prototype component under reactor-like pulsed and steady magnetic fields.

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.

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

3.5 Magnitude of Electromagnetic Effects in First Experiments

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, Para. 3.4.1, 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.

The test article is 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, written to calculate the forces and torques acting on the test piece is based on the line currents computed by EDDYNET2D and the specified dipole and solenoid fields. 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 3.7 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 quadrant.

Figure 3.8 shows the net force components acting on one quadrant of the plate. The insert sketches show the signs of the force components in all four quadrants. In no case is there a net force on the plate. The x and y components lead to tensile stresses, the z-component leads to a net torque about the y-axis.

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 midplane 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.

The plate described in Para. 3.4.1 is to be supported from its center. However, stress analysis shows that the calculated forces would lead to stresses many times larger than the yield stress of Type 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.

Temperature measurements will be a 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. (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

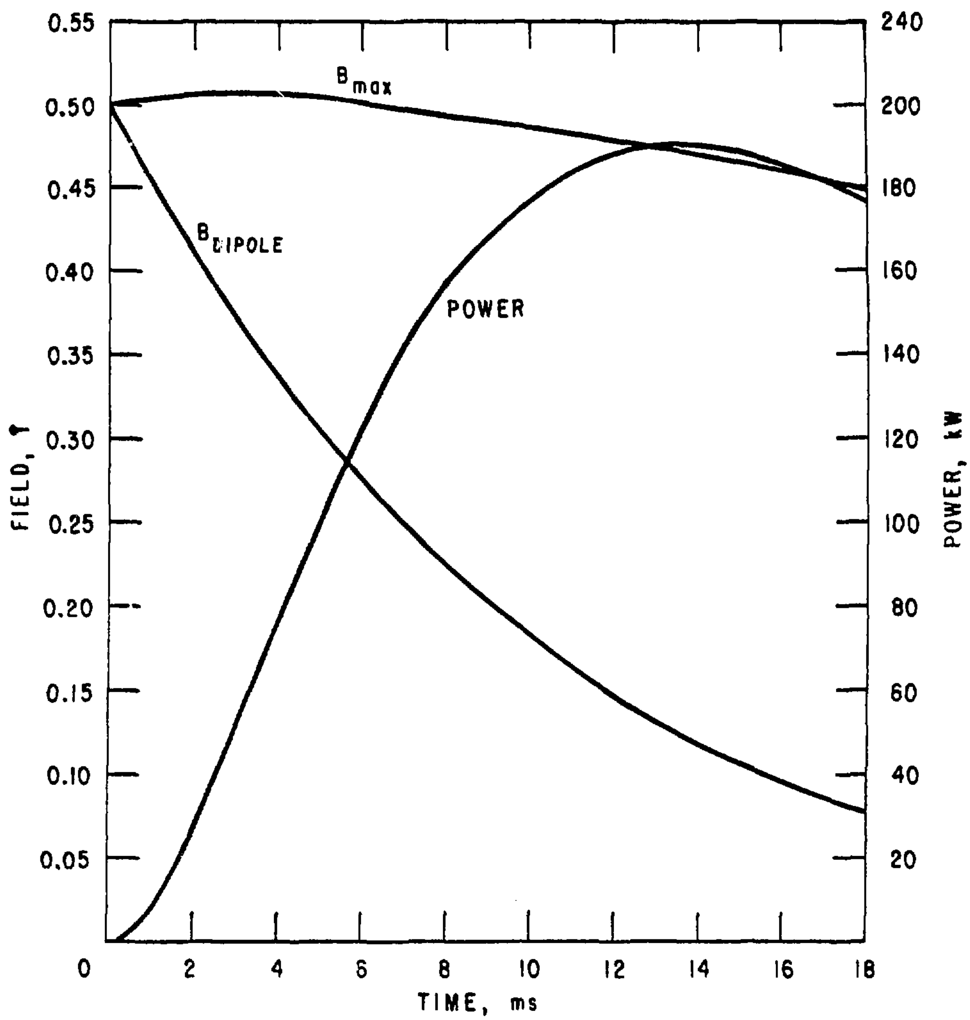


Fig. 3.7. Applied field, peak field, and power in FELIX plate experiment.

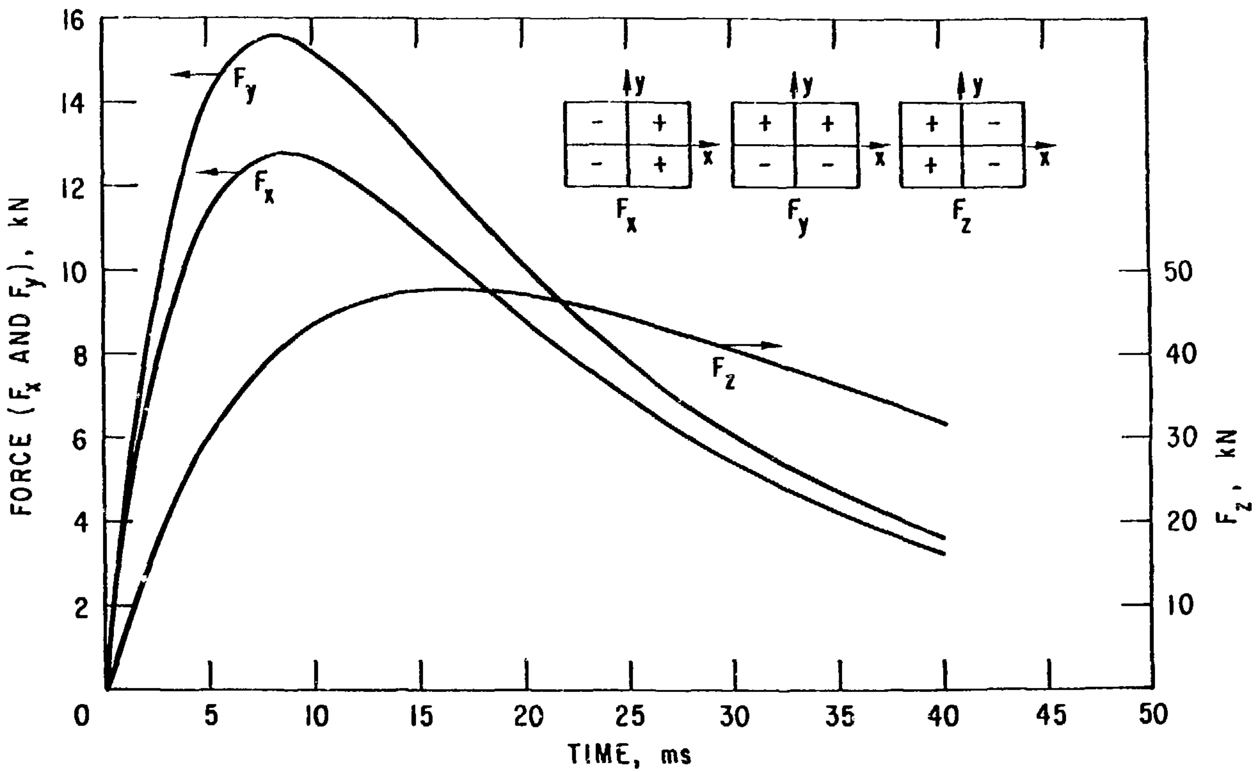


Fig. 3.8. Forces acting on one quadrant of plate.

heating is a practical concern for some reactor prototype equipment, particularly instrumentation. 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 values of parameters used in the calculation of temperature for the first FELIX experiment are given in Table 3.1. 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.

Table 3.1. 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 $\mu\Omega \cdot$ 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} $^0C \cdot m^4/A^2 \cdot s$
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}

A typical contour plot of temperature rise on one quadrant of the plate is given in Fig. 3.9 for a time of 10 ms. The pattern of temperature after 20, 40, and 160 ms is similar at all times, with highest temperatures occurring along the edges of the plate, intermediate temperatures in the interior and at the corners and lowest temperature at the center. At a repetition rate

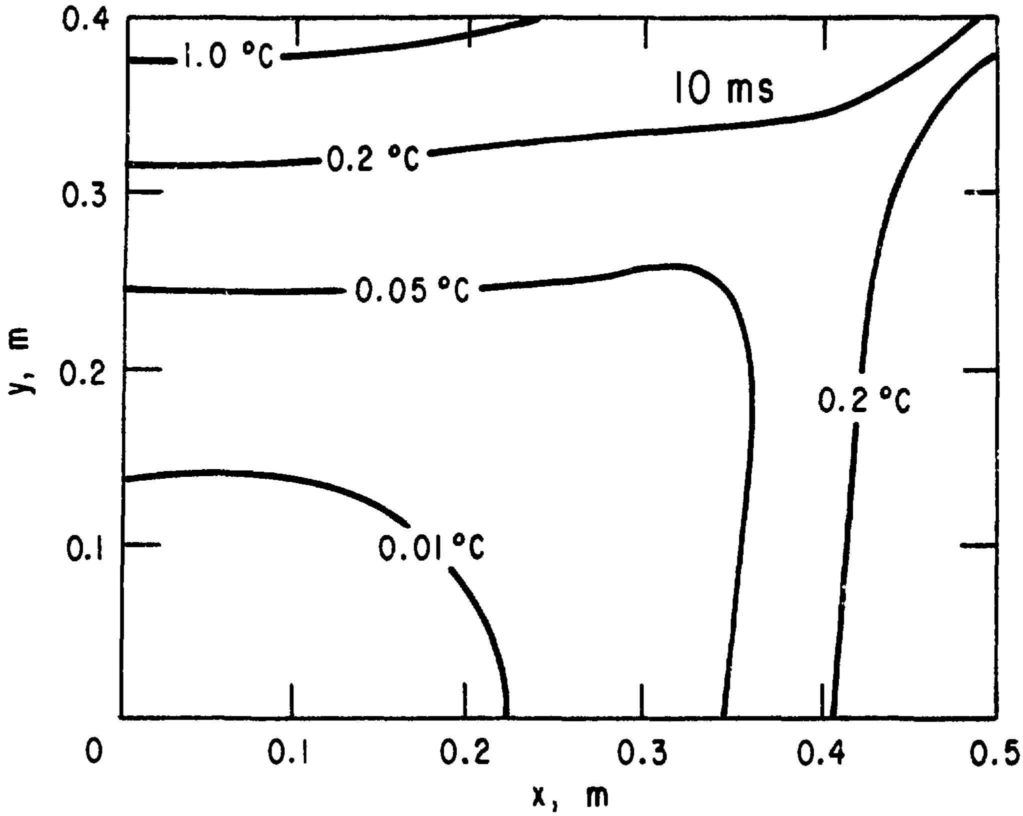


Fig. 3.9. Temperature distribution over one quadrant of plate at 10 ms.

of one pulse per minute, the plate may have to be cooled actively, perhaps by forced air between pulses to prevent overall heating which could affect the calibration of instrumentation.

3.6 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 1 cm^2 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: (1) by the use of the classic sensor with some form of signal protection or error compensation; (2) by the use of a special sensor developed to overcome the disturbing environment so that its electrical signal can be made immune to that environment; and (3) by the use of sensors that do not use electrical signals at or near the test area. In this last category are instruments that can optically scan gross effects from a "safe" distance.

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 are presented, since not all sensitivity and output signal levels are yet known.

3.6.1 Classic Strain Device

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 is 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 guage, but not under strain. The "dummy" gauge is made part of a 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 elminate 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 semimconductor crystal and obtain much larger gauge factors than the wire-pattern units. They have the same drawbacks with the lead wires and connecting loops. Piezoelectric-based strain devices may offer the same advantage with respect to signal level, but have the same lead-wire problems.

3.6.2 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 may be possible to filter out the transient magnetic error signals. 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.

3.6.3 Nonelectric Devices

If fiber-optic transducer concepts can be employed and if development costs are not too high, a solution to many sensor problems would be available. 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 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 0-100% 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.

3.6.4 Gross Effect Systems

A method now in commercial use allows 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, reflected from the surface is observed through a polarizing filter and the patterns 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 warmup or pretesting.

3.6.5 Other Instrumentation

FELIX also requires instrumentation other than strain gauges, in particular, temperature-measurement devices; associated problems are being studied. Thermogaphic imaging systems may be the only practical method of obtaining the time-related information because of the short time (0-50 ms) during the thermal gradients buildup. Vendor-conducted demonstrations of this equipment have given rise to confidence that infra-red (IR) scanning equipment will be capable of meeting the FELIX test article temperature mapping requirements.

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.

3.7 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 lmited 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 simultaneously 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, a number of specialized codes and at least one general three-dimensional code will probably be required, all of which must be verified and calibrated by experimental modeling. Figure 3.10 shows a schedule of how code development is correlated with facility construction, the experimental program, and distribution of experimental results.

The requirements for suitable codes will be an ongoing activity, 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 will 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 FWBS needs.

3.8 Community Participation

Outside groups may be involved in three areas: guidance for the overall FELIX program, participation in the experimental program, and participation in the computational method development and testing. Suggestions for experiments are being solicited both informally and through journal papers describing the program. Groups who desire to carry out experiments at the facility will be

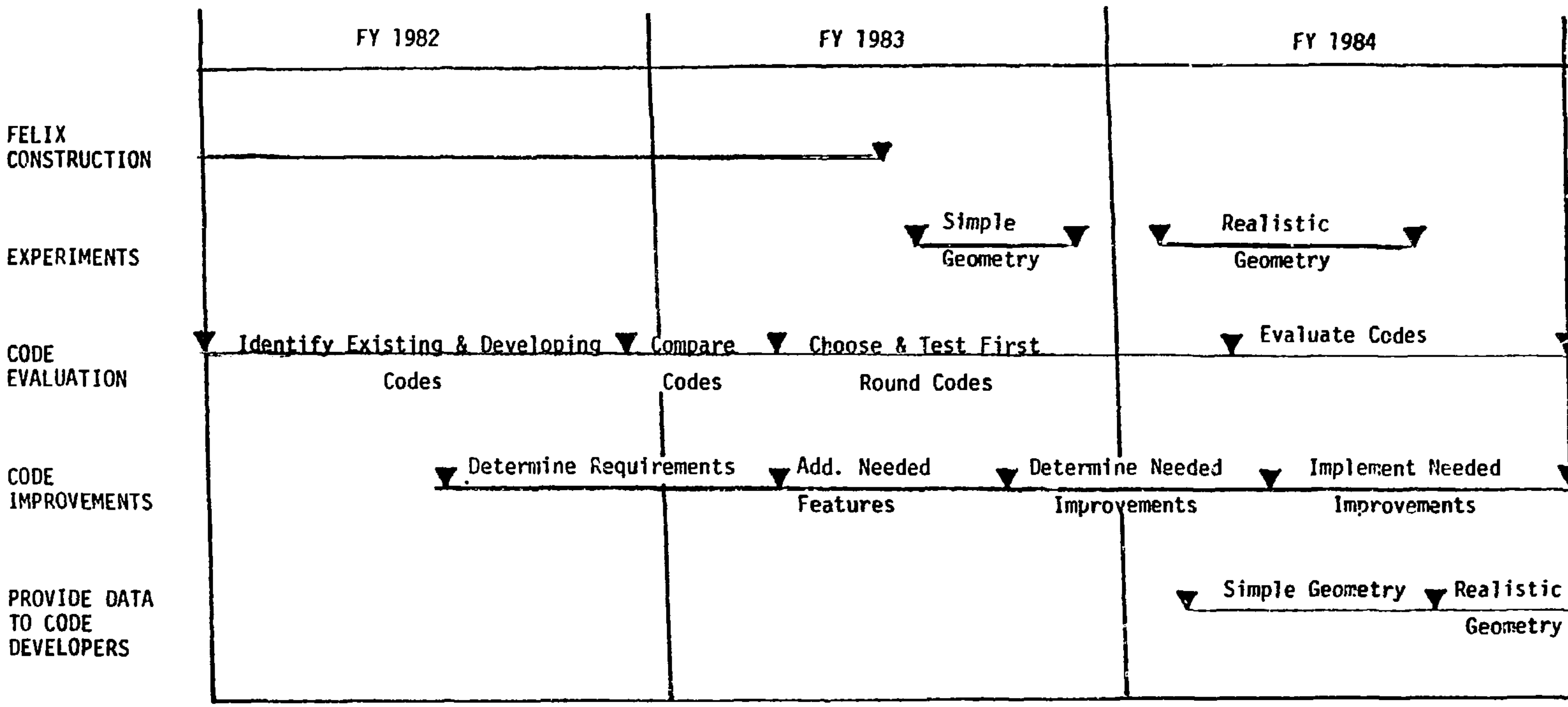


Fig. 3.10. Computer code evaluation schedule - TPE-III, Phase 1, FY 1982-1984.

welcomed. If this becomes more than an occasional occurrence, a community-wide panel will be established to evaluate proposals for experiments using the facility. 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 among the codes can be made.

4.0 Program Element IV

4.1 Background

Program Element IV (PE IV) of the FWBS ETP which addresses development of Assembly, Maintenance, and Repair (AMR) capability for FWBS systems of magnetically confined fusion devices and reactors has been assigned to the McDonnell Douglas Astronautics Corporation.

Because of budgetary constraints, Phase I is more limited in scope than originally planned and now has the following objectives:

- Evaluate and design a joint system applicable to non-circular vacuum joints at the FWBS.

- Evaluate, design and conduct initial tests on an electrical connector system suitable for creating a conducting first wall.

- Develop detailed technical plans for additional work packages necessary for achieving a remotely operable AMR capability for fusion FWBS systems.

- Continue development of Designer's Guidebook data and design guidelines.

Technical plans will be developed during Phase I to expand the evolution of a remote maintenance capability during and beyond Phase I. These plans will define a number of small but significant test programs that provide necessary data for the eventual remote maintenance of fusion devices.

The objectives for the development of the Designer's Guidebook in Phase I include:

- Define the Guidebook composition, format, and arrangement.

- Incorporate the results of selected surveys of current technology in Guidebook format useful to the designer.

- Prepare joint system and first wall electrical connector data developed in Phase I for inclusion in the Guidebook.

- Bring the guidebook to a level of completion which provides current guidelines to the designers of near-term fusion FWBS systems.

The Designer's Guidebook applies to the design of all types of magnetically confined fusion systems. In Phase I, the objective is to complete the initial draft of the Guidebook sections dealing with the features of fusion plants, fusion AMR concerns and requirements, various maintenance approach guidelines and general remote equipment design guides.

The importance of joint systems to ANL can be summarized as follows:

- Numerous joints are required to allow maintenance of FWBS for all magnetic confinement fusion reactor concepts.

- Joints are major contributors to reactor downtime.

- Fully remote maintenance designs are needed.

The program for development of an AMR data base for the first wall, blanket and shield is, of necessity, limited by the budget available. Therefore, choices must be made of the development tasks to be investigated first.

As a guideline, those developments needed to provide data for the "best" solution to the assembly and maintenance of a fusion reactor from the point of view of achieving maaximum availability have been selected. They apply primarily, but not only, to tokamak experimental devices and reactors because these configurations have received the most attention in the field of magnetic confinement.

Previous comparative studies of reactor designs, (Ref. 1-3,) have shown that the most extensive scheduled maintenance requirement is changeout of the first wall and blanket and that this can be accomplished most efficiently (i.e. minimum downtime) by replacement of large sectors of the torus through use of maintenance equipment external to the plasma chamber and by using only external access. The neutron dosage of experimental machines may not reach the level required for periodic first wall replacement but it is essential that the efficiency of this type of configuration be demonstrated. There are other approaches which require access to the first wall from within the plasma chamber butsuch maintenance is very time consuming, especially when a major part of the first wall is affected.

Accordingly, developments most critical to designing the large sector configuration were sought. Two have been selected which, if solutions are unavailable, could force the design away from large sectors and towards internal maintenance devices. Lack of these capabilities would have a major impact on reactor configuration.

One of these developments is the design of connectors to provide a conducting first wall between sectors. This is currently believed to be essential to minimize plasma disruption effects and is being recommended for all tokamak configurations. Two alternatives exist in the design approach; the sectors could be welded at the first wall, or mechanically operated connectors could be installed. Both approaches require access from within the plasma chamber, thus defeating one of the purposes of the large sectors. The "best" solution would be to use actuators operated from outside the plasma chamber. Many design variations exist and will be investigated. One feature common to all connectors, whether internally or externally operated, is the need for contact surfaces to carry the large currents expected during a plasma disruption without an accompanying large voltage drop. These currents could reach 600 kA per contact for the STARFIRE configuration (200 kA for the FED). A voltage drop exceeding 10V across each connector is considered excessive and likely to lead to arcing. The most pertinent available data is primarily in the area of power contactors or interruptors which are required to make/break circuits under high voltage conditions in the less than 100 kA range. (The make/break capability under load is not required for fusion reactor connectors.) In addition, power contactor data is insufficiently definitive to enable a designer to translate it to the fusion reactor solution without additional testing.

It is therefore appropriate to apply the limited budget available towards performing the test program described in Para. 4.3.1 Vol. II of this Program plan. The basic data developed can also be applied to aid in the resolution of many other problems. Several examples are listed in Table. 4.1. Application of these data to parts of a fusion reactor other than the first wall electrical connectors include segmented control coils and grounding jumpers. In tokamaks, the control coils are located inside the TF coils and can be segmented to permit remote replacement. Segment joints will require the use of materials which can carry large currents without welding. In addition, these joints require simple clamping mechanisms that can apply large pressures, which is the general subject of the second development area discussed below. The contact electrical data will guide the selection of contact prerssures for this application.

Grounding jumpers are also required on fusion devices to electrically connect all components. Maintenance is restricted because of the need for removal for component replacement. Use of a remotely operated contact is desirable.

Table 4.1 Examples of Connector and Remote Joint Data Applications

	TOK	TMR	OTHER
Contact Data			
Ground jumpers	X	X	X
Segmented copper coils	X	X	X
First wall connector	X		
Remote Joint			
Vacuum ducts	X	X	X
Coolant lines	X	X	X
Structural tie downs	X	X	X
Segmented copper coils	X	X	X

Another development critical to the design of large sector configurations and in fact all configurations is joint systems for the coolant, vacuum and other lines or closures. Those required for access to or to remove the first wall, blanket or shield are the most significant. Studies of tokamak reactors (Ref. 1-3) indicate that breaking and making joints for replacement of the large sectors is approximately 25% of the total downtime, even using advanced remotely operable joint concepts. The design of joints to appreciably reduce or even achieve this downtime is the objective of this present program's investigation. Mirror reactor availability and requirements are similar.

Again, because of limited budget, the scope of the tasks towards achieving this objective is appreciably reduced, and restricted to a design study of a joint in a large rectangular vacuum duct which must be disconnected for access to, or replacement of the first wall, blanket and shield sectors. This selection was made primarily because various design concepts exist for many coolant lines and relatively small diameter vacuum ducts, but not for large rectangular ducts. The most time consuming part of the joint connection is making and breaking the structural attachment. The entire joint design involves much more than this, but the best use of the limited budget is to search for innovative solutions to this problem rather than to dilute the effort by looking at the wide range of design issues presently existing for joint configurations.

To provide a basis for specific analysis a large joint from the FED design concept was selected. However, the underlying design requirements include the need for versatility of application as one of the criteria for concept(s) which are to be investigated further. The objective is to provide a generic solution rather than to provide a design suitable only for one joint in a specific configuration. Large rectangular vacuum joints appear to be a need for all confinement configurations being considered and the example chosen is representative.

In considering this structural attachment, a Helicoflex seal configuration was chosen. These seals are currently being used on TFTR and for several reasons have been accepted as the best mechanical seal for rectangular ducts in a radiation environment. Helilcoflex also was chosen because it is a seal system requiring maximum structural attachment loads. A design based on these loads can be easily applied to systems requiring lesser loads.

As for the contact material study, this investigation can result in data applicable to the resolution of many other problems. The examples listed in Table 4.1 include noncircular or circular vacuum ducts, vacuum doors, coolant lines, structural tie downs and segmented copper plasma control coils.

The application of a remotely operable structural attachment design to circular as well noncircular geometries is obvious. The use of a single concept appropriate to all remotely maintainable ducts in a reactor simplifies the tool requirements and has proven advantageous in other remotely maintainable systems, such as fuel recycling processes.

Structural tiedowns are also required in fusion reactors including the FWBS sectors. Data resulting from this part of the program would aid in defining the sizes and types required.

These specific design and development problems have been selected to advance the technology and to provide some of the data required for design guidelines. Many paths exist in each of the areas chosen; the objective in making these choices is to select the most advantageous. Should these first choices prove to be intractable, other directions and greater innovation will be pursued. For example, seal development could be investigated to include such concepts as brazed, liquid metal, differentially pumped or inflated vacuum seals. Ways to extend AMR investigations in this and other directions re currently being defined.

4.2 Phase I Development

The Phase I schedule and planned activities are given in Figure 1. There are directed towards (1) continuing development of the Designer's Guidebook, (2) producing a design of a remote operating mechanism for clamping a joint system, (3) conducting initial tests for development of an electrical

PHASE I – SCHEDULE

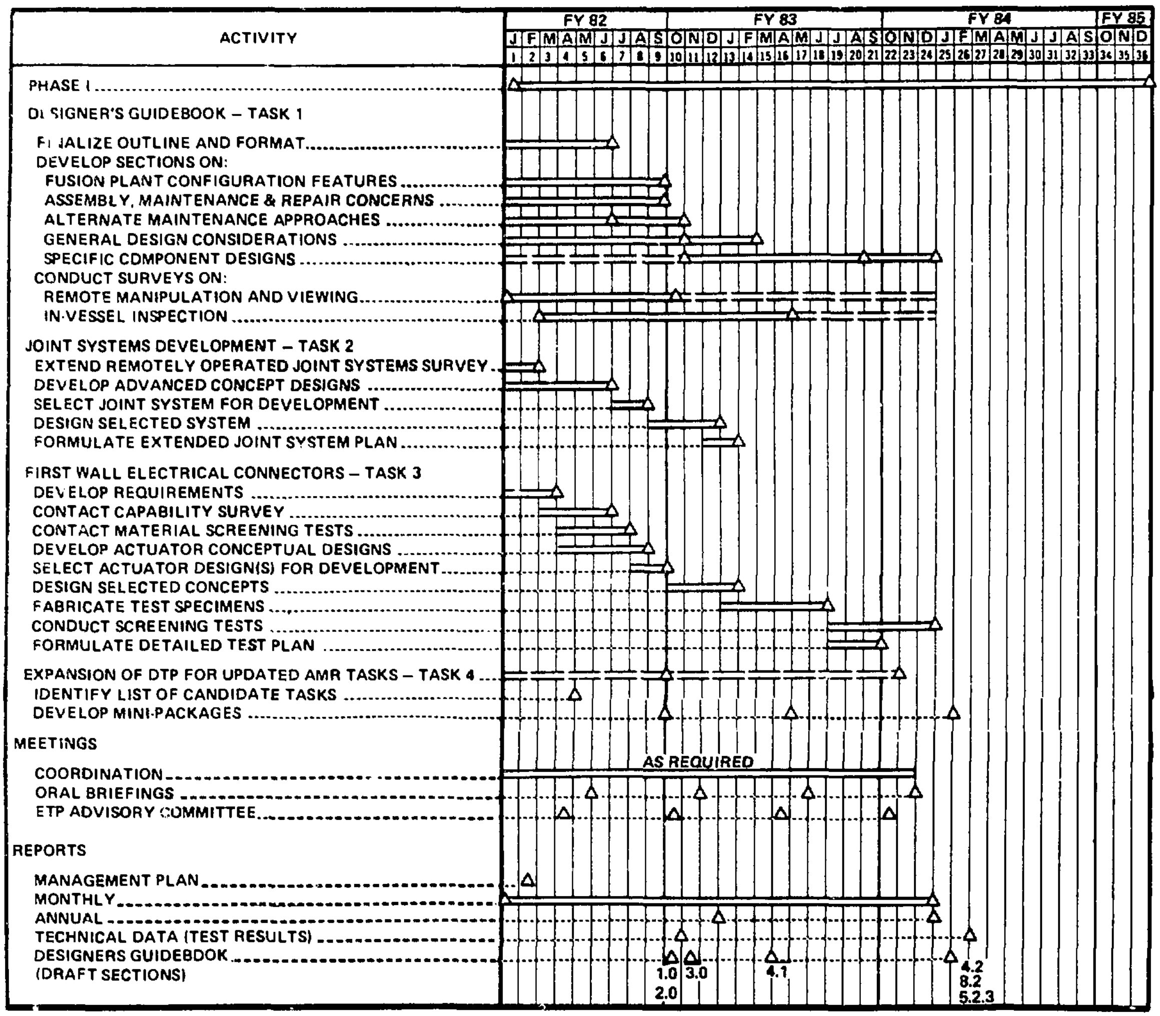


Figure 4.1

connector for the first wall, and (4) continuing the formulation of detailed technical plans for specific program elements applicable to the FWBS AMR.

4.2.1 Designer's Guidebook Development

In Phase 0, emphasis was given to performing a literature survey to obtain an understanding of fusion AMR concerns, and preparing an outline for the Guidebook. During Phase I, additional sections of the Guidebook will be prepared and drafts issued as information becomes available. Key tasks defined for Phase I include development of draft sections of guidelines for:

- Various maintenance approaches including contact, remote with provision for contact, and fully remote maintenance operations.

- General AMR design considerations.

- Specific component designs for AMR.

In addition surveys will be continued or started for existing technology and equipment concerning:

- Remote manipulation and viewing.

- In-vessel inspection.

- Remotely operated joint systems.

Data from the Phase I efforts on the joint system mechanisms and the first wall electrical connectors will also be compiled and included in the Guidebook where appropriate.

The Designer's Guidebook will serve as the output vehicle for all PE IV efforts. The results of the technology survey, component test activities and future technology development will be catalogued, summarized and incorporated in appropriate sections. The information will be an aid to fusion AMR designers, but will not establish requirements. The Guidebook will be a "living document" that will be added to and revised as the technology and data develop.

4.2.2 Joint System Development

The extensive requirements for joint systems in fusion devices led to the emphasis in Phase 0. Surveys of joint system applications in fusion reactors, seal designs and remotely operable joint system designs have resulted in the recognition of a need to develop non-circular remotely operable joint systems for hard vacuum applications. This arera was chosen primarily because of the frequent need in fusion device designs and because of the limited solutions available. Existing methods are both cumbersome and time consuming for maintenance operations.

Nominally rectangular vacuum system openings have been chosen for examination because: (1) This type of opening is the prevalent in FWBS systems for magnetic fusion devices such as TFTR, MFTF-B; (2) Insufficient space exists for circular openings; (3) mechanically operated (not welded) joints are essential for penetrations of the vacuum wall to attain the accessibility required for maintenance of the fusion device in an acceptable downtime; and (4) Vacuum joints have the most severe leakage requirements. There are also other lesser considerations.

A number of different seal designs have been developed. The consensus for the type of joint required in the environment encountered in DT fusion devices is to use a replaceable metallic seal. Several seal designs have been investigated and some data is available but many conditions of the environment to which seals will be subjected in DT fusion devices remain to be investigated.

The development of a complete remotely operable joint system for this application requires additional data on seals, load attenuation, alignment and other joint characteristics. To start the development of these data, the design of a remote operating mechanism for clamping the joint system has been selected for Phase I. The design of such a mechanism is believed to be within the scope of available resources.

In studies of maintenance downtime and operations for replacement of FWBS systems in tokamak and tandem mirror reactors, the downtime required to make and break coolant and vacuum connections for both scheduled and forced outages is significant. Figure 4.2 summarizes the number of joints, both vacuum and coolant, found in the reactors surveyed, and Figure 4.3 tabulates the results of these studies. Remote maintenance with operator controlled manipulators and advanced design of joint systems was assumed.

Figure 4.4 shows the location of typical vacuum and fluid (coolant) joints on the FED conceptual design. In the locations indicated, the joints will become activated and, therefore, require remote access, disassembly, reassembly and in situ repair of some parts at the joint fixed (standing) end. The survey of remotely operable connectors that was made in Phase 0 indicated that development is required to make these concepts remotely maintainable at the locations shown.

4.2.2.1 Joint System Requirement

The general requirements for any vacuum joint system employed in a radiation environment in the fusion device are:

- The seal system shall be leak tight.
- The joint shall be designed for use in removable duct or pipe sections (this type of removable section is commonly called a "jumper").
- The seal shall be maintained with repeated thermal cycling.
- The seal shall be maintained while exposed to the expected radiation environment.
- Each joint system must be individually leak checkable.
- Joints shall be capable of assembly/disassembly by remote means.

FUSION REACTOR JOINT SYSTEMS

	NUMBER OF JOINT SYSTEMS*		
	VACUUM	COOLANT	OTHER
FED (FEDC, 6/81)	138	376	208
STARFIRE (ANL, 9/80)	228	404	246
TMR (LLNL, 9/79)	?	688	554

*RELATED TO DISCONNECTABLE FW/B/S JOINT SYSTEMS EXTERNAL TO VACUUM VESSEL. ESTIMATES ARE INCOMPLETE.

Figure 4.2

REACTOR DOWNTIME FOR JOINT SYSTEMS

	TOTAL REACTOR PERCENT OF DOWNTIME(1)		
	TOKAMAK		TANDEM MIRROR
	CULHAM MK II	MODIFIED CULHAM MK II(2)	LLNL (1977)
FORCED OUTAGES			
COOLING PIPING CONNECTIONS, % OF DOWNTIME	UNDETERMINED	7	8
DAYS OUTAGE, PER FAILURE	3.0 NOMINAL	3.0 NOMINAL	4.3 NOMINAL
VACUUM PIPING CONNECTORS, % OF DOWNTIME	UNDETERMINED	2	1
DAYS OUTAGE, PER FAILURE	3.9 NOMINAL	3.9 NOMINAL	3.3 NOMINAL
SCHEDULED OUTAGE (SECTOR REMOVAL)			
VACUUM CONNECTIONS, % OF DOWNTIME	11.6	9.7	12
COOLANT CONNECTIONS, % OF DOWNTIME	22.5	17.3	14
DAYS REQUIRED/SECTOR, VACUUM CONNECT.	4.08	1.21	.61
COOLANT CONNECT.	7.88	2.14	.69

(1) ASSUMED: OPERATOR CONTROLLED MANIPULATORS
BASED ON: MDAC STUDY SPONSORED BY DOE, 1978-1979 (REFERENCES 4 & 3)

(2) ASSUMED: ADVANCED DESIGN LATCHING AND AUTOMATED TOOL EXCHANGE, ETC.

Figure 4.3

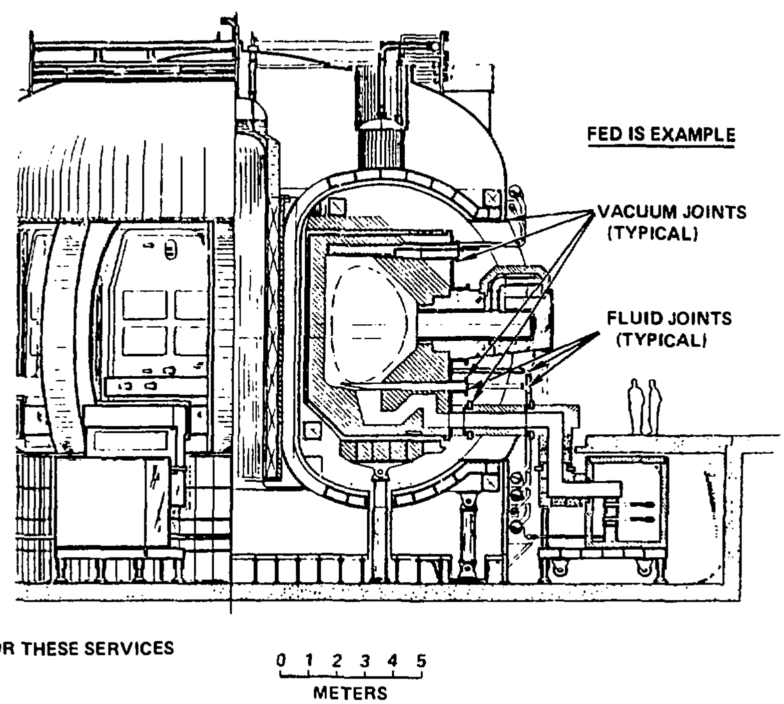
JOINT SYSTEM LOCATIONS ON CURRENT FED DESIGN

DESIGN FOR ENVIRONMENT

- ACCESS
- RADIATION DOSAGE
- TEMPERATURE CYCLES
- REMOTE HANDLING
- RAPID DISCONNECT

JOINT TYPES REQUIRED

- PRESSURIZED FLUIDS
  (CIRCULAR JOINTS)
- VACUUM
  (CIRCULAR AND
  NON-CIRCULAR JOINTS)



PROVEN DESIGNS UNAVAILABLE FOR THESE SERVICES

Figure 4.4

While this list cannot be considered complete and will vary with specific applications, it will be used to define the design goals for this program. Design objectives and performance characteristics are given in Figures 4.5 and 4.6 respectively. In general, many of the requirements and objectives are defined as guidelines since the definition of specific values for design parameters requires considerable additional study and, sometimes, a specific reactor configuration on which to base the exact values involved. Some of the data required will necessitate test programs to determine approaches that will result in the most effective joint system.

The compressive force required to achieve a seal with differing seal configurations has been estimated but the data from different sources vary. All sources may be correct but the conditions under which measurements are made could be the cause of differences. Thus, the combination of conditions existing for each test must be known before a practical design is possible. The manner in which the seal loading required varies in order to achieve a seal with different design parameters, such as size, flange stiffness, thermal gradients, external loads and selection of materials, must be determined (elastomeric seals will have too short a life in the radiation environment expected in the FWBS vicinity). Other critical requirements include the need for clamping force uniformity and repeatability in achieving a sealed joint after seal replacement, or opening and reclosure. Thermal cycling is very important, arising primarily from vacuum bakeout and reactor cooldown and heatup.

4.2.2.2 Operating Environments

These include the vacuum characteristics (for vacuum joint system), atmospheric characteristics, thermal characteristics, space allowances, ionizing radiation characteristics, and possibly microwave radiation.

The vacuum joint systems associated with the plasma chamber are the most critical for joint system development. The vacuum environment requirements for a joint system are those at the outside of the shield since this represents a widely used location. The primary vacuum characteristics at this

DESIGN OBJECTIVES – VACUUM JOINT SYSTEMS

DESIGN OBJECTIVE	POTENTIAL DESIGN FEATURE
MINIMUM ASSEMBLY/DISASSEMBLY TIME	– MECHANICAL OPERATION (NOT WELDED) – VARIABLE ACCESS DIRECTION – REUSE SEALS – NO PLANNED DISCONNECT REFURBISHMENT – JOINT IS SELF ALIGNING
USE EXISTING SEAL DESIGNS	– ONLY UNIFORM COMPRESSIVE LOADS ON SEAL(S) – CLAMPING TOLERANCES ADJUSTABLE • FOR UNIFORM SEAL LOADING • COMPENSATE FOR SEAL CREEP – EXTERNAL LOADS MINIMIZED THROUGH SEAL
MINIMUM ASSEMBLY/DISASSEMBLY SPACE	– MINIMUM AXIAL MOTION FOR SEPARATION • MINIMIZE COMPRESSION OF JOINT – FOR SEAL CLEARANCE FOR ALIGNMENT CLEARANCE – MINIMUM LATERAL SPACE • MECHANISMS CLOSE TO DUCT OR CLOSURE
RELIABLE SEAL/ASSEMBLY OPERATION	– MINIMUM SEAL LOADING VARIATION – MAXIMUM SEAL/JOINT LIFE – CONTINUAL LEAK CHECK – DESIGN FOR MICROWAVE ENVIRONMENT – REPEATABLE SEAL USE
MINIMUM COST	– MINIMUM REFURBISHMENT – USE GENERAL PURPOSE TOOLS

Figure 4.5

JOINT SYSTEM PERFORMANCE CHARACTERISTICS

BASIC FEATURES

MEDIA/PRESSURE RANGES/FLOW REQUIREMENTS
RANGE OF SIZES
TYPE OF CLAMP-UP
REMOTE OPERATIONAL REQUIREMENTS
QUANTITY/COST CONSIDERATIONS

DESIGN CAPABILITIES

FUNCTIONAL

GAS PERMEATION
VIRTUAL LEAKAGE
BAKE-OUT CAPABILITY
TIME TO OPERATE (ASSEMBLY/DISASSEMBLY)
SELF LEAK CHECK
SEAL LIFE
RESEALIBILITY

MECHANICAL

FLANGE SIZE TO SEAL DIAMETER RATIO
SEAL THERMAL EXPANSION
SEAL REMOTE INSTALLATION
SEAL RETENTION
SURFACE FINISH
SIZE FACTORS
SHAPE FACTORS
THERMAL CYCLING

STRUCTURAL

PRESSURE/FUNCTION CRITERIA
SHEAR/BENDING/TORQUE/THRUST ACROSS JOINT
SEALING FORCE
WEIGHT

ENVIRONMENTAL

SURVIVABILITY OF SEALS IN RF ENVIRONMENTS
TEMPERATURE/TEMPERATURE SOAK
RADIATION/RADIATION SOAK
CORROSION
CLEANLINESS/CONTAMINATION PROOF

Figure 4.6

location for a tokamak reactor are dependent to some extent on the plasma characteristics. Therefore, the characteristics defined in the following list should be considered as part of a range of values.

- Base Pressure - ≈ 1.3×10^{-6} Pa (1×10^{-8} torr)
- Operating Pressure - ≈ 1.6×10^{-2} Pa (1.2×10^{-4} torr) or higher
- Vacuum Species - e, n, He, D, T, impurities
- External Atmosphere - dry air, T, n
- Bakeout Cycle - 300°C for 36 h

These environmental characteristics are taken primarily from the STARFIRE study. Other characteristics dependent on the reactor design such as material compatibility with the vacuum environment, outgassing requirements and allowable leak rates require additional definition.

The external atmosphere will be at atmospheric pressure or slightly less. It is assumed that air will be used for the purpose of development work but inert atmospheres have been considered. CO_2, He, Ar, or N may be used so materials and lubrication will be selected with the potential option of operating in these atmospheres unless the restrictions impose design requirements that adversely influence maintainability.

The joint system thermal environments at FWBS penetrations arise from bakeout and from conduction of the coolant systems. Bakeout tests for TFTR have assumed a maximum of 300°C during bakeout. Bakeout is expected to be from internal heating in the plasma chamber.

Coolant water temperatures in TFTR are expected to be approximately 150-170°C but STARFIRE has postulated temperatures of 300°C. Therefore, 300°C maximum shield wall temperatures are assumed for design purposes. If other coolants, such as helium are considered, the coolant temperatures may be greater but reactor room convection cooling may result in a maximum temperature at the joint near 300°C.

The neutron flux generated by the plasma will result in eventual material damage to reactor components, especially those close to regions of high flux of high energy neutrons. To the extent possible, vacuum joint systems are located at the back of the outboard shield region in most reactor concepts examined. However, joints located in scavenging ducts behind limiters or at diverters are subjected to high neutron fluxes. The flux and energy spectrum of neutrons for which these joint systems must be designed vary significantly with each reactor configuration. Many reactor configuration variables can be used to reduce the neutron dosage characteristics on these joint systems and other reactor components. A design based on STARFIRE should be sufficient to satisfy the maximum operating conditions to be found in most fusion reactor concepts. However, when the data become available, examination of other concepts, such as EBT and TMR, should be conducted to verify this assumption.

In those fusion devices or reactors that use ECRH for plasma heating, the microwave energy permeates all vacuum volumes connected to the plasma chamber unless protected by a microwave shield. Microwave energy at the output power levels and frequencies proposed for fusion devices (1.25 MW and 83 GHz for FED) will create arcing in small gaps. (EBT-P will use 28 GHz, and eventually may use 90 GHz.) The size of the gap which becomes critical depends on the microwave frequency and should be less than 1/2 wave length to reduce the ability of the gap to act as a waveguide and have potential for arcing. For 90 GHz, for example, 1/2 wavelength is approximately 0.17 cm. So the location of the joint is important; joints at vacuum closures between gaps in the shielding large enough to act as waveguides are likely to be affected. Wherever feaasible however, joint systems are expected to be protected by microwave shields. All design practices associated with equipment operating in electrical fields will be followed.

4.3 First Wall Electrical Connector Development

A need for development of electrical connectors which interconnect the first wall segments of FED and similar fusion device designs was identified during Phase 0. These will provide a continuous conducting path for currents induced in the first wall during normal operation and during plasma disruptions. Only initial estimates of the performance requirements were defined. Therefore, the Phase I program will make further investigations. The initial requirements based on FED and STARFIRE estimates typically will include:

- A peak current on the order of 6000 A/cm of first wall periphery.
- A current rise time on the order of 10 ms.
- A decay time of 100–300 ms.
- Driving voltage on the order of 10 VDC.
- Accommodate plasma charge displacement current.
- Provide for recovery after failure.
- Provide connector life > first wall life.
- Provide conducting path compatible with the environment.

The design objectives for AMR operations are similar to those for the joint system. These include the development of a remotely operable and maintainable connector with no access required for operation, and minimum service required during sector removal.

During Phase I the initial development work for electrical connector design will be conducted. as shown in Figure 4.1. Subsequent to determining the requirements and design objectives, a survey of connector materials and screening tests will be conducted. Actuator conceptual designs will be made and evaluated and an actuator constructed; further screening tests will be performed. A detailed test plan to fully develop the selected connector system will be prepared later in Phase I.

The ability to control current flow in the first wall of a tokamak reactor is receiving increasing attention. In experimental devices such as TFTR a nonconducting first wall in the toroidal direction is desirable to allow generation of maximum current in the plasma. However, increasing analysis of the FED concepts indicates the desirability of making the first wall a conductor in the toroidal direction. Since the maintenance approach in the FED, and also in the STARFIRE and other conceptual designs is to have separated segments of the First Wall/Blanket/and Shield system around the torus, a conducting first wall will require electrical connectors between segments.

FED type devices have the first wall, blanket and shield system divided into a number of toroidal segments or sectors, separated from each other by a gap of from 1 to 3 cm as shown in Figure 4.7. This gap allows the sectors to be installed and removed without interfering with each other. It also allows for thermal expansion without requiring deflection systems such as bellows or provisions to allow for growth. To make the first wall a conducting shell in the toroidal direction, connectors will probably be placed between the sectors in the region indicated in Figure 4.7.

The effects of a conducting first wall are summarized in Figure 4.8. With a sufficiently negligible resistance a significant plasma image current is induced in the first wall. This current generates a field which opposes plasma motion in the poloidal direction and thereby can aid in control of the plasma. The magnitude of this effect must be determined.

The principal reason for desiring a conducting first wall is the necessity to avoid structural damage in the event of a plasma disruption. The loss of a plasma current in such a case results in the generation of induced currents of the same magnitude as the plasma current in the reactor toroidal structures. If the first wall, which will carry a large portion of this current is not a conducting shell, arcing through the low grade plasma between sectors could cause major damage. To avoid this, sufficiently low resistance connectors between sectors must exist to provide a preferred current path. If the gap resistance without connectors is too great for arcing, the induced current in the first wall may seek a conducting path through the vacuum shell behind the shield. In this case, the current flow normal to the torus axis is expected to produce large deflecting forces and possibly distort the sector. The connectors between sectors must also be designed to minimize this eventually also. They are therefore, located as close to the plasma as possible. In the FED conceptual design, the connectors are located at the inboard edge of each sector shield.

One potential disadvantage of a conducting first wall is that the startup current in the plasma may be decreased by bleeding off the ohmic heating

FIRST WALL ELECTRICAL CONNECTORS PROVIDE A CONDUCTING SHELL

- PERMITS USE OF LARGE REMOVEABLE SECTORS
- MUST BE REMOTELY OPERABLE

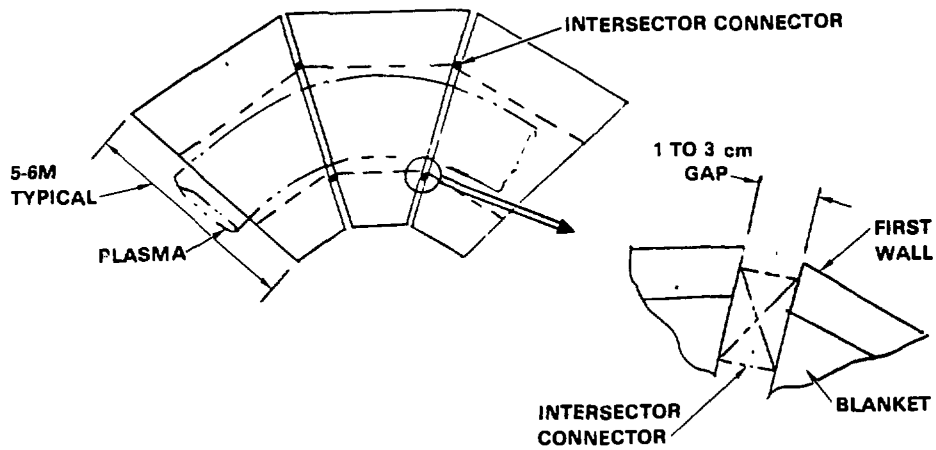


Figure 4.7

FIRST WALL ELECTRICAL CONNECTOR FUNCTIONS

- REQUIRED TO STABILIZE PLASMA
  - IMAGE CURRENT CIRCULATION IN FIRST WALL OPPOSES PLASMA MOTION AND REDUCES CONTROL PROBLEMS
- SECTOR FIRST WALL MUST CARRY SIGNIFICANT SHARE OF PLASMA CURRENT DURING A PLASMA DISRUPTION
- MUST BE LOCATED CLOSE TO PLASMA
  - REDUCES EMF FORCES
  - MINIMIZES ARCING
- STARTUP MAY IMPOSE CONFLICTING REQUIREMENTS WITH ENHANCED INTERSECTOR CONDUCTANCE

Figure 4.8

energy to induce a current in the first wall also. This apparent conflict in requirements may impose the need for an open connection prior to start-up, and the means to close the connection at some point during or after start-up. However, initial development will address a connector that will carry the required current and survive the environment. The disconnect/reconnect capability will be considered only as an adjunct to the development of the basic connector.

4.3.1 Design Requirements and Objectives

The information available at this point from which design requirements and objectives can be derived is incomplete. A preliminary set of requirements has been derived based on the analyses conducted for FED and STARFIRE and on theoretical assumptions. These are listed in Figure 4.9. Preliminary design objectives are summarized in Figure 4.10.

Analyses of the phenomena existing during a plasma disruption have not yet been examined but it is apparent that a connector system should be designed to carry the sum of all currents passing across the gap between sectors. A peak current of ~ 6000 A/cm of FW periphery based on the STARFIRE plasma current estimates and which assumes an instantaneous plasma disruption with all of the current induced in the first wall is a reasonable starting point. This would result in a total current equal to the plasma current and would be a worst case situation. The postulated condition therefore requires the capability to pass approximately 6000 amperes/centimeter of the peripheral distance around the first wall in the poloidal plane at the joint between FWBS sectors. The driving voltage for this current is most frequently estimated at approximately 10 volts. Present analyses indicate that the disruption will not be instantaneous and that the current will be distributed among the elements of the vacuum chamber and FWBS systems. Therefore, estimates of plasma disruption times on the order of 1 to 100 ms and current decay times, based on the L/R of the first wall of 100 to 300 ms are assumed for the FED concept.

FIRST WALL ELECTRICAL CONNECTORS – PRELIMINARY DESIGN REQUIREMENTS

- PROVIDE A TOROIDAL CONDUCTING FIRST WALL BETWEEN SECTORS
- MAINTAIN ELECTRICAL CONTACT DURING PLASMA DISRUPTION*
  - PEAK CURRENT ≈6000 A/cm OF FIRST WALL PERIPHERY
  - PLASMA DISRUPTION TIME ~ 1-100 ms
  - CURRENT DECAY TIME (L/R OF FIRST WALL) ~ 100-300 ms
  - DRIVING VOLTAGE ~ 10-100 VDC
  - CONTACT PRESSURE ~ 100 PSI DURING CURRENT FLOW
  - ACCOMMODATE PLASMA CHARGE DISPLACEMENT CURRENT
- PROVIDE FOR RECOVERY AFTER FAILURE (TYPICAL FAILURE MODES)
  - RESISTANCE WELDING OF CONTACTS
  - VACUUM BONDING OF CONTACTS
  - FAILURE TO DEPLOY/RETRACT/CONNECT REMOTELY
  - STRUCTURAL INTERFERENCE WITH SECTOR REMOVAL
  - ACTUATOR LEAKAGE
- PROVIDE CONNECTOR LIFE ⩾ FIRST WALL LIFE
- PROVIDE CONDUCTING PATH IN INTERSECTOR GAP ENVIRONMENT
  - RESISTANCE < LOW GRADE PLASMA IN GAP
  - RADIATION EXPOSURE IN GAP
  - THERMAL LOADS FROM PLASMA/SECTORS/BAKEOUT
  - COMPATIBLE WITH MICROWAVES

*ASSUME FED/STARFIRE ESTIMATES

Figure 4.9

F/W ELECTRICAL CONNECTOR – PRELIMINARY DESIGN OBJECTIVES

- MAINTAINABILITY
  - MINIMUM REFURBISHMENT ON SECTOR REMOVAL
  - HIGH RELIABILITY DURING REACTOR OPERATION
- REMOTE OPERATIONS
  - SECTOR REMOVAL UNINHIBITED BY CONNECTORS
  - MINIMUM OPERATIONS FOR ENGAGEMENT/RELEASE
  - OPERATE WITHOUT SPECIALIZED SERVICES/EQUIPMENT
- PERFORMANCE
  - MINIMUM OUTGASSING/VIRTUAL LEAKS
  - DISCONNECT DURING REACTOR STARTUP
- DESIGN
  - MINIMUM FIRST WALL REDESIGN TO ACCOMMODATE CONNECTORS
  - MINIMUM COST
  - PASSIVE OPERATION (NO MOVING PARTS)

Figure 4.10

The first wall connector system resistance must be low enough to provide a preferred path for the current. It is anticipated that a plasma, possibly only low grade, will exist in the gap between sectors. Plasma pressures may be on the order of 10^{-4} torr and even higher in the region where the plasma dumps to the wall. At these pressures, the plasma may provide little resistance to arcing so the first wall connector must provide even less. The low driving voltage also requires a low resistance in the first wall connector system to provide a preferred path. If the resistance is too high, alternative current flow paths could occur and damage may result and the connector system will not have accomplished its purpose. Additional analysis of specific designs must be conducted to determine a specific value.

Exposure to the plasma radiation of the first wall connector components that bridge the gap between sectors imposes the same environment on them as that for the first wall. This requires the potential use of armor or other shielding materials, and requires that the connector be cooled. The connector environment will be unbalanced, which must be considered in stress analyses, design of protective shields and in selection of materials. The thermal and radiation environmental influences on design are closely interactive. Microwave design considerations also apply if ECRH is used since shielding in this case appears to be impractical. Several optional concepts have been identified but extensive evaluation and exploratory testing are needed before even a conceptual design can be recommended.

The ability to recover from a first wall connector failure must be achievable by only remote means and without the use of special tools if at all possible. This is because the narrow width and staggered path of the gap appears to make access through any usual path impractical or, at least very time consuming.

The failure modes listed in Figure 4.9 are indicative of the design problems that must be considered to achieve a failure safe capability. Accordingly, the connector system must be designed to afford disconnect and removal backup capability before rework can begin. A minimum requirement is that the connector life be greater than or equal to the life of the first wall; connector system replacement should not be the cause of sector removal. Since connectors will usually comprise several component parts, (some of which are moving), the life and reliability requirements are expected to be difficult to achieve. However, as first wall life matures to the point of approaching reactor life, it is expected that the frequency of plasma disruptions will decrease because of better control techniques, thus enhancing the expected connector life.

4.4 Detailed Technical Plan for Phase I

The total effort required to develop an Assembly, Maintenance, and Repair (AMR) data base for the design of FWBS system was shown during Phase 0 to be very extensive. As much data as possible on critical AMR issues will be acquired and organized in a manner most useful for the support (but not requirements) of fusion designers. Four realistic tasks, have been defined for the first two years of Phase I. Additional effort will be identified during this period so that additional budget required to step up progress is known.

The broad interactions among the four tasks planned for Phase I are shown in Figure 4.11. The development of a joint system design and of an intersector first wall electrical connector will be instituted because of their criticality to reactor operations and AMR. Development to the extent that useful data for design guidelines can be produced is believed feasible within the projected Phase I funding. These and other existing data gleaned from current and past works will be organized and inserted into the Designer's Guidebook. The fourth task will formulate additional technical plans for extension of the joint system and first wall connector developments and for probing other AMR areas where a data base is needed. These additional plans will be started as appropriate.

4.4.1 Task 1 - Designer's Guidebook

As previously stated the Designer's Guidebook will serve as the output vehicle for all Phase I efforts. That is, the results of the technology

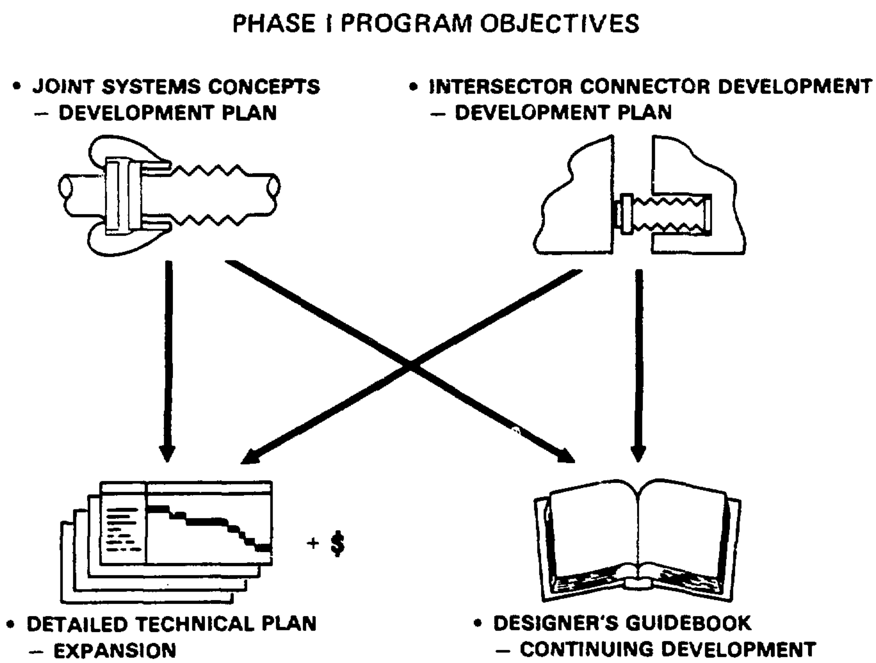

PHASE I PROGRAM OBJECTIVES
• JOINT SYSTEMS CONCEPTS
– DEVELOPMENT PLAN
• INTERSECTOR CONNECTOR DEVELOPMENT
– DEVELOPMENT PLAN
+ $
• DETAILED TECHNICAL PLAN
– EXPANSION
• DESIGNER'S GUIDEBOOK
– CONTINUING DEVELOPMENT

Figure 4.11

survey and component test activities will be summarized and incorporated into appropriate sections. The key tasks in formulating the Guidebook and a proposed schedule is shown in Figure 4.12.

The relationship of these tasks to the work breakdown structure for the Designer's Guidebook is shown in Figure 4.12. Figure 4.14 indicates that Sections 1.0 and 2.0 were started during Phase 0, and that the first draft will be completed in Phase I. First drafts for Sections 3.0 and 4.1 are to be completed and submitted in Phase I. The work on Section 4.2 will be started but this large task will be completed in another fiscal year. Section 4.3 has been deleted since these data are being included in the Materials Handbook for Fusion Energy Systems. Survey results will be integrated into the Guidebook sections as indicated in the figure. The sections will be submitted for review and inclusion into the Guidebook as they are completed. Phase I effort on the Guidebook will be limited to the following key sections.

<u>Section 1.0 - Fusion Plant Features</u>. Brief easy-to-understand descriptions, including sketches where feasible, will be employed to help the designer understand the basic fusion reactor plant designs and the terms used. The interface between maintenance systems, the reactor and the surrounding building will be shown. The descriptions will cover major types of magnetic fusion reactors.

<u>Section 2.0 - AMR Concerns and Requirements</u>. A low level effort to further develop and refine the concerns and requirements will be continued. This will consist of adding data to the Phase 0 activity.

<u>Section 3.0 - Optional Maintenance Approaches</u>. This section will contain information, with sketches where appropriate, that describes the advantages, disadvantages, limitations, etc. of the basic maintenance approaches used on radioactively contaminated equipment applicable to fusion plants. This includes contact, remote with provision for contact, remote only, and semi-remote approaches. A first draft of Section 3.0 will be completed six months after Phase I begins.

<u>Section 4.0 - General Remote Equipment Design Guides</u>. There are many design guides that have general application to any remotely maintained

PROPOSED SCHEDULE FOR PHASE I GUIDEBOOK DEVELOPMENT

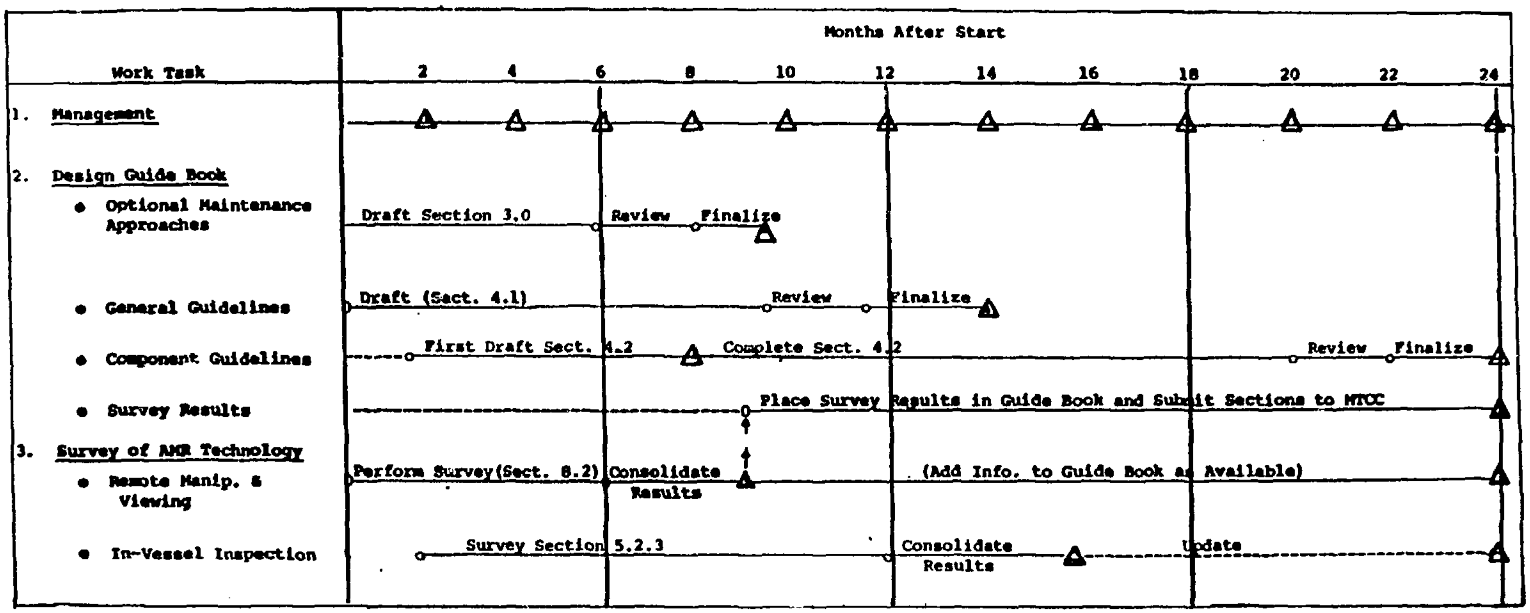


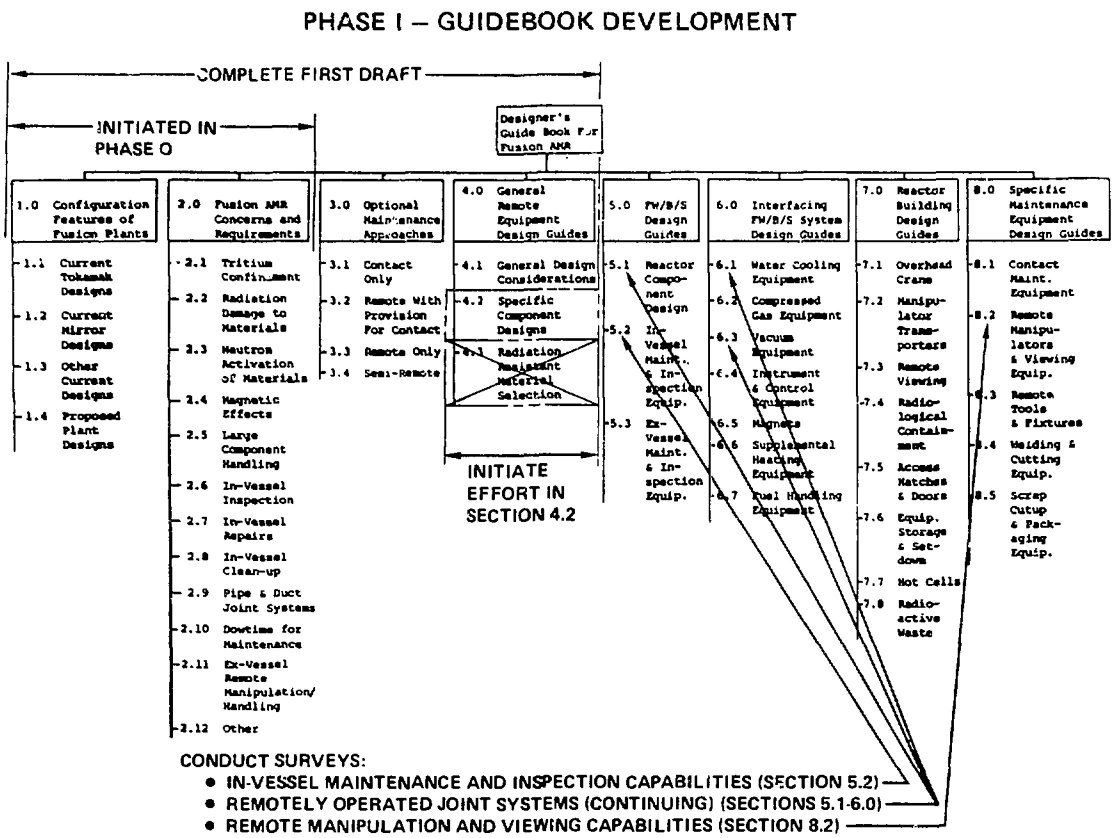
Figure 4.12

OUTLINE FOR DESIGNER'S GUIDEBOOK

Designer's Guide Book For Fusion AMR

- **1.0 Configuration Features of Fusion Plants**
  - 1.1 Current Tokamak Designs
  - 1.2 Current Mirror Designs
  - 1.3 Other Current Designs
  - 1.4 Proposed Plant Designs
- **2.0 Fusion AMR Concerns and Requirements**
  - 2.1 Tritium Confinement
  - 2.2 Radiation Damage to Materials
  - 2.3 Neutron Activation of Materials
  - 2.4 Magnetic Effects
  - 2.5 Large Component Handling
  - 2.6 In-Vessel Inspection
  - 2.7 In-Vessel Repairs
  - 2.8 In-Vessel Clean-up
  - 2.9 Pipe & Duct Joint Systems
  - 2.10 Dowtime for Maintenance
  - 2.11 Ex-Vessel Remote Manipulation/Handling
  - 2.12 Other
- **3.0 Optional Maintenance Approaches**
  - 3.1 Contact Only
  - 3.2 Remote With Provision For Contact
  - 3.3 Remote Only
  - 3.4 Semi-Remote
- **4.0 General Remote Equipment Design Guides**
  - 4.1 General Design Considerations
  - 4.2 Specific Component Designs
  - 4.3 Radiation Resistant Material Selection
- **5.0 FW/B/S Design Guides**
  - 5.1 Reactor Component Design
  - 5.2 In-Vessel Maint. & Inspection Equip.
  - 5.3 Ex-Vessel Maint. & Inspection Equip.
- **6.0 Interfacing FW/B/S Systems Design Guides**
  - 6.1 Water Cooling Equipment
  - 6.2 Compressed Gas Equipment
  - 6.3 Vacuum Equipment
  - 6.4 Instrument & Control Equipment
  - 6.5 Magnets
  - 6.6 Supplemental Heating Equipment
  - 6.7 Fuel Handling Equipment
- **7.0 Reactor Building Design Guides**
  - 7.1 Overhead Crane
  - 7.2 Manipulator Transporters
  - 7.3 Remote Viewing
  - 7.4 Radiological Containment
  - 7.5 Access Hatches & Doors
  - 7.6 Equip. Storage & Set-down
  - 7.7 Hot Cells
  - 7.8 Radioactive Waste
- **8.0 Specific Maintenance Equipment Design Guides**
  - 8.1 Contact Maint. Equipment
  - 8.2 Remote Manipulators & Viewing Equip.
  - 8.3 Remote Tools & Fixtures
  - 8.4 Welding & Cutting Equip.
  - 8.5 Scrap Cutup & Packaging Equip.

Figure 4.13



PHASE I – GUIDEBOOK DEVELOPMENT
COMPLETE FIRST DRAFT
INITIATED IN PHASE O
Designer's Guide Book For Fusion AMR
1.0 Configuration Features of Fusion Plants
1.1 Current Tokamak Designs
1.2 Current Mirror Designs
1.3 Other Current Designs
1.4 Proposed Plant Designs
2.0 Fusion AMR Concerns and Requirements
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2.9 Pipe & Duct Joint Systems
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3.1 Contact Only
3.2 Remote With Provision For Contact
3.3 Remote Only
3.4 Semi-Remote
4.0 General Remote Equipment Design Guides
4.1 General Design Considerations
4.2 Specific Component Designs
4.3 Radiation Resistant Material Selection
INITIATE EFFORT IN SECTION 4.2
5.0 FW/B/S Design Guides
5.1 Reactor Component Design
5.2 In-Vessel Maint. & Inspection Equip.
5.3 Ex-Vessel Maint. & Inspection Equip.
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8.3 Remote Tools & Fixtures
8.4 Welding & Cutting Equip.
8.5 Scrap Cutup & Packaging Equip.
CONDUCT SURVEYS:
• IN-VESSEL MAINTENANCE AND INSPECTION CAPABILITIES (SECTION 5.2)
• REMOTELY OPERATED JOINT SYSTEMS (CONTINUING) (SECTIONS 5.1-6.0)
• REMOTE MANIPULATION AND VIEWING CAPABILITIES (SECTION 8.2)

Figure 4.14

equipment in any type of nuclear facility. The purpose of Section 4.0 is to compile all of these guides into what could be considered a set of fundamental guides or rules. Section 4.0 is divided into two subsections, 4.1 and 4.2.

Section 4.1 will contain a description of fundamental design features that are recommended for general application on remotely maintained equipment independent of the type of plant. For the Designer's Guidebook, Section 4.1 will serve as a set of basic requirements that are applicable to (1) design work on the TFTR and FED projects and (2) the joint system or first wall connector design work. The first draft will be prepared during the first nine months of Phase 1. Following a detailed review, it will be revised and completed for inclusion in the guidebook.

Section 4.2 of the guidebook will contain specific guidelines that are applicable to remotely maintained equipment at a component level, for example, lifting handles, captive screws, remote clamps, motors, gear boxes, piping jumpers, guide and locating devices, joint system components, electrical connectors, etc.

4.4.1.1 Survey of AMR Technology

The current Phase I program does not allow for a technology survey of all equipment items listed in the Designer's Guidebook outline. A prioritized approach based on priorities has been established for the survey as follows:

- Remote Manipulation and Viewing

  A six-month period is needed to complete the survey (started during Phase 0) of equipment listed i Section 8.2 of the Guidebook. This includes electric master-slave manipulators, power manipulators, mechanical master-slave manipulators, shielding windows, CCTV, periscopes and robotic systems. The consolidated results will be completed about nine months after the start of Phase I. Revisions and additional information will be incorporated throughout Phase I.

- In-Vessel Inspection Equipment

  A survey of equipment and techniques for remote inspections inside the first wall vacuum vessel will be performed. A period of 12 months is needed since much of the information will be solicited via mail. The results will be consolidated into the Guidebook during the second half of Phase I.

- Remotely Operated Joint Systems

  The survey of remotely operated joint systems will be extended to include other joint closure devices and to define the characteristics and the potential for remote operation incorporated in each device. This extension will be a continuing low level effort conducted when opportunities arise in conjunction with other activities.

4.4.2 Task 2 - Joint Systems Development

The development of joint system designs for use in fusion devices and reactors requires extensive additional design and test. Effort in Phase I is formulated to provide as much information as possible; it will be conducted in conjunction with a parallel development of first wall electrical connectors until a cutoff point is reached after which emphasis will be placed on the electrical connector development. Figure 4.15 illustrates the tasks to be conducted and the duration planned for each task.

Figure 4.16 illustrates a stylized joint system and its component functions. Listed under each function are some of the capabilities that must be determined and provided for in a remotely operable vacuum system. One of the more important is the clamping system, which holds together the two faces of the joint and provides the required loads on the seal system. The clampin system design is also extremely critical in establishing a high degree of maintainability. Therefore, in Phase 1 this is the functional element of a joint system on which development will be concentrated.

PHASE I JOINT SYSTEM DEVELOPMENT SCHEDULE

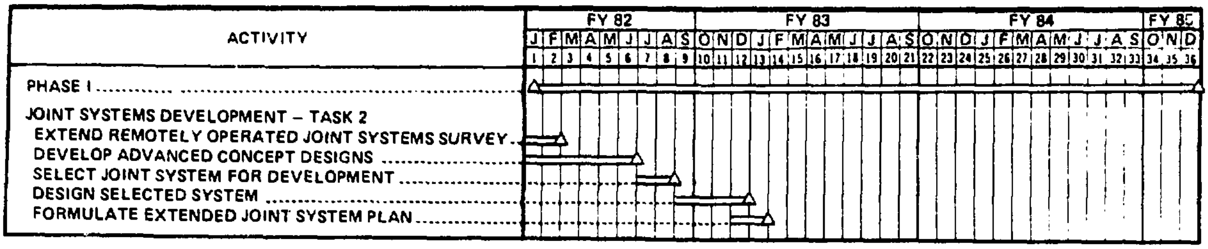


Figure 4.15

NON-CIRCULAR JOINT SYSTEM DEVELOPMENT REQUIRED

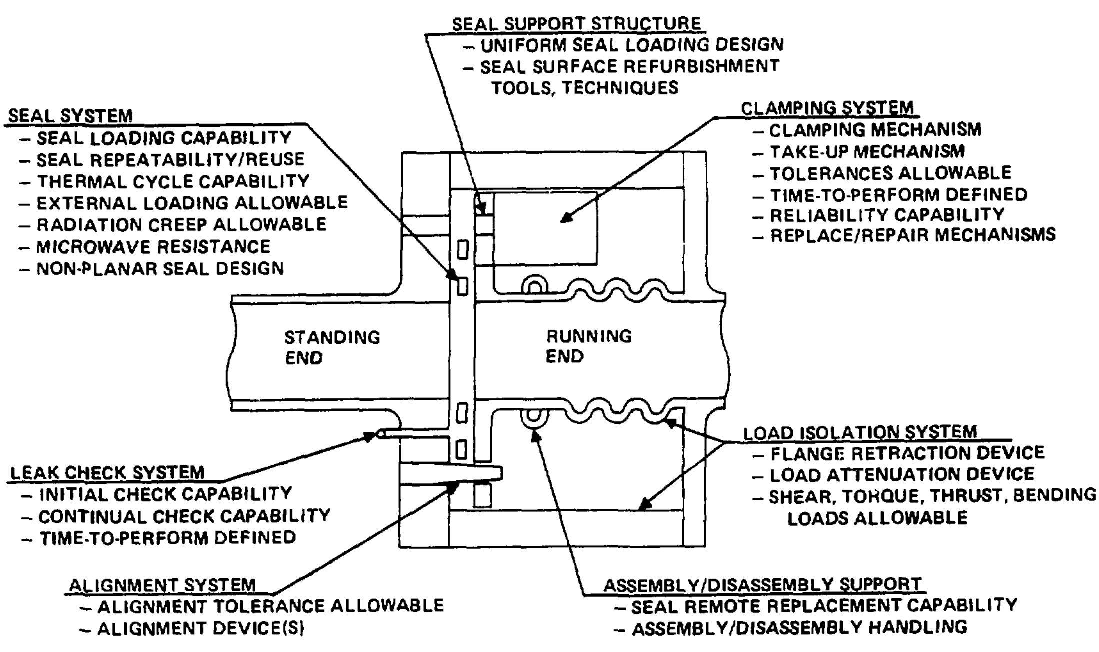


Figure 4.16

The particular objective is to design a remote operating mechanism for closure of vacuum joint systems, suitable for use in fusion devices employing a DT plasma. A mechanism design for use in rectangular or other non-circular openings in the plasma chamber and interfacing system vacuum walls will be defined. Only non-circular configurations are addressed because (1) these have a greater impact on maintenance operations than other components associated with a joint system; (2) advances in capability are required for these mechanisms in remote maintenance assembly/disassembly work; (3) it appears that useful results can be achieved within the available scope of Phase I resources; and (4) this development appears more urgent than the advancement of clamping systems for circular openings since several design concepts exist in this area.

4.4.2.1 Joint System Design

Several advanced conceptual designs will be proposed, following evaluation, one will be selected for the detailed design necessary prior to test. Before these efforts can begin, existing designs must be compared with the required operating capabilities and evaluated to determine which characteristics are of most benefit. Figure 4.17 lists the steps involved in the general approach to be taken for development of a selected design.

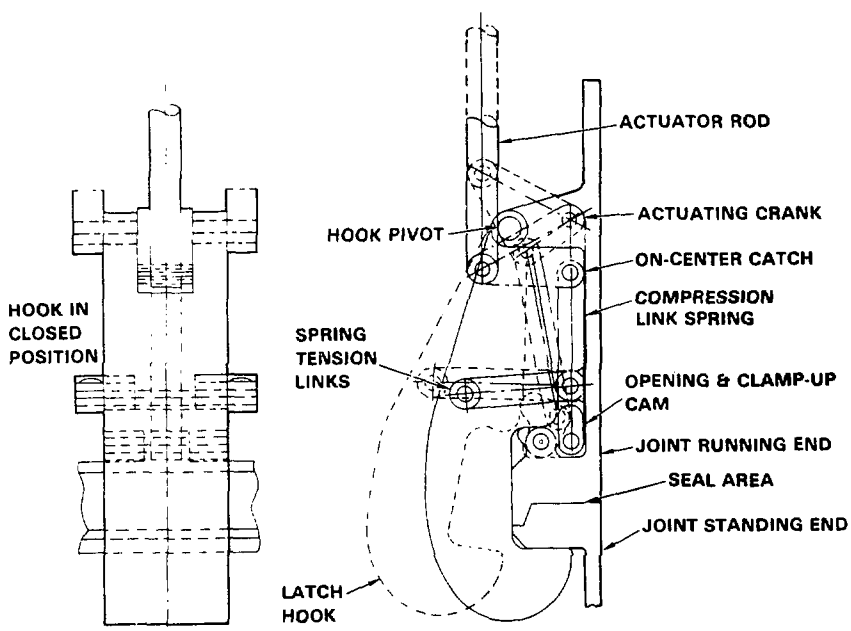
Because each subsystem joint design in the fusion reactor will have separate requirements depending upon many factors, no one general all-conforming joint configuration is obvious. However, certain elementary mechanical aspects of remote joint operations can be considered and evaluated in order to provide a library from which applicable joints can be assembled according to needs when the particular subsystem matures.

A hook-type device which would hold the two joint flanges together as shown in Figure 4.17, is an example of a clamping mechanical arrangement. These clamp sets could be located every few inches around the flange periphery and could be linked to powered actuators. They could be easily released individually in case of malfunction. Clamp devices permit the use of small flanges and load paths directly through the seal cross sections, thus minimizing flange load eccentricities which lead to sealing breakdowns.

PHASE I JOINT SYSTEM DESIGN

- DEVELOP ADVANCED CONCEPTS
  - VACUUM, NON-CIRCULAR, LARGE SIZE
  - MINIMUM OF 3 SOURCES
    - MDAC
    - GENERAL ATOMIC
    - REMOTEC
- EVALUATE AND SELECT FOR JOINT SYSTEM DEVELOPMENT
- DESIGN JOINT SYSTEM
  - SIZE FOR APPLIED LOADS
  - THERMAL ANALYSIS
  - MATERIAL SELECTION
- CONTINUE TEST PROGRAM FORMULATION
  - MECHANICAL
  - LEAK CHECK
  - EXTERNAL LOADS
  - THERMAL CYCLING
  - RADIATION EFFECTS

Figure 4.17



LATCH FASTENER DEVICE CONCEPT

Figure 4.18

At least three configurations will be defined to the level of detail required for evaluation; two subcontracts will be let for this purpose. (See Fig. 4.17) The same set of requirements and evaluation criteria will be given to each group at the outset to bound the problem by the same factors for each design team. The conceptual designs will include techniques for satisfying each of the functions delineated in Figure 4.16. Also, each conceptual configuration will be sized for a complete set of applied loads which will be arbitrarily selected based on the combined experience of the participants. In addition, the thermal and radiation environment will be defined and the major impacts of these environments will be considered in the designs. The requirements for vacuum closures, such as doors, are generally simpler than for vacuum ducts. Therefore, the designs for ducts will receive emphasis and each design will be defined for a range of duct sizes. The survey of seal designs appropriate for hard vacuum systems in a radiation environment has disclosed that only a few are satisfactory for this application. New seal design efforts will not be undertaken however unless a design which promises improved performance through use of a previously undeveloped principle is devised. It is believed that existing designs can be made to function for the selected application. A conceptual design is difficult to evaluate unless the tools required for its assembly, maintenance and repair are also defined.

The selected joint system will be designed in further detail in preparation for conducting demonstration and development tests. The design effort will concentrate on the clamping system and its interfaces with the other functional elements of the joint system concept. A range of sizes will be defined to determine the size limits, if any, that may exist. Detailed design will include materials selection, process definition, if required, parts drawings specifying finishes, tolerance, etc., stress analyses, thermal analyses and the definition of maintenance procedures. The equipment necessary to conduct the test programs will also be defined.

Evaluation of the conceptual joint system designs will include those devised as part of this plan and also those included in the results of the remotely operable connector survey which may be readily adaptable to the requirements of the selected application. A weighted comparison of the criteria defined by the vacuum joint system requirements will be employed. Several sets of weighting factors may be used to determine the sensitivity of the selection to a variation in the criteria that are deemed important to the acceptance of the design by reactor designers.

4.5 Task 3 - First Wall Electrical Connector Development

Development of a first wall electrical connector system in Phase I will be accomplished in three parts. The first is to conduct a survey and perform screening tests of potential contact materials; the second is to define suitable actuator conceptual designs, evaluate them and design the selected actuator; and the third is to design and fabricate test specimens and conduct demonstration and/or developmental tests. The data developed will be reduced for incorporation as guidelines in the Designer's Guidebook. The planned schedule for this approach is shown in Figure 4.19; it is based on a two-year period and will be developed further once the design requirements and detailed test plan are more fully determined. Development will be conducted in conjunction with a parallel development of joint systems. It is believed that the existence of facilities that can be used in the test program and the small size of the devices anticipated will enable meaningful tests.

4.5.1 Development Objectives

The principal objective of this part of Phase I is to develop a connector and an actuator which can be used in a system which interconnects two FWBS sectors in a tokamak reactor. Since this is at present defined only in a preliminary manner, the initial effort will be to identify and quantify the requirements to the extent possible. Requirement definition in the areas shown in Figure 4.20 is needed.

4.5.2 Electrical Connector Requirements

In addition to the design performance requirements for a connector system, data on the limiting capabilities of contacts for high current flows at low resistance are needed. Contact designs and materials used for these contacts will be surveyed and a set of materials with potential application

PHASE I FIRST WALL ELECTRICAL CONNECTOR DEVELOPMENT SCHEDULE

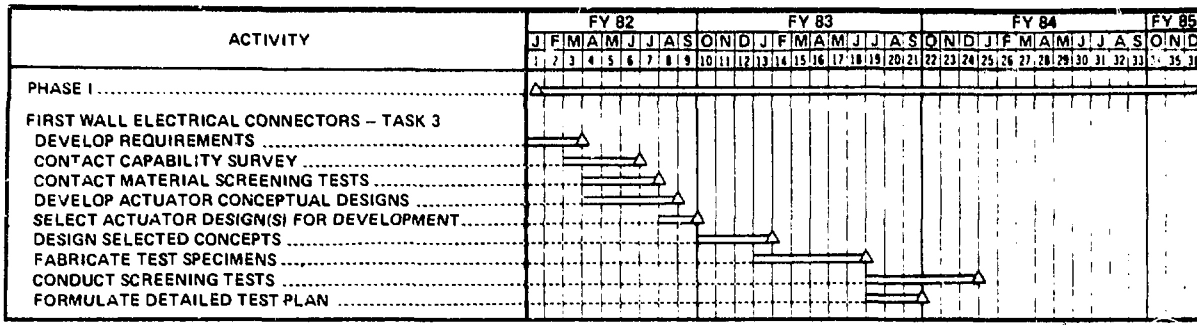


Figure 4.19

PHASE I – CONNECTOR SYSTEM DEVELOPMENT

- ESTABLISH REQUIREMENTS
  - CURRENT DENSITY AND PROFILE*
  - VACUUM ENVIRONMENT*
  - SECTOR RELATIVE MOTION
  - INSTALLATION AND REMOVAL LIMITS
  - NUCLEAR AND SURFACE HEATING LOADS
  - RADIATION DOSE
  - CONTINUOUS OR SWITCHABLE CONTACTS*

- SURVEY CONTACT CAPABILITIES
  - CURRENT DENSITY LIMITS
  - MATERIAL TYPE
  - CURRENT PROFILE EFFECTS
  - CONTACT SIZE, SHAPE AND SURFACE FINISH
  - ENVIRONMENT EFFECTS (VACUUM PRESSURE)
  - TEMPERATURE LIMITS

*CONSULT WITH
RON PRATER – GA
KEN EVANS – ANL
JOHN MURRAY – ORNL/
JIM PIPKINS – MDAC
GEORGE BRONNER – PPPL

Figure 4.20

will be selected, and tests will be defined to compare performance limits. A preliminary survey of facilities that could possibly be used for these screening tests was made and some of their capabilities are shown in Figure 4.21. In addition several more facilities have been identified. When the design requirements for the contacts and the test conditions for screening materials have been defined, a more detailed examination of leading candidate facilities will be made. The proposed plan is based on the use of an MDAC facility, for initial tests other than that shown in Figure 4.21. This other facility will produce 36,000 amperes with a 200 V driving voltage and a rise time of 10 ms. Because of the cost of testing, initial screening tests on a facility of limited capability such as this MDAC facility or an ANL facility are planned.

Screening tests are planned with predetermined contact forces to be tested in a vacuum over a range from 10^{-2} to 10^{-6} torr. The number of tests and variations in test parameters being considered are indicated in Figure 4.22. This figure also lists additional steps in the development plan.

The design of the first wall electrical connector system will be conducted in two parts. A series of conceptual designs will first be explored, then a single concept will be selected for detail design in preparation for fabrication and test.

4.5.2.1 Conceptual Design. In parallel with the contact material screening tests the designs of several actuator systems will be studied. These will be a part of a total connector system concept for interconnecting FWBS sectors at or near the first wall. The connector actuator for closing and opening the gap between sectors will be emphasized. Requirements will continually be evaluated in the light of analyses being conducted for such projects as FED to ascertain the best estimates of connector spacing and total current capacity. Also, a range of sizes will be estimated to handle variations in current requirements and determine capacity and size limitations. Conceptual designs of the actuator will include definition of size requirements for contact pressures, access required, maintenance procedures, materials and estimates of radiation and thermal effects. Since the actuator must also be a

POSSIBLE CONTACT TEST FACILITIES

	ENERGY CONTENT	PEAK CURRENT	DURATION	$\Sigma i^2 t$
MDAC	180 COULOUMBS @ 12 KV	200 KA 20 KA	RISE 15 μSEC DECAY TO 100 KA IN 50 μSEC DOUBLE EXPONENTIAL 200 μSEC RISE 8 cm SEC DECAY TO 10 KA	2 X 10^6 AMP^2 SEC
GENERAL ATOMIC – D-III POLOIDAL COIL POWER SUPPLY	> 20 MJ	100 KA	20 mSEC (RISE) 80 mSEC (FLATTOP) 20 mSEC (DECAY) 1 PULSE/5 MIN	10^9 AMP^2 SEC
UNIVERSITY OF TEXAS	10 MJ TERMINAL VOLTAGE 0 TO 45V ADJUSTABLE	800 KA	1 SEC RC DECAY TIME 50 mSEC RISE	–
ANL	5V DC	50 KA	CONTINUOUS SHAPED PULSE AS REQUIRED	

Figure 4.21

PHASE I – CONTINUING CONNECTOR SYSTEM DEVELOPMENT

- CONDUCT CONTACT STICKING TESTS
  - 1 TO 3 MATERIALS
  - 5 TO 10 CONTACT PRESSURES
  - 1 TO 3 CONTACT SIZES
  - 5 CURRENT DENSITIES
  - 1 TO 3 CURRENT PROFILES
- DEVELOP ACTUATOR DESIGNS
- FABRICATE AND TEST ACTUATOR DESIGN (AS FUNDING PERMITS)
  - TPE III FACILITY – ELECTROMAGNETIC
  - TPE I – HEATING
  - LIFE CYCLE TESTING – MDAC OR OTHER

Figure 4.22

conductor with very low resistance, this aspect of the design will be thoroughly investigated to assure that the electrical characteristics of each concept meet the postulated requirements. Means for varying these characteristics over an expected range by varying design parameters within the concept will be explored to assure the potential validity of the concept should analyses and tests necessitate a revision of the design requirements. This selected concept will be designed in sufficient detail for fabrication and testing. The evaluation process for the conceptual design will apply the same principles as those used to select the joint system design.

4.5.2.2 Detail Design. Detail design of the first wall electrical connector will encompass the actuator and contacts, and the test fixture required to mount the test article in the facility selected for testing. The contact design will use materials selected from the screening tests.

Definition of mechanical capabilities such as operating forces for making and breaking the contacts and for maintenance operations, the specification of finishes, tolerances, etc., stress analyses, thermal analyses, parts drawings for fabrication and the definition of maintenance procedures and processes will be included. The mount for the test article and the services required to interface with the test facility will also be designed.

4.5.2.3 Test Plan Formulation The test plan for the electrical connectors is highly dependent upon the requirements, the conceptual designs, and the budgetary limitations. Therefore, this plan will be formulated subsequent to determination of the requirements for the conceptual designs and the completion of a survey of the facilities in which the tests may be conducted.

The objective of the tests will be to evaluate the performance of the connector as predicted and also to determine its behavior, if possible, under conditions of electrical and magnetic fields that simulate those in a reactor. Other tests will include the effects of radiation heating and life cycle of the repeated operations to determine fatigue or other operating limits that influence its life. The PE-III facility at ANL may be useful for electromagnetic testing. The PE-I facility at Westinghouse may be suitable for radiation heat testing. Mechanical cyclic tests could be conducted at MDAC or other locations, depending upon the complexity. If the connector is pressurized by coolant, heated and subjected to high current flows in a vacuum, the test installation becomes somewhat complex and the available facilities would be limited.

4.6 Task 4 - Program Element Planning

The planning necessary to define additional work in the AMR critical areas of FWBS development and operation will be conducted insofar as possible during this task. This planning is primarily intended to formulate a series of "mini packages" that may be individually funded but which in combination lead toward a comprehensive capability to conduct AMR efforts on advanced fusion experimental devices or reactors. A "mini package" is defined as an experimental or test program that will achieve a specific limited objective within a given dudgetary limit.

The range of programs to be examined include extensions of testing for the selected joint system or its components, or of testing the electrical connector system. These additional programs must be logical extensions toward attaining the development of useful devices for these functions.

In addition, other program elements needed to define a complete AMR capability have been grouped into six general areas, listed in Figure 4.23. The subelements of the program identified under these general areas were generally defined in a workshop for an EPRI study and are being reduced in that study to those elements deemed of importance. The task in Phase I is to determine other useful work elements and define the means to accomplish them. Any apparent overlap with the experiments proposed in the EPRI study will be resolved.

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1. Zahn, H. S. et al., "Developing Maintainability for Tokamak Fusion Power Systems, Phase I Report," DOE Report No. COO-4184-4, October 1977, Prepared for the U.S. Energy Research and Development Administration by McDonnell Douglas Astronautics Company - St. Louis Division.

PROGRAM ELEMENT PLANNING

- PURPOSE – DEVELOP DETAILED TECHNICAL PLANS FOR FW/B/S AMR PROGRAM ELEMENTS

- EXPANSION OF PROGRAM ELEMENTS – FOR EXAMPLE:

  - REMOTE IN-VESSEL INSPECTION AND REPAIR
  - REMOTE COMPONENT ASSEMBLY/DISASSEMBLY
  - REMOTE WELDING AND CUTTING
  - MAINTENANCE SYSTEM DEFINITION
  - RELIABILITY
  - MATERIAL RECYCLE

- TECHNICAL PLAN OBJECTIVE – PROVIDE PLANNING DATA FOR EXPANSION OF AMR PROGRAM

- *TECHNICAL PLAN COMPOSITION – BY PROGRAM ELEMENT*

  - TECHNICAL TASKS
  - TEST PLAN
  - ELAPSED TIME SCHEDULE VS FUNDING
  - FACILITIES REQUIRED/CONSTRUCTED
  - TOTAL COST

Figure 4.23

2. Fuller, G. M., et al., "Developing Maintainability for Tokamak Fusion Power Systems, Phase II Report," DOE Report No. COO-4184-6, November 1978, Prepared for the U.S. Department of Energy by McDonnell Douglas Astronautics Company - St. Louis, Division.

3. Zahn, H. S. et al., "Developing Maintainability for Fusion Power Systems, Final Report," DOE Report No. COO-4184-8, November 1979, Prepared for the U.S. Department of Energy by McDonnell Douglas Astronautics Company - St. Louis Divison.

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