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A USER'S VIEW OF FERF

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MASTER

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Introduction

The Fusion Engineering Research Facility's (FERF) job is to provide adequate space and fluence of 14 MeV neutrons to perform the extensive materials and system testing required prior to power reactor final design.

A secondary but essential purpose for building and operating FERF is to gain experience in the problems associated with the practical integration of the complex subsystems of a fusion reactor into a reliable machine(1,2). The aim of this study is to optimize FERF for its primary function, the testing of materials and systems.

The study is based on the use of a mirror reactor for FERF. The basic machine geometry and neutron yields are those reported in Reference 3. The magnet orientation and supporting structure have been modified to improve access and maintainability.

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*Work performed under the auspices of the United States Energy Research & Development Administration

The features that make this mirror machine attractive for FERF are:

- Small size - a mirror machine is smaller and potentially less costly to build and operate than other confinement schemes.
- Reactor level first wall flux - 1.4×10^{14} n/cm^2-s.
- Maintainability - the first wall is easily replaceable.
- D.C. operation - the mirror reactor will operate at steady state for relatively long periods (weeks) providing high availability for irradiations.
- Accessibility - the unique geometry of the Yin-Yang magnet set provides excellent access to the high flux region of the reactor.

Testing Program

In order to design facilities for testing materials and systems in FERF, one must have some understanding of the type and scope of tests that will be required. Basically there are two types of tests;materials properties and operating systems.

The overall CTR materials irradiation testing program has already started with the use of existing 14 MeV neutron sources, fast fission reactors and various simulation techniques. Much of the testing work can be economically done by these means if accurate scaling and extrapolation laws can be established. One of the functions of FERF will be to verify these extrapolations.

We have focused this study on a testing program for candidate first wall structural materials. These materials will have to suffer the maximum flux of the most damaging particle species in a power reactor. In addition, in most reactor designs the first wall structure forms the containment for a high pressure coolant which further distresses the structural material.

Because of the expense in fabrication, installation and loss of revenue while down for replacement, maximizing the useful life of the first wall is basic to the economics of fusion power reactors. Many other material studies are necessary. Our view is that all the other materials needed can be conveniently tested in facilities that are satisfactory for high flux, high fluence testing of first wall materials.

Systems tests will principally be concerned with first walls and blankets. Functional as well as compatibility tests are required prior to finalizing power reactor designs.

In the following sections we describe the requirements of a materials and system testing program, and we subsequently describe a set of facilities in a mirror FERF to accommodate the program.

Materials Testing Program

We have outlined some of the materials testing requirements related to the proposed LLL FERF. Many of the anticipated tests will use minimal equipment, while others will require sensitive and sophisticated in situ instrumentation for measuring the various experimental variables such as stress, strain, temperature and flux.

Most materials tests will need localized static dosimetry for determining irradiation fluence during exposure. Some others will require continuous dynamic flux measuring instrumentation for materials tests involving kinetic rate processes which are sensitive to flux levels; e.g., creep, precipitation, and diffusion.

Instrumented tests may be long-term (to 1000 hr) or short-term (to 3 hr) having steady state or transient experimental conditions. For example, a creep test would be a long-term steady state materials test, and a stress-relaxation test would be a short-term transient experiment.

We have concentrated our initial analyses for in situ testing requirements mainly related to creep, tensile, and fracture tests. These tests should be among the most complicated and difficult in-reactor tests to conduct. Of these three types of tests, creep will be more difficult to do experimentally in FERF because of its long duration and requirements of constant stress, temperature, and flux. There is some tendency to underestimate the difficulty of successfully conducting in situ mechanical properties tests during irradiation. However, scientists at HEDL, with their past experience in fission reactor materials tests, indicated that there can be serious problems in conducting in-pile mechanical tests. Some problem areas are: extensometry irregularities and malfunctions; temperature control problems; deformation of load applying grips; general misalignment problems; and containment and corrosion failures. Each experimental setup must be engineered to resolve these problems.

Table I through IV indicate what we feel are ambitions, but reasonable, guidelines for adequately characterizing the mechanical properties of a single material using creep, tensile, and fracture-toughness tests. Though this is a relatively extensive testing program, most candidate materials will be eliminated in practice by simpler screening tests, and only several key materials would be fully evaluated by testing of this broad a scope. A listing of some potential materials for CTR application is given in Table V.

TABLE I

TEST PROGRAM OUTLINE FOR CHARACTERIZATION OF THE CREEP PROPERTIES OF ONE MATERIAL IN FERF

STRESS RUPTURE

Strain-Time Tests

Flux, Stress, Temperature = Constant

12 Tests required 1000 hours each for 3 temperatures, 2 stresses, and 2 heat treatments.

STRESS EFFECT ON CREEP RATE

Change of Stress Tests

Flux, Temperature = Constant

8 Tests required 500 hours each for 4 temperatures and 2 heat treatments.

TEMPERATURE EFFECT ON CREEP RATE

Change of Temperature Tests

Flux, Stress = Constant

8 Tests required 500 hours each for 4 stresses and 2 heat treatments.

FLUX EFFECT ON CREEP RATE

Change of Flux Tests

Temperature, Stress = Constant

4 Tests required 500 hours each for 4 temperatures.

TABLE II

SUMMARY FOR CREEP PROPERTY EVALUATION

Total number of Tests	=	32
Strain-Time Tests	=	12 000 hr
Stress Effects Tests	=	4 000 hr
Temperature Effects Tests	=	4 000 hr
Flux Effects Tests	=	2 000 hr
OVERALL TOTAL		22 000 hr

Utilizing 4 sample tubes, 7-8 months required to complete Creep testing on one material.

TABLE III

TEST PROGRAM OUTLINE FOR CHARACTERIZATION OF THE TENSILE AND FRACTURE PROPERTIES OF ONE MATERIAL IN FERF

TEMPERATURE EFFECT ON STRENGTH AND DUCTILITY

Stress-strain tests at various temperatures

Strain Rate, Flux, Fluence* = Constant

8 Tests required for 4 temperatures and 2 grain sizes.

STRAIN RATE EFFECT ON YIELD STRESS

Stress-strain tests at various strain rates

Temperature, Flux, Fluence* = Constant

6 Tests required at 3 strain rates and 2 grain sizes.

TEMPERATURE EFFECT ON FRACTURE PROPERTIES

Fracture toughness tests at various temperatures.

Strain rate, Flux, Fluence* = Constant

6 tests required at 3 temperatures and 2 grain sizes.

*Testing would occur at a fluence of approximately 10^{25} n/m^2 and essentially remain constant due to short duration of actual test.

TABLE IV

SUMMARY FOR TENSILE AND FRACTURE PROPERTIES EVALUATION

Total number of tests	=	20
Stress-strain at various temperatures	=	22 100 hr
Stress-strain at various strain rates	=	16 600 hr
Fracture properties tests	=	16 600 hr
OVERALL TOTAL	=	55 300 hr

Utilizing 8 sample tubes 9-10 months continuous *in situ* time required to complete tensile and fracture testing of one material.

TABLE V

SOME POTENTIAL MATERIALS FOR CTR APPLICATION

* Al_2O_3
* Be
* BeO
* CONCRETE
* COPPER
* GRAPHITE
* LEAD
* MgO
* Mo-1/2 Ti
* Nb-1 Zr
* SAP ALUMINUM ALLOYS
* STAINLESS STEELS
  - 21-6-9
  - 304
  - 316 (20% CW)
* PE-16
* URANIUM
* VANADIUM ALLOYS
* ZIRCONIUM ALLOYS

Systems Test Program

There are two reasons for operating test systems in FERF: (1) to check for unanticipated materials effects in real fabrications under operating conditions and (2) to gain experience in operating loops such as blanket cooling or tritium breeding and recovery systems in a realistic reactor environment.

Even with a thorough materials test and development program there is a real probability of adverse effects on system components when they are placed in actual service. Adequate space for realistic models of proposed reactor systems will be necessary in order to test for cooperative effects between components operating with reactor fluids and in a reactor environment.

The critical highly irradiated systems are those comprising the first wall and blanket. Blanket designs are typically one meter thick, contain various piping systems, and are composed of breeding material neutron multipliers, moderators, coolants and structural materials.

An adequate test space for blankets should approximate the thickness of a real blanket and provide enough breadth to allow a model with full size piping. Additionally, the facility should provide the utility systems to support the operation and diagnostics of the test assembly. In order to properly simulate working conditions, the test volume must have a reactor level particle flux at its front face.

Special consideration must be given to safe operation of blanket models especially those of hybrids that contain fissile materials. A serious failure in a blanket module could cause an extended reactor shutdown thereby seriously damaging the materials test program. Compatibility testing will require exposure to fluences that can at least be extrapolated to expected useful lifetimes. (A few years.)

Neutron Availability

The variation in average first wall 14 MeV neutron flux with axial position in FERF is shown in Figure 1. The flux peaks at 1.38 x 10^{14} $cm^{-2}s^{-1}$ at the mid-plane and drops to 4.8 x $10^{13}cm^{-2}s^{-1}$ on the 1 m plane. In this region (from -1.0 m to +1.0 m) the total first wall area is 4.6 m^2.

In the area beyond the 1 m plane the flux continues to drop off while the first wall area increases. The usefulness of this area for materials testing has not been thoroughly evaluated.

By the use of "rabbit tubes" placed axially behind the first wall, an area of approximately 7 m^2 lying between the mirror points could be utilized for simple uninstrumented irradiations. The flux of uncollided (14 MeV) neutrons in this area will range from 8 x 10^{12} to 1.2 x 1-^{14} $cm^{-2}s^{-1}$.

The first wall neutron flux is approximately the same as that proposed for power reactors. It is therefore not possible to do accelerated testing of first wall materials in FERF.

In order to provide significant fluences in a reasonable period of time the reactor must have a high availability. For the purposes of this study we have assumed a 67% availability at design power. On this schedule the annual 14 MeV neutron fluence at the mid-plane first wall will then be 4.4 x 10^{21} cm^{-2}. The mid-plane first wall total neutron flux is calculated to be 2.8 x 10^{14} $cm^{-2}s^{-1}$ for an annual fluence of 8.8 x 10^{21} n cm^{-2}.

Materials Testing Facilities

Some desirable characteristics of the materials testing facilities are:

1 - Adequate flux.

2 - Easy access for complex capsules.

3 - Adequate volume for large specimen testing.

4 - Environmental control.

5 - Insertion and removal without reactor shutdown.

6 - Laboratory facilities for post irradiation examination and test.

Figure 2 shows the location of the sample tubes in relation to the first wall. The tubes pass through the lobes (or turnarounds) of the Yin-Yang coils, cross each other and then are tangent to the back side of the first wall. The tubes form reentrant spaces in the vacuum volume of the reactor. They are 60 mm inside diameter and the useful experimental length is .5 m. There are 12 tubes per coil lobe for a total of 48. The total available volume is 68 ℓ. Several of the sample tubes about the large beam port (described in a later section) will vary in usefulness depending on the concurrent experimental use of the beam port.

A plot of the average 14 MeV neutron flux of the sample tube location is shown in Figure 3. At presumed reactor availability of 67% the annual 14 MeV neutron fluence varies from 2.5×10^{21} cm^{-2} at the middle tubes to $1. \times 10^{21}$ cm^{-2} at the far position.

While the experimental capsules for fusion testing will have their own special requirements, they probably will be quite similar to those presently used in fast fission reactor materials testing. A sample design is shown in Figure 4. The most complex capsules considered are those for measuring in situ creep, which require the load, temperature, and atmosphere be carefully controlled while very precise elongation measurements are made over prolonged periods of time (months).

The capsule forms the front end of a test assembly that is 16 m long and weighs approximately 1 ton (Figure 5). The assembly is inserted from one of the handling rooms adjacent to the reactor vault, (Figures 6, 7, and 8). The test assembly projects through the shield wall and forms a shield plug to stop the beam of neutrons that would otherwise stream into the handling room. In order to create an effective shield plug the wiring and plumbing will travel in a helical path through the shield fill material and the outer wall will be stepped. The various systems required to operate and monitor the test will be connected from the back end of the assembly to a standard connection pad on the wall of the handling room.

The major piece of equipment in the handling room is the handling machine. This tool provides 6 degrees of freedom for the test assembly. Its functions are to receive assemblies for test, insert and retract assemblies, deliver irradiated units to the hot laboratory, and place test assemblies on a storage rack. The handling machine can be digitally controlled so that it may be pre-programmed to do these functions with a minimum of manual control required.

An over-head manipulator is provided in each handling room to make and break connections and to aid the handling machine when required.

The handling room is behind the biological shield for the reactor vault but shares the same nitrogen atmosphere. With effective shielding plugs on the test assemblies it will be possible for an operator in a breathing suit to enter the room to do contact maintenance on the handling machine and the manipulator.

Adjacent to the handling rooms are two hot laboratories. Each laboratory serves two handling rooms. The laboratories are equipped with air locks to permit the input of new test assemblies and discharge of irradiated assemblies. The new assemblies will be checked out in the laboratory and then transferred to the handling room for insertion or storage.

Irradiated assemblies will be transferred to the laboratory for post-irradiation examination and test. The labs will have equipment for disassembly of the capsule and subsequent testing and examination by the standard techniques used in hot cell metallurgical work.

Some testing programs call for re-irradiation of specimens after examination. The labs will be equipped with the tooling necessary to re-assemble for reinsertion into the reactor.

Post irradiation tests and examinations that are not possible in these laboratories can be conducted in other hot cells located in the facility.

This design is based on maximizing the amount of high quality testing access (suitable for the most complex tests) to FERF. As the testing program needs are further refined it will be possible to increase or decrease the number and size sample tubes. The support facilities can also be tailored to a well defined program with the goal of reducing installation and operating costs.

System Test Facilities

The principal system test facility proposed is a large diameter beam port looking at the central region of the reacting plasma (Figure 2 and 8).

This port takes the place of one of the neutral beam injectors. The three remaining injectors have been increased in output to compensate for this change.

The beam port is .8 m in diameter and is open to the plasma. The useful depth is 1.5 m yielding an experimental volume of .75 m^3.

The average first wall uncollided neutron flux profile along the face of the port is shown in Figure 9. The flux varies from a maximum of 1.4×10^{14} n $cm^{-2}s^{-1}$ to a minimum $.75 \times 10^{14}$ n $cm^{-2}s^{-1}$. The port will "see" all the reaction products of the plasma plus a large neutral beam load from the injectors.

The port will be used in the following way. The test assembly is mounted in a tubular outer structure, its circuitry is connected to the outside through vacuum tight connectors. When the machine is shut down and the magnet de-energized the tube is attached to the beam port valve. The tube is pumped down to operating vacuum and checked for leaks.

If there are no leaks the valve is opened and the assembly is inserted by an integral operator. The experimental systems are then checked and the reactor can be brought back to power. The reactor will be down for injector replacement every 6 weeks so the insertion and removal of the beam port experiments can be timed to have minimal effect on reactor availability.

A dummy beam port plug with its own first wall section will be in place whenever the port is not in use.

The port is large enough to handle representative portions of the reactor blankets proposed to date. Figure 10 shows a mirror hybrid blanket submodule(4). Figure 11 shows a set of these submodules mounted in a system test assembly. These illustrations simply indicate that significant portions of a blanket first wall section can be placed in FERF for testing.

The diversity of blanket and wall designs precludes standardization of any but the most basic support facilities for the beam port. Each experiment will be required to provide its own controls, diagnostics, processing systems, etc.

The facility will provide control room and diagnostic space along with power, cooling, installation and removal services.

These assemblies will be handled in the hot shop that services the reactor. It is possible to provide other beam ports in FERF. The large port represents the approximate upper limit on size and is presented as a reasonable facility for large scale system tests. Other smaller ports can be provided in the design as the need and parameters for such facilities are determined by the CTR development program.

Conclusion

This report represents a first attempt at coordinating a testing program with a FERF design. Our purpose was to gain insight into the value and problems associated with using FERF in a real materials and systems test program.

A comparison to the current survey of CTR materials test requirements(5) shows that FERF can provide virtually all the appropriate experimental space and flux requested (except for very large blanket sections). However, the maximum fluences are beyond the practical capability of this or probably any other reactor source. The high fluence tests would require irradiation times of tens of years which go beyond the practical life of the reactor.

Although the requirements and design of the system need many iterations before a final workable facility can be built, the overall concept of using a mirror FERF for materials testing appears quite feasible.

It should be added that the reactor itself will be the best test specimen in the program.

REFERENCES

(1) Tokamak Fusion Reactor
Research and Development Plan
February 1975 (Draft)
ERDA
S. O. Dean, et al

(2) G. K. Hess, Jr.
Mirror Study - 1975
Feb. 1975
ERDA (Draft)

(3) Batzer, et al

(4) R. Moir, et al
Conceptual Design of a Mirror Hybrid

(5) P. J. Persiani, "A Summary Report on the CTR Radiation Test Facilities for the Surface and Materials Program" (Draft) Dated July 1974, ANL, (to be published)

FIGURE CAPTIONS

Fig. 1 Flux map

Fig. 2 Location of sample tubes

Fig. 3 Sample tube flux

Fig. 4 Capsule design

Fig. 5 Test assembly

Fig. 6 Facility plan

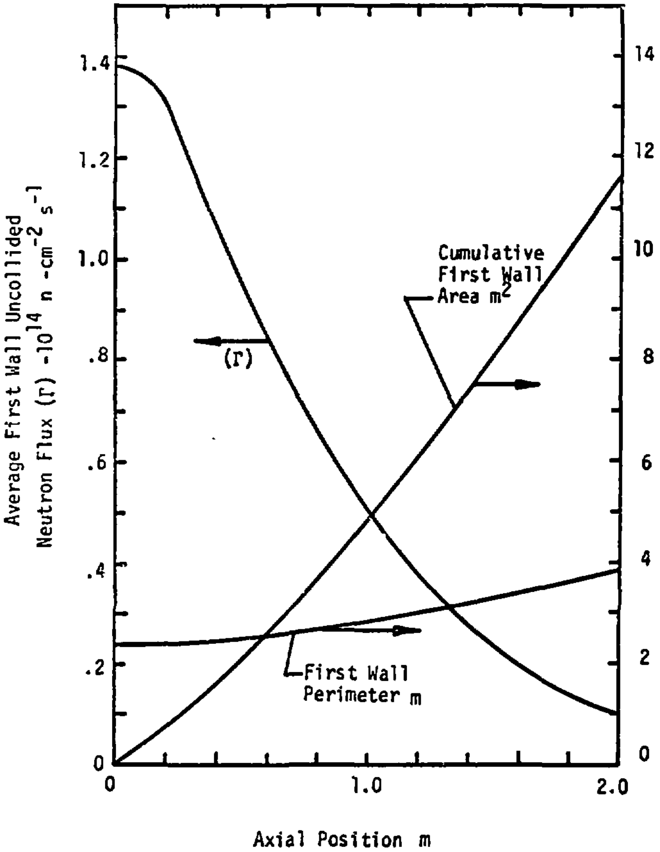
Fig. 7 Facility transverse section

Fig. 8 Facility longitudinal section

Fig. 9 Beam port flux

Fig. 10 Blanket submodule

Fig. 11 System test assembly



AVERAGE UNCOLLIDED NEUTRON FLUX AT THE FIRST WALL

Figure 1

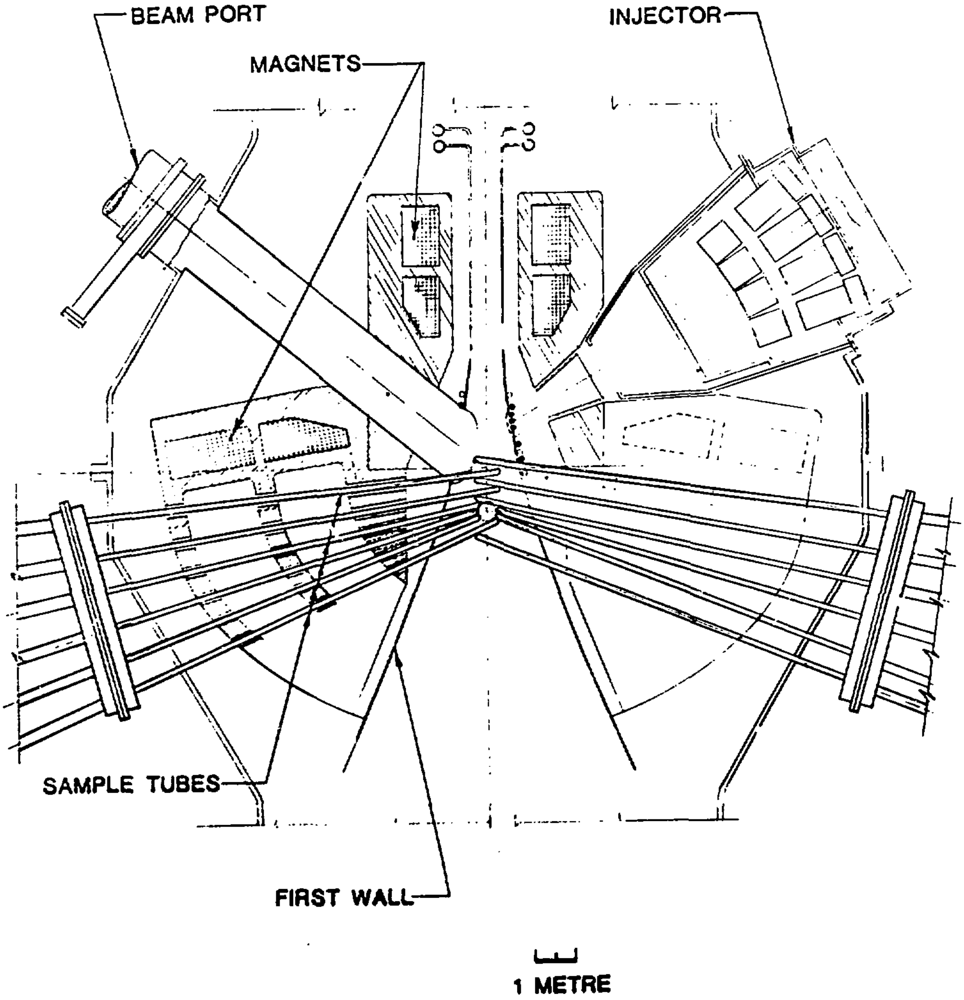
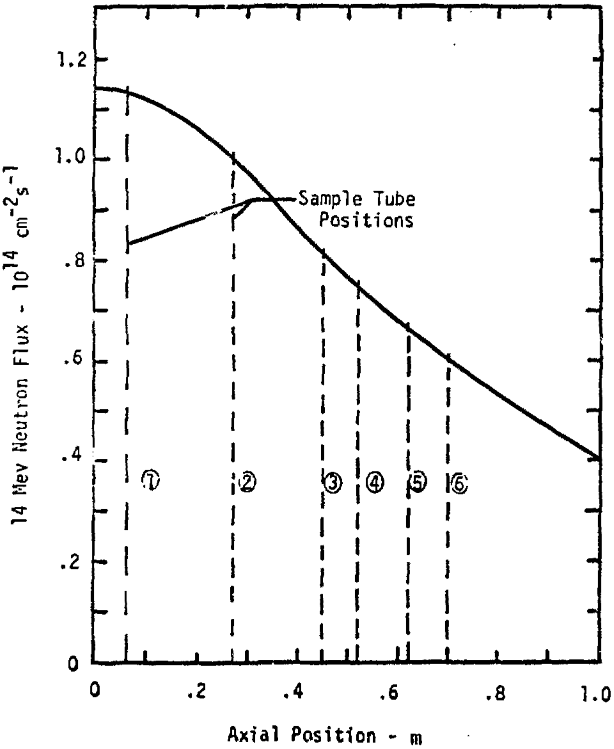


Figure 2



UNCOLLIDED NEUTRON FLUX AT THE SAMPLE TUBES

Figure 3

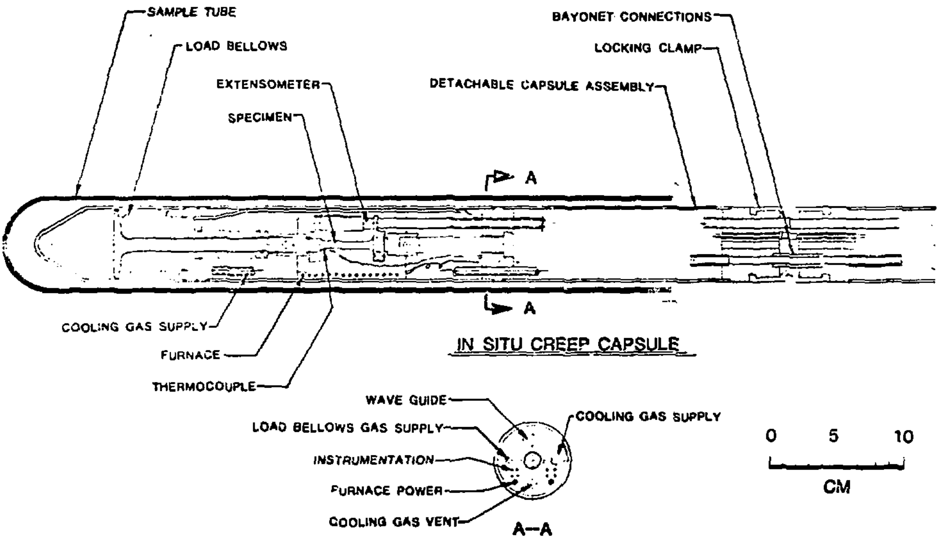

SAMPLE TUBE
LOAD BELLOWS
EXTENSOMETER
SPECIMEN
BAYONET CONNECTIONS
LOCKING CLAMP
DETACHABLE CAPSULE ASSEMBLY
A
A
COOLING GAS SUPPLY
FURNACE
THERMOCOUPLE
IN SITU CREEP CAPSULE
WAVE GUIDE
LOAD BELLOWS GAS SUPPLY
INSTRUMENTATION
FURNACE POWER
COOLING GAS VENT
COOLING GAS SUPPLY
A—A
0
5
10
CM

Figure 4

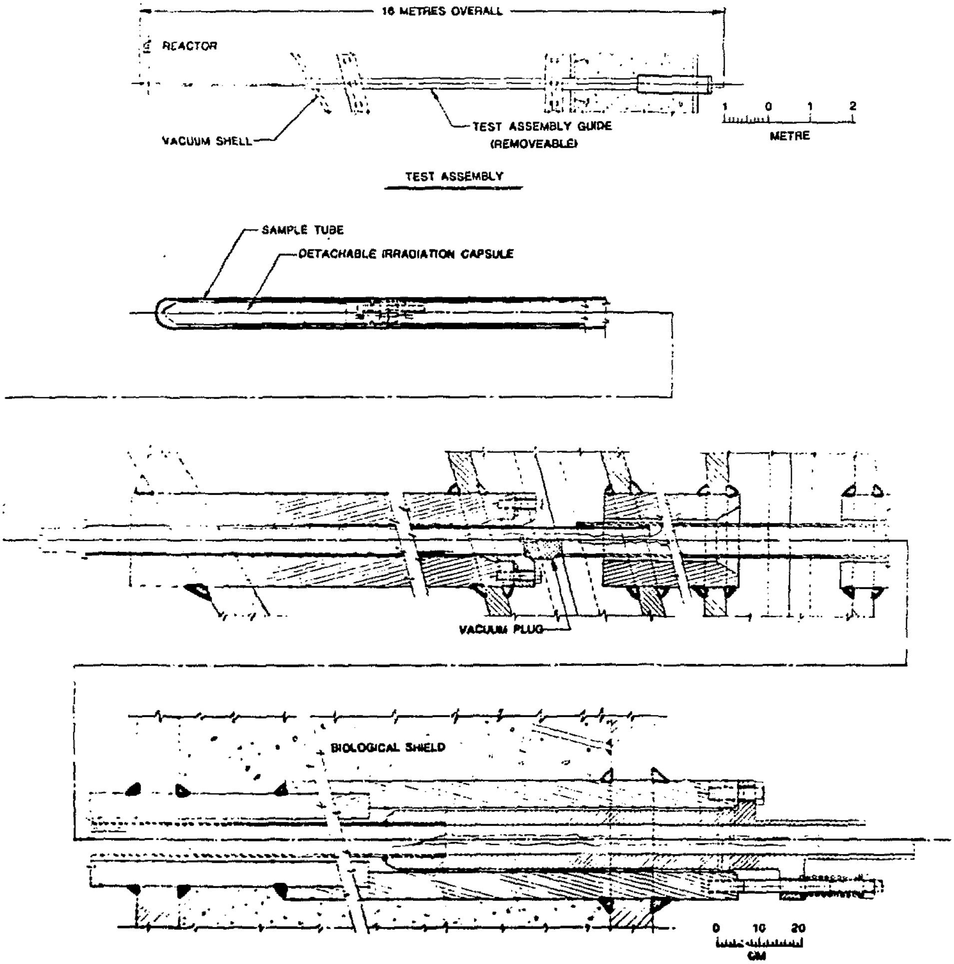

16 METRES OVERALL
℄ REACTOR
VACUUM SHELL
TEST ASSEMBLY GUIDE (REMOVEABLE)
1 0 1 2
METRE
TEST ASSEMBLY
SAMPLE TUBE
DETACHABLE IRRADIATION CAPSULE
VACUUM PLUG
BIOLOGICAL SHIELD
0 10 20
CM

Figure 5

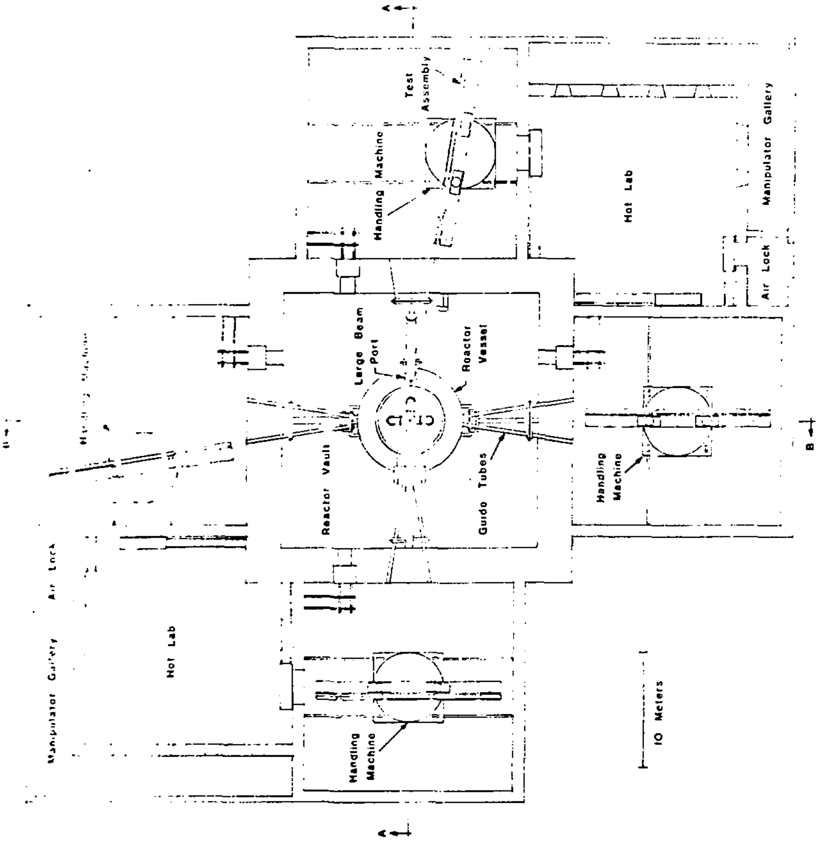

A
Test Assembly
Handling Machine
Hot Lab
Manipulator Gallery
Air Lock
Large Beam Port
Reactor Vessel
Reactor Vault
Guide Tubes
Handling Machine
B
B
Handling Machine
Air Lock
Manipulator Gallery
Hot Lab
Handling Machine
10 Meters
A

Figure 6

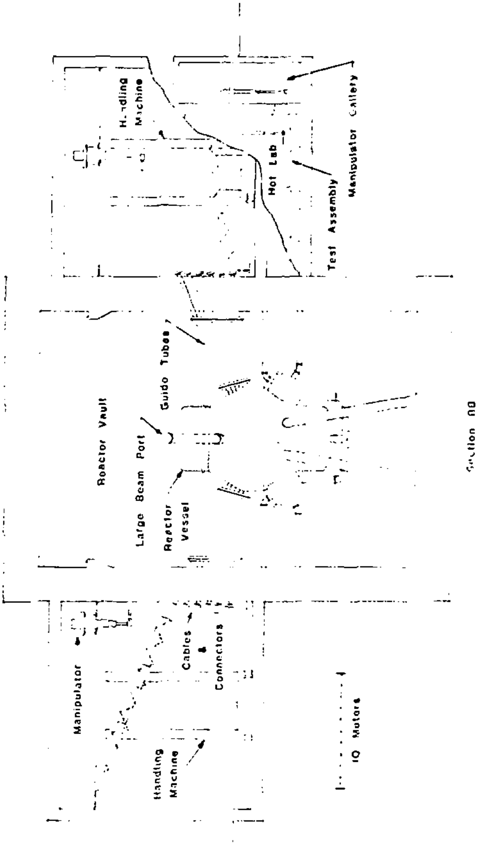

Manipulator
Reactor Vault
Large Beam Port
Reactor Vessel
Guide Tubes
Handling Machine
Cables & Connectors
Handling Machine
Hot Lab
Test Assembly
Manipulator Gallery
IQ Motors
Section AA

Figure 7

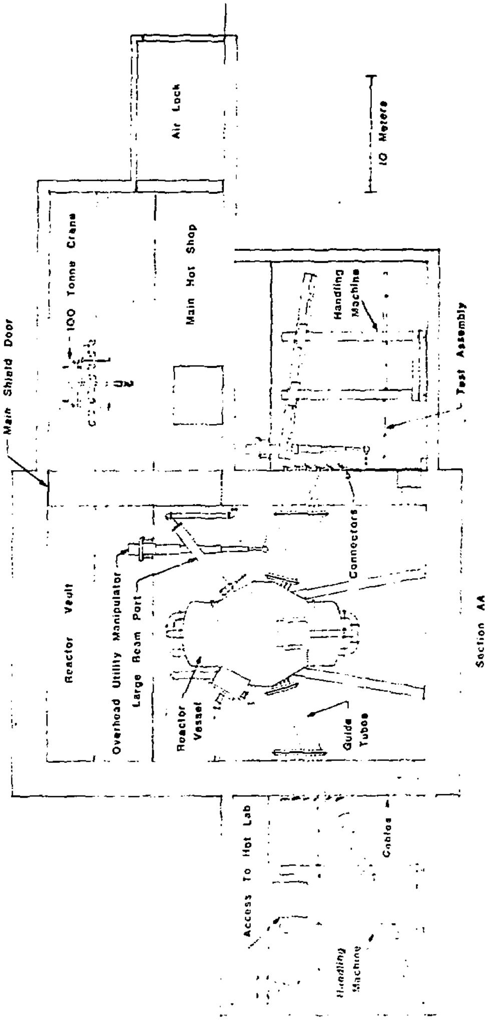
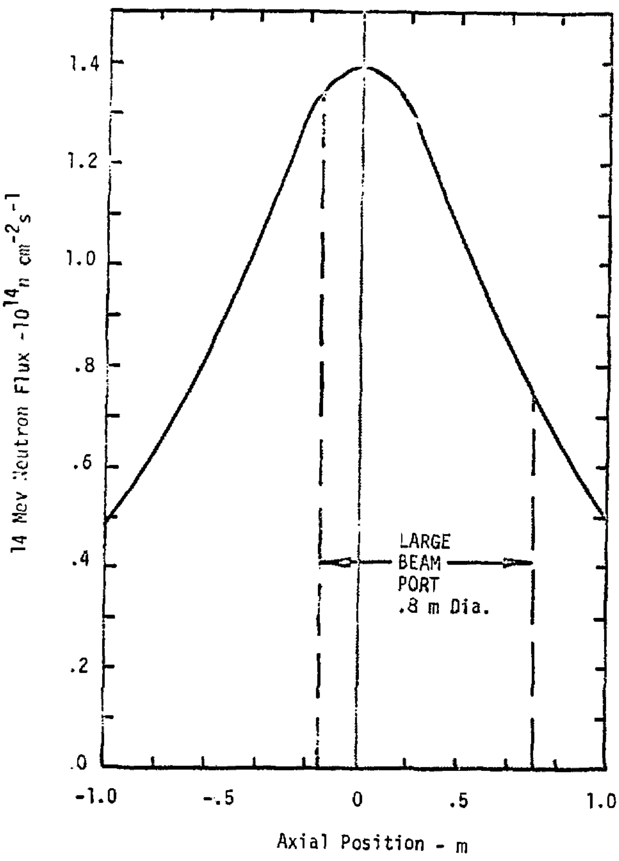

Main Shield Door
100 Tonne Crane
Air Lock
Main Hot Shop
10 Meters
Handling Machine
Test Assembly
Connectors
Reactor Vault
Overhead Utility Manipulator
Large Beam Port
Reactor Vessel
Guide Tubes
Section AA
Access To Hot Lab
Cables
Handling Machine

Figure 8



LARGE BEAM PORT 14 MEV NEUTRON FLUX

Figure 9

FAST FISSION BLANKET SUBMODULE

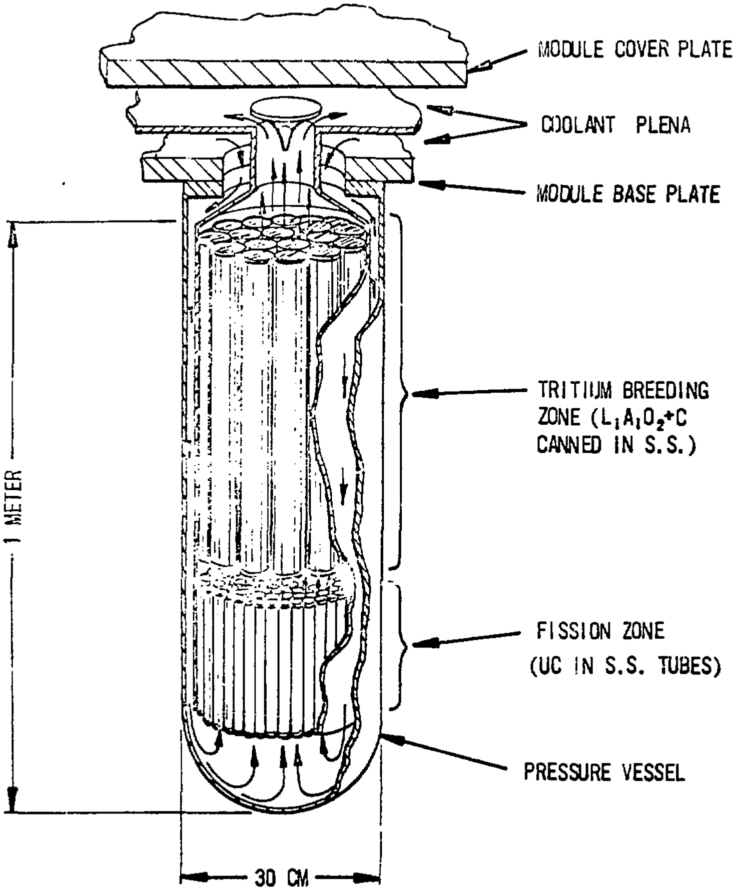


Figure 10

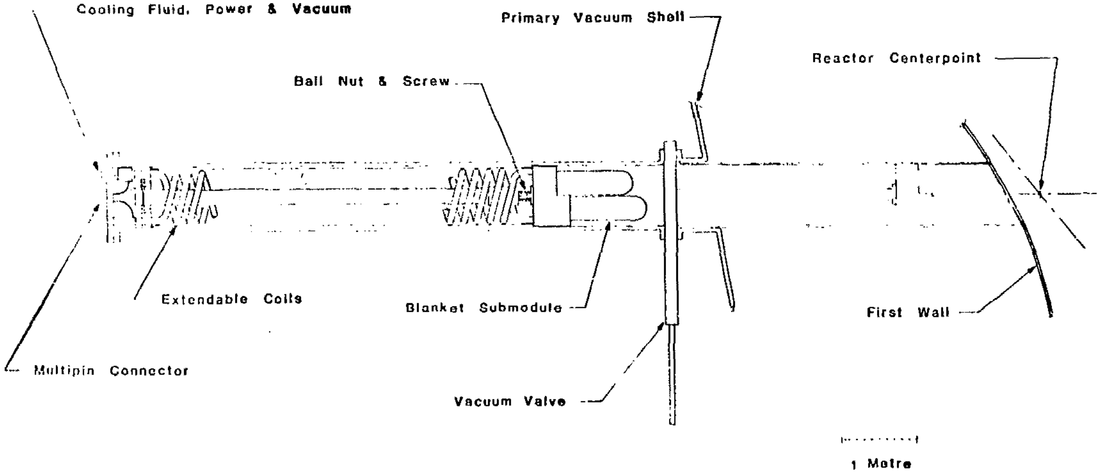

Cooling Fluid, Power & Vacuum
Primary Vacuum Shell
Reactor Centerpoint
Ball Nut & Screw
Extendable Coils
Blanket Submodule
First Wall
Multipin Connector
Vacuum Valve
1 Metre

Figure 11