ITER TEST PROGRAM: KEY TECHNICAL ASPECTS

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ABSTRACT

ITER is envisioned to operate in two phases: the Physics Phase, ~ 6 yrs, is devoted to the physics issues followed by the Technology Phase, ~ 8 yrs, used mainly for technology testing. The nuclear testing program of ITER is intended to provide powerful, albeit partial, demonstration of the ultimate potential of a fusion blanket. The ITER test group, which consists of a number of ITER designers and experts from the home teams concerned with the long-term development of fusion technology, has carried out several tasks, including: 1) Definition of the testing requirements on the major parameters of ITER; 2) Definition of the test program (time-space matrix and priorities of tests); 3) Engineering design of test modules; 4) Ancillary equipment to support test module operation and 5) Allocation of available test space among countries. Recommended ITER parameters are: neutron wall load ~ 1 MW/M^2, lifetime neutron fluence ~ 3 MW y/m^2 and several periods of continuous operation (~ 100% availability with back to back pulses or steady state) of ~ 1 to 2 weeks each. The requirements on plasma burn and dwell times are quantified. Steady state operation is a desirable goal. If this goal cannot be achieved, a burn time of ~ 1 to 3 hours, depending on the breeder temperature, is needed for tritium release tests in solid breeders. The requirements for ancillary equipment outside the torus, required to support the test modules (e.g., heat rejection systems, tritium processing, etc.) are extensive and they substantially influence the overall design engineering. The space available for testing in ITER is not sufficient for 4 complete programs (one for each country). An effective strategy for allocation of test ports among countries is being evolved. It involves a combination of collaboration on some tests, and allocation of testing space and time by party.

1. INTRODUCTION

The ITER design has evolved an important strategy to best achieve the role of ITER in physics and technology demonstration. A key part of the strategy is to develop two separate, albeit interrelated, elements for ITER: 1) Basic Machine: a conservative design of the basic machine components (including the blanket) maximizes reliability, flexibility and safety of ITER, and 2) Test Program: specially designed ports for insertion of test modules allows testing of advanced concepts and partial but powerful demonstration of the ultimate potential of fusion. Another part of the strategy is to operate ITER in two phases. The first phase, which lasts for 6 years, is devoted to machine check-out and physics testing. Some useful technology tests are also planned during the Physics Phase. The second phase, which lasts for 8 years, is devoted primarily to technology testing.

The objectives of the ITER test program are: 1) screening of concepts in tests which require the integrated fusion environment, 2) calibration of fusion integrated tests to results from non-fusion tests, 3) validation of candidate blanket concepts, and 4) testing of advanced concepts. The ITER objectives and characteristics contained in ANNEX I to the Terms of Reference state that ITER will provide the data base "necessary for the design and construction of a demonstration fusion power plant".

The ITER test group consists of a number of designers and testing experts from the home teams of Europe, Japan, USA and USSR, who are concerned with the long-term development of fusion technology. This group has investigated many of the technical issues related to the ITER test program. Among the tasks carried out are: 1) definition of the testing requirements on the major parameters of ITER, 2) definition of the test program (time-space matrix and priorities of tests), 3) engineering design of the test modules, 4) ancillary equipment to support test module operation and 5) allocation of available test space among countries. A detailed description of the results is contained in references 1 and 2.

This paper summarizes the key technical aspects of the ITER test program. Sec. 2 describes the technology test program for ITER. Sec. 3 describes the ancillary equipment outside the torus necessary to support the test modules (e.g., heat rejection and tritium recovery systems). The international collaboration aspects of conducting the test program on ITER are summarized in Sec. 4. Successful testing on ITER imposes important requirements on the machine's major parameters (e.g., wall load, fluence, burn time). These requirements have substantially influenced the ITER design and are summarized in Sec. 5.

2. TEST PROGRAM DESCRIPTION

2.1 Introduction

This section describes the test program developed for ITER. The technology tests considered to date are mostly related to the blanket and materials. Other tests such as those for high heat flux components are important and should be addressed in the future.

The numbers of ports available for testing in ITER are 3 during the Physics Phase and 5 during the Technology Phase. The allocation of the 3 ports during the Physics Phase is as follows: one port for neutronics tests (including possible sharing with some materials tests), one port for liquid metal blankets (both self cooled and separately cooled), and the third port for all types of solid breeder blankets, (gas cooled and water cooled).

During the Technology Phase the 5 ports are allocated as follows: 1) one port for solid breeders, gas cooled, 2) one port for solid breeders, water cooled 3) one port for self cooled liquid metals, 4) one port for separately cooled liquid metals, and 5) one port for material and other types of tests.

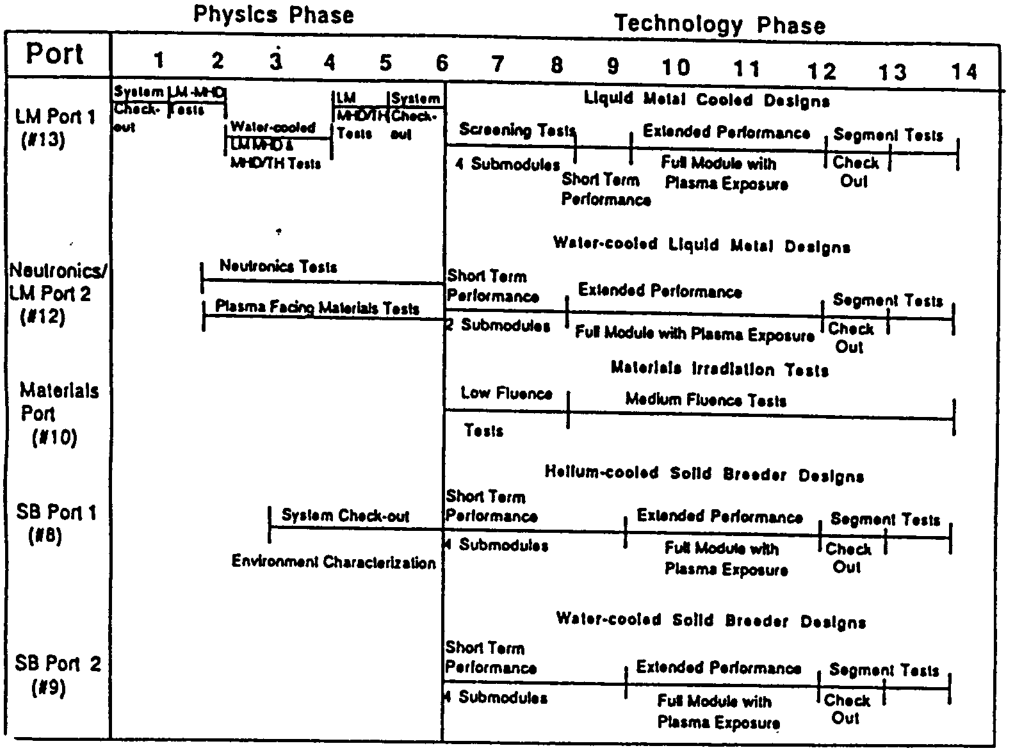


Fig. 1 Blanket Test Schedule

A strategy for allocation of these ports among various countries has been developed and it involves a combination of collaboration on some tests, and allocation of testing space and time by party.

2.2 Reference Device Parameters

Device parameters for the Technology Phase are based on the reference long-pulsed hybrid operating scenario, and are listed in Table 1. The wall load has an average peaking in the test port of ~1.2. The minimum achievable dwell time is ~ 300 s, and may be as high as 400 s or more. The reference plasma burn time is 2250 s, but other options for plasma steady state operation during the Technology Phase are being explored. The availability of 18% is a minimum value which is required to achieve the goal fluence within the 8-year Technology Phase, and is based on operation only at the reference conditions.

2.3 Test Schedule

The overall test schedule is shown in Fig. 1. The dedicated testing ports on ITER are 3m x 1m at the first wall. During the Physics Phase, three ports have been allocated for testing. One port will be used for liquid metal blanket tests, one port will be used for solid breeder blanket tests, and one port will be used for neutronics and materials tests for plasma exposure. The tests in the liquid metal port are focussed on MHD and MHD/thermal-hydraulics due to the effect of the ITER magnetic field on liquid metal flow patterns and heat transfer. In addition, time is allocated for ancillary system check-out in preparation for the Technology Phase. The solid breeder port is to be used for helium cooled concepts. The neutronics port will be used for tests of shielding performance and tritium breeding for all types of blankets. A small portion of this port will be allocated for plasma exposure of material test samples.

TABLE 1 Technology Phase Reference Parameters

Device parameter	Reference Value
Average neutron wall load, Mw/m^2	
- device average	0.8
- at the test module	1.2
Number of ports	5
Port size	3.74 m^2
Total testing area	18.7 m^2
Plasma burn time	2250 s
Dwell time	> 300 s
Technology testing phase duration	8 years
Average availability	18%
Total neutron fluence, MW-yr/m^2	
- device average	1.02
- at the test module	1.5

During the Technology Phase, five ports will be available for blanket testing. Two ports are allocated for liquid metal blankets, one for liquid metal cooled designs and one for water cooled designs. Another two ports are allocated for solid breeder blankets, one for water cooled designs and one for helium cooled designs. The last port is devoted to materials irradiation testing. The general approach to blanket testing is to first perform screening tests or short-term performance tests of several designs using sub-modules. The lead designs would then be selected for extended performance testing to determine their potential for use in advanced reactors. Finally, DEMO candidate blankets would be tested using full segments. The materials tests would consist of irradiation of many small samples in a well characterized environment. The tests would be conducted at different temperatures and neutron fluences, and the samples would be removed or replaced at relatively frequent intervals.

2.4 Neutronics Tests

Many important neutronics issues will require testing in ITER. They include (1) the demonstration of tritium self-sufficiency for the various test blankets, (2) verification of the adequacy of current neutron transport codes and nuclear data in predicting key parameters as tritium production rate, heating rate, gas production and activation, (3) verification of adequate radiation protection of machine components, (e.g., SC magnets) through the bulk shield as well as adequate protection to personnel, and (4) confirming the safety factors implemented in the design of the shield system to account for streaming through gaps and penetrations, such as the NBI and main exhaust ducts. A number of these tests will be carried out prior to the introduction of the test blankets in the machine.

Neutronics tests needed to resolve these issues can be classified into three categories which are discussed below:

A. Dedicated Neutronics Tests

These tests aim at examining the accuracy in predicting key neutronic parameters in the fusion environment. The goal is to identify the source of discrepancies between the analytical predictions and the experimental data related to parameters such as tritium production rate, nuclear heating, induced radioactivity and decay heat.

While in principle a small size submodule (~ 0.3m x 0.3m) could be used for predictive capability verification, a full test module (3.4m x 1.1m x 1.5m) is preferred, since the derived uncertainties will be lower for extrapolation to the full coverage blanket case.

The measurements will include neutron yield and external DT source characterization, local tritium production and heating rates, neutron and gamma rays spectra and gas (hydrogen, helium) production at several locations inside the test module.

These measurements will require, in general, very low fluence, from 1 W sec/m^2 to 1 MW sec/m^2, and they are suited for early stages of reactor operation. An exception is for gas production rate and activation rate measurements, which require larger fluence, more than 0.02 MW yr/m^2, in order to accumulate enough measurable products.

B. Tritium Self-Sufficiency Tests

Direct demonstration of tritium self-sufficiency of one test blanket requires a fully integrated reactor system. This does not appear possible in ITER. Then it will be necessary to rely on indirect demonstration through extrapolation of information from the operation of the basic machine (driver blanket) and test elements.

A segment test, rather than only a module test, will be necessary because there are strong poloidal variations in tritium production rates. One main parameter to be measured will be the tritium from the purge gas in solid breeder blankets or from the liquid metal traps in the self-cooled liquid metal concept. It will be necessary to operate the reactor for the time needed to get tritium saturation in the blanket and structures of the recovery system. Once saturation is reached, the amount of tritium generated in the segment will be equal to the amount of tritium released in the purge gas system, regardless of the tritium trapped in the segment. This method of verifying the predictive capability for tritium breeding could be applied in any phase of operation of the machine, provided saturation in the tritium released to the purge gas is reached.

C. Neutronics Measurements for Engineering Performance Tests

These measurements are intended to provide the source terms for non-neutronic tests, in particular those related to the tritium recovery and thermo-mechanics tests foreseen in the test ports used for the various test blanket investigations. In general, these neutronics measurements require very short time (typically 20 s to 1 minute at 5 x 10^{12} n/cm^2 sec neutron yield), and can be made in the DT-stage of the Physics Phase. Measurements which require larger accumulated fluence (>0.2 MW yr/m^2), such as gas production and activation rate measurements, will have to be carried-out for the various test blankets in the Technology Phase.

D. Neutronics Measurements for the Basic Machine

As mentioned, a number of measurements described will have to be carried out already during the commissioning of ITER. They include measurement of the afterheat level, accumulated activation level and personnel exposure level behind the shield. Of interest are the measurements of neutron and gamma flexes, energy deposition and leakages across and behind the driver blanket and shield. Tritium self-sufficiency measurements of the driver blanket are also foreseen.

2.5 Liquid Metal Blanket Test Program

The liquid metal blanket test program in ITER includes self-cooled, separately cooled, and water cooled concepts. The self-cooled designs use either pure Li or Pb-17Li as the coolant/breeder, the separately cooled design uses liquid Pb as the coolant with a Li breeder, while only Pb-17Li has been proposed for the water cooled concept. The approach to blanket testing results from the limited amount of test space and test time that is available in ITER, along with the desire to screen several different designs. The following approach is proposed.

Make extensive use of all testing possibilities outside of ITER. Nearly all separate effects relevant to a blanket design can and should be investigated in the test loops (out-of-pile as well as in fission reactors) prior to tests in ITER. This is especially true for some complicated and highly instrumented MHD tests and long time corrosion tests.

Perform as many tests as possible during the ITER Physics Phase. This phase is especially suited for MHD tests and MHD/thermal-hydraulics tests since these tests do not require long, repeated burns and, for some of the tests, no neutrons at all. What is needed is the real geometry and the real distribution of the magnetic field. This means that some of the tests can be performed even without a burning plasma. For availability reasons, all these tests will be performed with modules which are not exposed to the plasma. It is proposed that electric heaters be installed at the front surface of the modules in order to simulate plasma surface heating.

Divide the test port into parts in order to conduct parallel tests during the first years of the Technology Phase. The allocation of submodules is shown in Fig. 2. It is proposed to test four submodules for liquid metal cooled blankets and two submodules for water cooled blankets during the first couple of years of the Technology Phase to screen a number of designs using either Li or Pb-17Li. In the next step the size of the submodules is increased and they will be exposed to the plasma for the first time. Again, short time tests will be performed, and the submodules will be exchanged at least once.

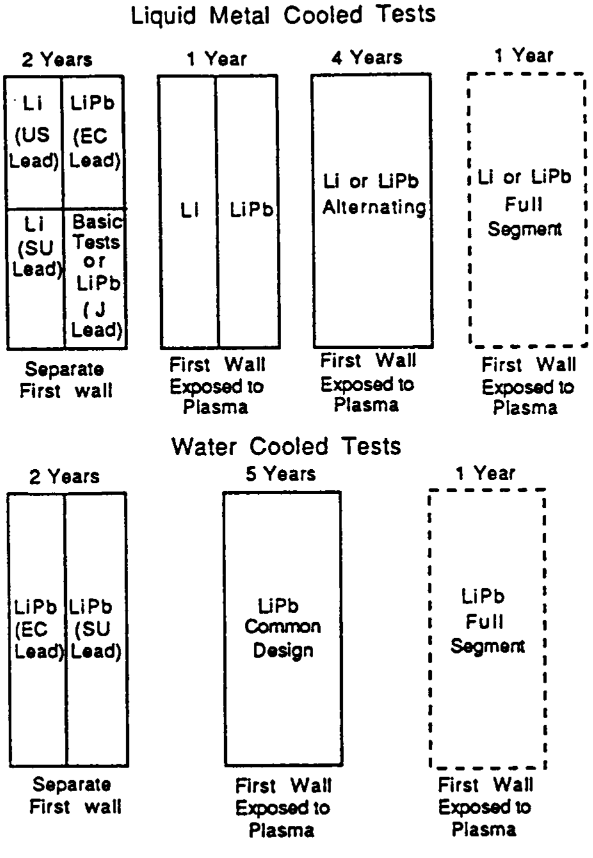


Fig. 2 Test Sequence for Liquid Metal Blankets

Perform sequential tests with full size modules during the second half of the Technology Phase. It is expected that the screening tests will reduce the number of concepts to be tested. Therefore, two to three designs for the liquid metal cooled and one or two designs for the water-cooled concepts will be tested using full size modules. These tests are not high fluence tests, but they should allow the selection of one or two leading designs that have the potential to meet the requirements of the DEMO reactor.

Test segments of one or two liquid metal blanket designs towards the end of the Technology Phase. These tests are highly recommended to test the integrated performance of the blankets that could be installed in a DEMO reactor.

The overall test schedule for liquid metal blankets is shown in Fig. 3. An example of a test module design is shown in Fig. 4 for the self-cooled Pb-17Li blanket concept.

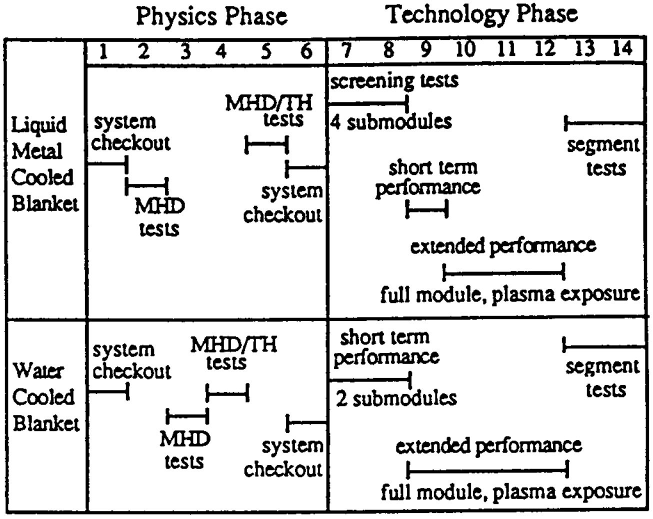


Fig. 3 Liquid Metal Test Schedule

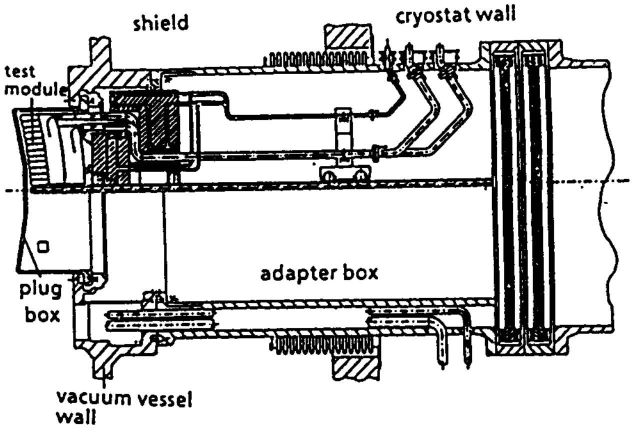


Fig. 4 Test Module for the Self-Cooled Pb-17Li Blanket Concept

2.6 Solid Breeder Blanket Test Program

Among the ITER participants, the European Community (EC), Japan and the USA are active in the development of a DEMO or power reactor relevant blanket with a helium cooled solid breeder, while the water-cooled version is investigated by Japan, the USA and the USSR.

The main technical issues for the development of these blankets are summarized below:

a) Ceramic breeder material (Li_2O, Li_4SiO_4, $LiAlO_2$ either as pebbles or as pellets):

- tritium transport (tritium residence time)
- lithium transport in presence of temperature gradients
- mechanical stability
- compatibility with beryllium and structural material
- thermal conductivity

b) Structural material (austenitic and ferritic steels, molybdenum alloy, SiC):

- mechanical stability (embrittlement, swelling)
- compatibility with beryllium and ceramic breeder

c) Beryllium multiplier

- mechanical integrity (embrittlement, swelling)
- compatibility with structural material and ceramic breeder

d) Blanket structure

- Behavior under high neutron fluences and temperatures, stationary and cycling thermal stresses and other stresses.

The overall R&D testing strategy including testing in ITER for the solution of these problems is based on the following approach:

a) Out-of-pile and in-fission-reactor measurements of the relevant basic properties of the materials. Especially for the metallic structural materials and the beryllium it is necessary that experiments with a high intensity dedicated neutron source are carried out to investigate the effects of the 14 MeV neutrons.

b) Exhaustive out-of-pile testing (thermal cycling, flow distribution and others) of the blanket structures, starting from small modules and going to more complex ones.

c) Tests in ITER of submodules, modules and possibly segments of the blankets. ITER tests are necessary, because in out-of-pile tests it is not possible to obtain the correct power and temperature distribution, while in-fission-reactor experiments allow only too small test-samples.

The neutron fluence of ~ 1 MWa/m^2 foreseen now for ITER does not allow investigation of very slow processes like corrosion or structural material swelling, however the tests in ITER are necessary because they are the only ones which can be performed with the correct power and temperature distribution in the right neutron environment for large size test articles (modules or possibly segments). Shakedown tests, validation of the codes obtained with the experiments of points a) and b) and the investigation of synergistic effects is of particular importance.

The test program in ITER for the solid breeder blanket foresees that initially there will be 3 concepts for each coolant. Namely, 3 concepts with EC, Japan and USA leas with the helium cooling and 3 concepts with Japan, USA and USSR lead with water cooling respectively.

The test program will be implemented as follows:

1. During the Physics Phase, a horizontal port will be allocated to the solid breeder blanket. The purpose of the tests in this phase is to characterize the neutronic environment, to check out blanket systems, and to check out instrumentation.
2. During the Technology Phase, two horizontal ports will be allocated to the solid breeder blanket: one for designs with gas cooling and one for designs with water cooling.
3. During the first three years of the Technology Phase, three submodules will be tested in each of the two ports available. In the port for gas-cooled designs, the EC, Japan, and the US shall have the lead on the design, construction and operation of one of the three modules respectively. The port for water-cooled designs is partitioned in exactly the same way. The lead for submodule design, construction and operation shall be taken by Japan, the US and the USSR.
4. During the following three years of the Technology Phase, a single module of the chosen reference solution with helium and water cooling shall be tested in each of the two ports. Failing to achieve agreement on a single reference solution, the three single modules for the three different concepts will be tested successively for a period of one year each.
5. The tests of the submodules will be performed behind a first wall similar to the driver blanket first wall. In case of a single reference blanket, the blanket module will be tested for the first year behind a driver blanket-type first wall and with its own first wall facing the plasma for the two remaining years.
6. For various designs it may be necessary to perform tests with complete segments or even sectors during a final period of the Technology Phase (the last year) and during a possible extended phase operation.

Fig. 5 and 6 show schematically the proposed international collaboration scheme and the testing schedule for the solid breeder blankets. Fig. 7 shows two examples of test modules placed in the horizontal port.

2.7 Plasma Facing Components

A limited amount of work has been done to identify the test requirements for plasma facing components. The specification of the test program is complicated by the close coupling of the plasma facing components with the overall physics operation. Certainly, additional work is required to specify a comprehensive test program.

Types of tests:

There are several types of tests that can be performed in ITER and they can generally be divided into plasma physics related tests and engineering related tests.

Plasma Related Tests

There are usually short-term tests aimed at determining the plasma operating parameters for a specific configuration of the impurity control system. Specific tests in this category are:

1. Impurity buildup in the main plasma. Determine distribution of α-particles and high-Z impurities in the plasma.
2. Plasma edge characteristics. Determine plasma density and temperatures in the plasma edge and scrape-off.
3. Plasma characteristics at the divertor. Determine particle flux and energy distribution at the divertor.
4. Vacuum system pumping capability. Determine characteristics of neutral gas in pump ducts and assess pumping behavior.

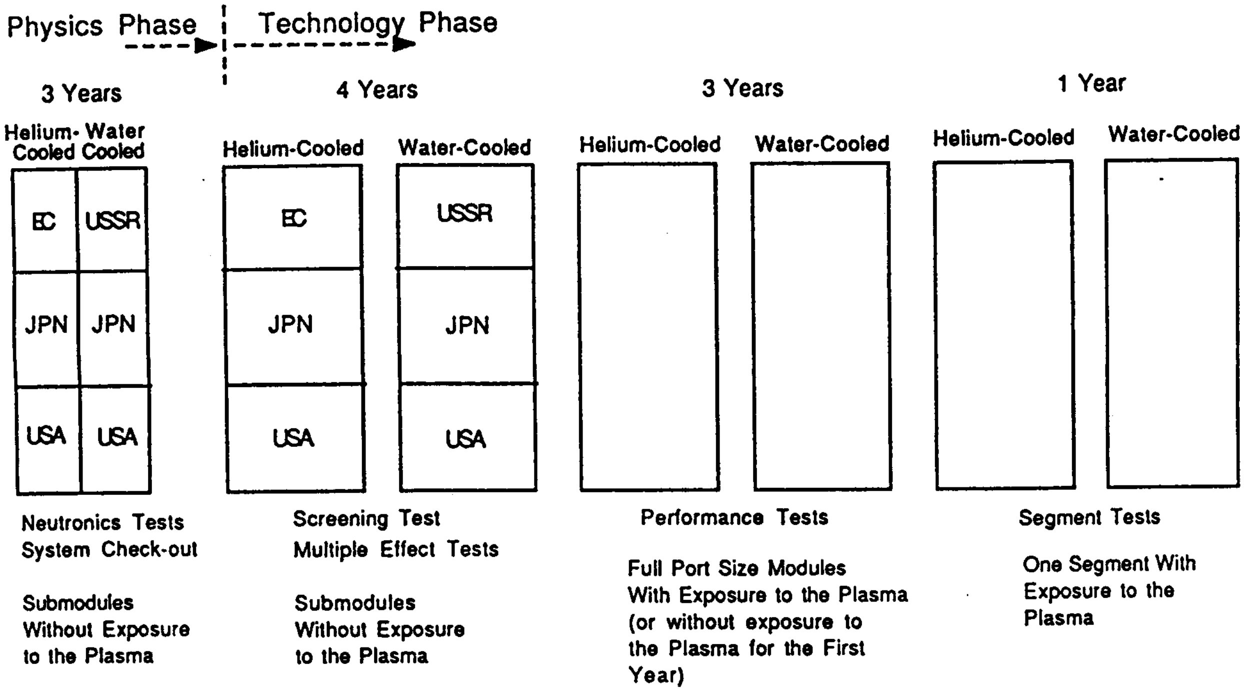


Fig. 5 Test Port Allocation to Helium- and Water-Cooled Solid Breeder Blankets

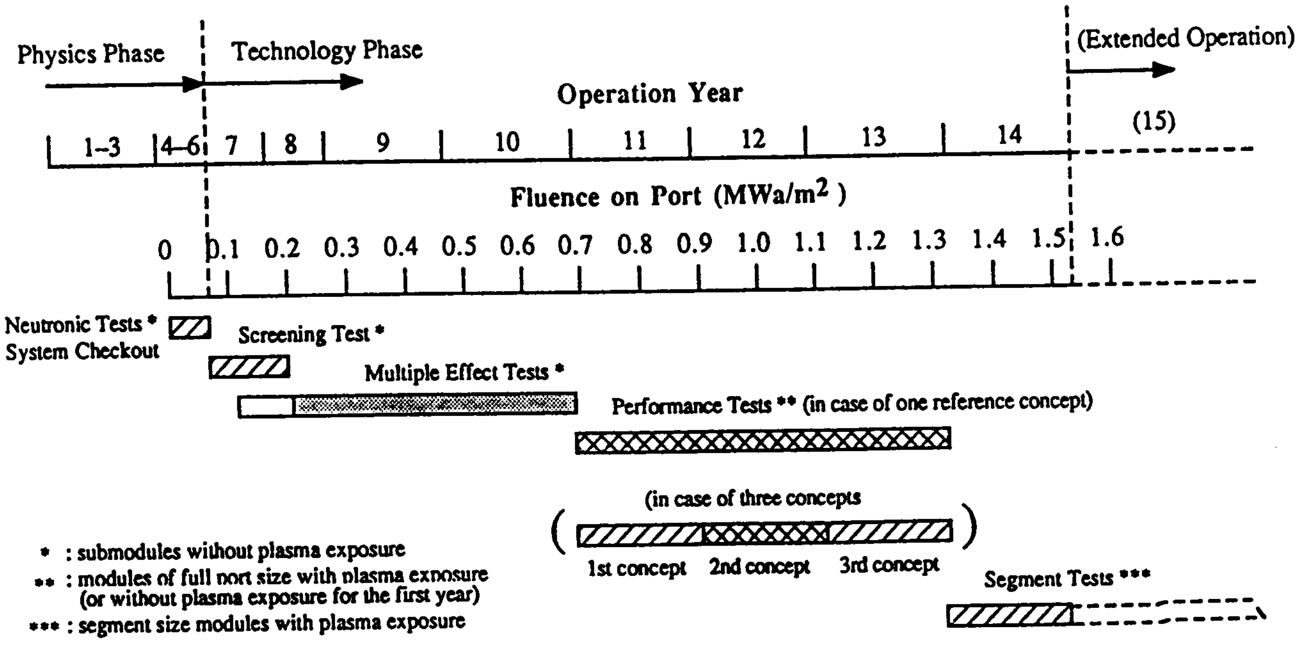
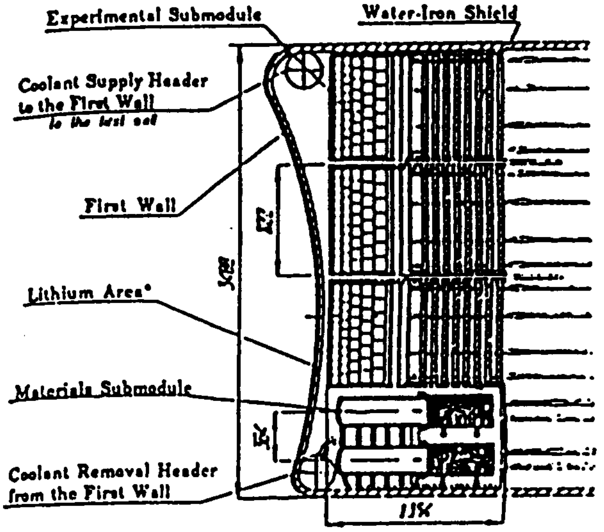
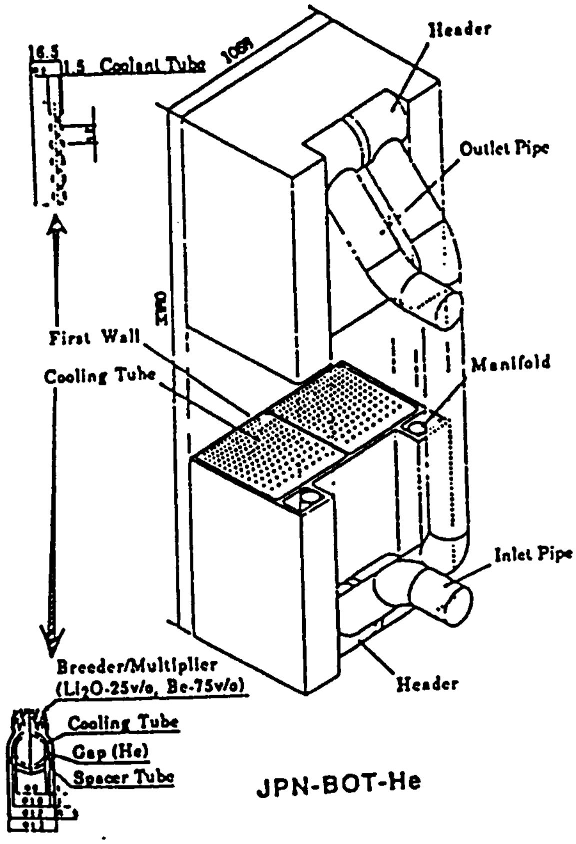


Fig. 6 Testing Schedule for Helium- and Water-Cooled Solid Breeder Blankets



USSR-BIT-H2O



JPN-BOT-He

Fig. 7 Examples of Test Module Design

The overall plasma performance will depend on the characteristics of the impurity control system (e.g., the type of divertor material exposed to the plasma), and initially these tests will be part of the initial ITER physics program. However, these types of tests will need to be performed whenever there is a change in the impurity control system configuration.

Engineering Related Tests

Engineering related tests are similar in scope to those conducted on blankets, and they include the following types:

1. Thermal-hydraulics performance. Assess the capability of efficiently removing heat from the impurity control system. These tests could be performed using different coolants and/or higher coolant temperatures than the base design.
2. Alternate pumping and impurity removal systems. Standard vacuum pumping systems could be replaced by advanced approaches such as helium surface burial or He exhaust enrichment using palladium membranes.
3. Thermo-mechanical behavior. Divertor plates subjected to high heat fluxes and a high number of cycles will be subjected to high thermal stresses. One of the goals of divertor designs is to minimize the influence of thermal stress cycles on performance.
4. Extended performance of divertors. Over a long period of time, the effects of surface erosion and neutron radiation will strongly influence the divertor lifetime. Extended tests are desirable to assess the capability for long lifetimes.
5. Transient response. The response of the impurity control system to both normal and off-normal transients needs to be determined. In particular, surface erosion and electromagnetic forces during disruptions could severely reduce the operating life.
6. Advanced divertor targets. Alternate designs, such as liquid metal droplet divertors, have been suggested. Many of the engineering concerns with standard plate designs would be eliminated, but new concerns will arise, and the alternate concepts will need to be tested.

2.8 Material Testing

The purposes of the material testing in ITER are: 1) to calibrate results of material irradiation tests in fission reactors and simulation facilities, and 2) obtain information on materials properties in the fusion reactor environment as close to DEMO as possible. However, the fluence goal is limited by the present ITER design. Surveillance tests on the basic machine will be conducted in addition to insertion of test samples for advanced materials.

Surveillance testing

- acquisition of thermo-physical and mechanical properties sufficient for remaining life-time correction of heavily loaded elements of FW, blanket, divertor welding and brazing joints in the in-vessel components.

Advanced material testing and fundamental investigations

- establish correlations between property changes and operation time, neutron fluence, temperature, environment, pulse characteristics, etc.
- establish correlations between the radiation damages in fission and fusion spectra to develop database extrapolation according to the available fission reactor data.

3. ANCILLARY EQUIPMENT, CONFIGURATION AND MAINTENANCE

3.1 Test Ports and Testing Space

Testing will be performed primarily through horizontal access ports around the machine. Fig. 8 shows a cross sectional view of the test port locations in ITER. The area of these ports is ~ 1.1m wide by 3.4m high. The testing group has also made strong recommendations for full segment tests (outboard divertor-to-divertor).

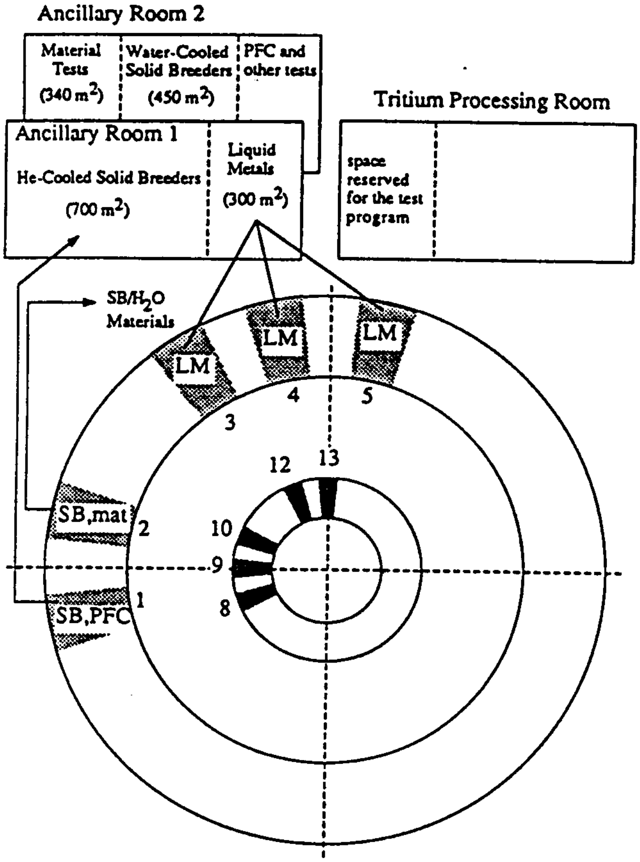


Fig. 8 Space Allocation During the Technology Phase

Tests have been allocated to ports according to the type of breeder and coolant. This provides the simplest arrangement for ancillary equipment and the most compatibility between submodule tests performed simultaneously within the ports.

3.2 Ancillary System Configuration and Space Requirements

For each test location in the machine, a specific set of external equipment must be provided in the ITER plant, with supply lines to the test location. The main equipment required to supply and support the tests are:

- heat rejection
- tritium recovery systems and test-specific intermediate tritium processing
- chemical (impurity) control systems
- coolant and purge fluid storage, start-up, dump tanks, and volume control systems
- emergency and safety systems
- remote handling equipment
- test rooms and hot cells for examinations
- control and data acquisition systems

Ancillary equipment needs will change from the Physics Phase to the Technology Phase as additional ports and ancillary rooms become available.

Most of this equipment is specific to the individual tests, and cannot be integrated into the main system of the plant. Coolant and purge systems operate with fluids and conditions (temperature and chemistry) which are different from the basic machine components, and also require separate monitoring as an integral part of the testing.

Test ports will be occupied by submodules, full-port modules, and possibly full segment tests. The ancillary equipment needs depend on the test type, as shown in Table 2. In some cases, equipment can be designed to handle the higher power and tritium levels and then shared among the various types of tests.

TABLE 2 Approximate Power and Tritium Handling Requirements

Test Type	Size (mxm)	Power Level	Tritium Production Rate
submodule	0.5x1.7	1 MW	0.15 g/FPD*
module	1.1x3.4	5 MW	0.6 g/FPD
segment	1.1x10	15 MW	1.5 g/FPD

* Full Power Day

Space Requirements

Preliminary designs of the required ancillary equipment have been performed for some of the proposed tests. Estimates of the total volumes required for ancillary equipment for all the test modules are shown in Table 3. In general, as the size of a test object increases, the space required for ancillary equipment increases only moderately. The greatest space requirement comes from submodule tests, because the majority of the ancillary equipment can not be shared. The cooling and tritium processing systems may be different in design, and must be allowed to operate independently.

Design of the ancillary equipment rooms must include proper tritium containment and protective measures. In addition, some parts of the ancillary systems will require accessibility for maintenance and replacement.

The distance between the test modules and ancillary systems is also very important. This concern arises due to the following concerns:

- Safety requirements constrain the total amount of potentially hazardous materials present, particularly a concern for liquid metals and tritium entrained in process lines.
- Time constants for system equilibrium depend on the volume of fluids and distance to the ancillary equipment. Time-related test requirements will increase if the distance to the ancillary equipment increases.
- The test ports contain highly-instrumented, complex systems. In some cases, there are several submodules within a single port, and the total number of process lines and instrumentation cables is

expected to number in the hundreds. Running these lines over long distances will make the systems complicated and may lead to problems with reliability and maintenance. Some piping will require special measures (such as guard heaters for liquid metal systems) to control the process fluid conditions.

- In general, the behavior of and interactions with ancillary systems are an integral part of tests, especially for integrated tests. The design of the ancillary systems must be prototypic, including the process lines, in order to obtain valid information from the tests.

For these reasons, it is strongly recommended that space be provided for the installation of ancillary equipment as close as possible to the torus. Fig. 8 indicates the location of the rooms allocated to the ancillary equipment.

TABLE 3 Estimate of Ancillary Equipment Space Requirements

Port	Test Article Type	Space Requirements (Area x Height, m^{2}xm) behind test ports	ancillary rooms	plant services*
SB/gas				
	3 submodules		730 x 11	300 x 11
	full module or segment		370 x 11	130 x 11
SB/H2O				
	3 submodules		450 x 11	30 x 5
	full module or segment		150 x 11	10 x 5
LM/self				
	4 submodules	300 x 11		
	full module or segment	300 x 11		
LM/H2O				
	2 submodules	50 x 11	100 x 11	
	full module	100 x 11	100 x 11	
	segment	100 x 11	200 x 11	
Materials				
	Test assembly	120 x 5**	220 x 11	525 x 11
Total Floor Area		400-500 m^2	1600 m^2	855 m^2

* plant services include space allocated in the main tritium processing hall and post-irradiation examination rooms (hot cells)

** pneumatic system, may be located in ancillary room

3.3 Maintenance and Handling Requirements

From the proposals of the four parties, a crude estimate has been made of the number of insertion/extraction cycles likely to be expected for each type of test article, for examination and replacement. This is summarized in Table 4. The machine shutdown times required for these operations are likely to be significantly different depending on whether or not the primary vacuum would have to be broken.

4. INTERNATIONAL ASPECTS OF THE TEST PROGRAM

4.1 Introduction

The plasma-facing area required to implement the full test program of the four parties has been described previously and was found to exceed the total available space. Subsequently, the test plans were reduced and fuller utilization was made of international combined testing in order to optimize the use of the available port space. The current design of ITER allows for 3 full ports during the Physics Phase and 5 full ports during the Technology Phase.

TABLE 4 Handling Requirements for the Test Objects

Test Articles	Typical Size - Weight	Maximum # of Articles with/without Plasma Exposure	Maximum Frequency Load/Unloads	Maximum # of Load/Unloads per with/without Plasma Exposure
Material Specimens	1-100cc/<1kg	- / 1000's	1-3yr	- / 1000's
Sub-module	0.5-0.2 m^3/1t	6-7/12	2/yr	12-14/24
Module	0.5-2m^3/<10t	4/4	1/yr	4/4
Segment	10m^3/30t	4/-	0.1-1/yr	4/-

Besides relieving limitations on test space, international collaboration in the test program is the most cost-effective and efficient means to satisfy the testing objectives of the 4 parties. However, difficulties arise due to differences in design choices, differences in the overall strategies for fusion development, and even differences in the approaches to testing among the various parties.

Collaboration in the test program is fundamentally different from collaboration on the basic device. ITER itself is a single, clearly-defined machine with generic capabilities to perform testing of components and to demonstrate the physics and engineering potential of fusion. On the other hand, the test program is tightly coupled to, and in most cases plays a key role in the entire R&D plans for nuclear components.

Increased international collaboration in ITER naturally leads to a greater amount of common R&D to develop and test components. This has far-reaching implications on the design and operation of ITER and on R&D programs in fusion nuclear technology throughout the world.

4.2 Aspects of International Collaboration in ITER

International collaboration in the ITER test program can take several forms. While it is necessary to jointly plan the testing use of the machine, there are many options for implementing the test program. In the definition of the test program, the key features related to international collaboration include:

1. The amount of common testing. Test programs can be fully independent, fully in common, or some combination of joint and independent testing. Different parties can be given a lead role for testing components, with the remaining contributing at different levels.
2. The degree of design specificity. All the test space can be pre-designed for particular applications, left as generic slots, or some combination of pre-design and flexibility.
3. Allocation of available testing spaces to countries. The available testing space can be pre-allocated to separate parties, left open as a "user" facility, or principles can be established for the allocation of

space based on some form of selection criteria.

In the conceptual design phase, some of these options have been clearly defined, and others have been left yet unanswered. For the future Engineering Design Phase, it is important to clearly define aspects of international collaboration in the test program so that the design of the machine allows the maximum benefits from testing and so that R&D programs can proceed in a timely way toward the development of test modules for introduction into ITER.

4.3 Basis for the Conceptual Design Phase Test Program

The testing group has defined a single integrated test program for ITER which features the sharing of test ports among countries. Test ports are allocated according to the type of tests to be performed, and all interested parties have worked together to define the test schedule within the ports where testing of their preferred design options will take place. During the Technology Testing Phase, 5 ports are allocated for nuclear testing, and have been assigned as shown in Table 5 (3 ports are reserved during the Physics Phase, allocated to liquid metals, solid breeders, and neutronic tests). A key element of this test plan is the intent to test several submodules simultaneously during the early years of the Technology Phase, followed by a selection process and narrowing of concepts for full-port and segment testing during the final years of the Technology Phase.

TABLE 5 Sharing of Ports for Nuclear Technology Testing

PORT	PARTICIPANTS			
	EC	Japan	US	USSR
Gas-cooled solid breeders	√	√	√	
Water-cooled solid breeders		√	√	(√)
Liquid-metal-cooled liquid metals	√		√	√
Water-cooled liquid metals	√			√
Materials	√	√	√	√

Sharing of space and joint planning of the test programs is an important aspect of collaboration, but is also desirable to enhance the amount of joint testing, in which a single test object is developed and tested by more than one party. Common interests in the world programs allows for a range of bilateral and multilateral collaborations on different design concepts. During the submodule testing (scoping) phase, it was decided that the ports will be divided and different parties will take the lead role in developing and testing submodules. Participations by the other parties is encouraged, but the nature of this cooperation has not been fully defined. More effort will be required in the future to move towards combing R&D programs outside of ITER and planning "true" joint testing in ITER.

Materials testing is probably the most truly-integrated test program within ITER, since mutual interests exists for a variety of materials. Testing needs are well-defined and, to some extent, independent of the component design.

5. TESTING REQUIREMENTS ON ITER PARAMETERS

5.1 Introduction

ITER plays a critical role in the development of components and systems for fusion reactors. As such, it is important that the design of the facility provides a proper environment to perform useful testing. The analysis and recommendations presented here attempt to define the testing value of ITER as a function of the major device parameters.

Test requirements have been formulated based on results of technical analyses performed by all parties involved in the nuclear test program. Test requirements have been considered in two main categories: requirements on parameters and requirements on engineering. The latter category includes concerns such as testing space (total space, configuration of space), ancillary systems, and maintenance and handling requirements. These are treated elsewhere in this paper. Test requirements on the major device parameters are the subject of this section.

The most important parameters which affect the value of testing are neutron wall load, neutron fluence, and time-related parameters (burn time, dwell time and continuous operating time). The requirements are based on extensive analysis of the behavior of nuclear components as a function of these parameters.

Tests in ITER are expected to provide information useful for predicting component performance in devices beyond ITER, up to commercial reactors. The majority of ITER parameters will most likely by lower than those of a demonstration reactor (DEMO) and commercial reactors. Therefore, if the test modules are designed to "look like" components in DEMO and commercial reactors, temperatures, stresses and other operating parameters are reduced and information from the tests is generally not useful. Therefore, "act-alike" modules have been designed using engineering scaling to preserve important phenomena so that data from tests at "scaled down" conditions can be extrapolated to reactor conditions. Engineering scaling involves altering physical dimensions (e.g., increasing the thickness of a solid breeder plate in a blanket to increase temperature differences and thermal stress) and changes in operating conditions (e.g., reducing the mass flow rate of the coolant to maintain coolant temperature rise). However, there are limits to engineering scaling. Therefore, there are minimum values for the major device parameters below which the test information is not useful, because results can not be extrapolated to reactor conditions.

Engineering scaling requirements are different for the various issues. In general, it is found that it is nearly impossible to design an "act-alike" module that can simultaneously provide testing for all the issues. Thus, several "act-alike" modules are generally required, with each one properly scaled to obtain useful test information for the subset of the technical issues.

Analysis has been performed to help define the benefit of testing as a function of these device parameters. This subject is very complex, since the test program involves multiple objectives for the various parties and because behavior of components in the fusion environment is complex and highly uncertain.

Below, the conclusions are summarized and some key supporting analyses are presented. Previous works document in more detail the issues and analyses.[3-10] It is worth noting that extensive studies were performed in this area prior to ITER.[7-10] The results of analysis at this time has been focussed on blanket and materials testing. Test requirements for other important tests, such as impurity control systems, have been examined in less detail.

TABLE 6 Nuclear Testing Requirements - Summary of Recommendations and Reference Values

Device Parameter	Minimum	Highly Desirable	ITER Conceptual Design Reference Paremeters (Technology Phase)
Average neutron wall load at the test module, MW/m^2	≥1	2	1.34
Number of ports	5	7 (+ segment or sector)	5
Minimum port size	2-3 m^2	segment or sector	3.74
Total test area	10 m^2	20-30 m^2 (+segment or sector)	18.7 m^2
Plasma burn time	≥100 s	1-3 hours (to steady state)	2250 s**
Dwell time	*	≤20 s	300-400 s
"Continuous" test duration	≥1 week	2 weeks	
Number of "continuous" tests per year	2-3	~5	
Average availability	10-15%	25-30%	18%
Annual neutron fluence (at the test module), MW-yr/m^2	0.1	0.4	0.14
Total neutron fluence (at the test module), MW-yr/m^2	≥1	2-4	1.53
Total neutron fluence (average at the first wall), MW-yr/m^2	1.5-2	4-6	1.7

* Minimum acceptable dwell time is highly dependent on the design concept, and is difficult to specify. Further analysis in this area is recommended.

** Alternate plasma scenario B2 provides for steady operation

5.2 Recommendations

Table 6 summarizes the recommendations on ITER major parameters from the nuclear testing standpoint. Both minimum and highly desirable goals are provided. Minimum values are determined primarily from analysis of the important blanket phenomena under scaled conditions. One can show that test device parameters below the minimum value in any category will seriously limit the usefulness of nuclear testing for at least one identifiable phenomenon. There is a high probability that results could not be extrapolated to reactor conditions under these circumstances. Conversely, the desirable ranges provide values above which there is confidence that results could be extrapolated to reactor conditions. The desirable values are determined partly from analysis and partly from engineering judgement. While testing at prototypical values is clearly more beneficial, the large majority of nuclear issues can still be adequately addressed if the desirable parameters are achieved in ITER.

Table 6 also shows the reference parameters for ITER in the long-burn hybrid operating scenario. In every case, the design of ITER meets or exceeds the minimum values; however in several cases, the highly desirable goals are not met. Note that an alternate plasma scenario (being considered for ITER) provides steady state burn.

5.2.1 Time-related parameters: burn, dwell, and continuous operating time

Steady-state operation is a highly desirable ultimate goal for ITER during the technology testing phase. If not initially achievable, then high priority should be given to attaining it during some later phase of operation. Pulsing has several negative effects on testing, including:

1) difficulty obtaining and sustaining equilibrium conditions for processes with long time constants,
2) difficulties in maintaining equilibrium conditions during the dwell time because of the very short time constant for physical parameters (e.g., temperature and temperature gradients),
3) undesirable changes in behavior which are not representative of equilibrium conditions,
4) difficulty interpreting and extrapolating data, and
5) negative impact on machine availability and achievable fluence, due to the damaging effects of pulsing on the basic device.

If pulsing is unavoidable, then long burn times (in the range of 1-3 hours) and short dwell times (less than ~20 seconds) are highly desirable. Dwell time is defined as the sum of ramp-down, off-time to reset the magnets and evacuate, and ramp-up to full power. As discussed below, a longer dwell time will make the need for longer burn time more critical.

Assigning precise numbers to both minimum allowable burn and maximum allowable dwell times is difficult. Uncertainties arise due to several factors, including the following: 1. There are a large number of design variations under consideration for testing in ITER, with widely differing time-dependent behavior. In fact, it is likely that before the technology phase begins, advanced, entirely new design concepts with their own unique behavior will have been developed. 2. Behavior of nuclear components to be tested in the ITER environment is complex, and not currently well-understood. 3. Integrated concept performance and validation involves complex component and system interactions, and cannot be accurately modelled today. System time constants tend to be much longer than those of individual components.

Equilibrium conditions generally require a long time to reach, but only a short time to destroy. This is partly a result of the exponential time-dependence of many phenomena and the fact that interrelated phenomena with widely-varying time constants are often present. Notice, for example, in Fig. 9 that the temperature of typical solid breeders decrease very rapidly during the dwell time. Maintaining the temperature variation to within 5% of the average value requires keeping the dwell time to no more than a few seconds. Such short dwell times are not practically achievable in a device such as ITER. The current pulsing options for ITER indicate that dwell times will be long enough in all cases to drop the test module equilibrium through a series of sequential pulses is difficult. In that case, it is more important to extend the burn time than to attempt to maintain a short dwell time. Longer burn times also lead to fewer net cycles, which is advantageous for extending machine lifetime. However, very long dwell times may reduce the duty cycle, leading to an unacceptably low rate of fluence accumulation. If the dwell time exceeds ~ 20 s, then the burn time should be much longer than 1000 s, and should approach or exceed 3000 s.

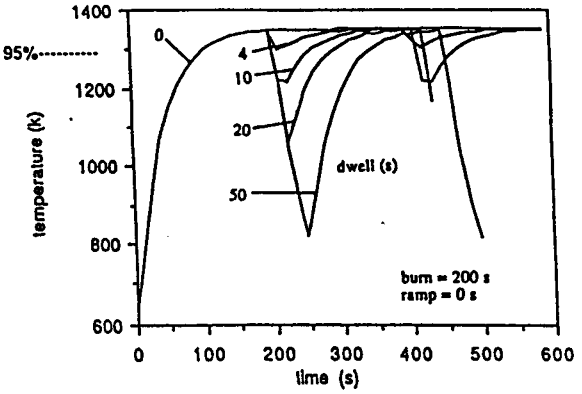


Fig. 9 Variation of Temperature with Time for Different Dwell Times (for $LiAlO_2$)

Since the dwell time under pulsed operating scenarios will be long enough to significantly degrade the test conditions, it becomes important to obtain the maximum amount of test information possible within a single cycle. With a burn time greater than ~1 hour, integrated tests should be able to approach equilibrium conditions for many technical issues (assuming a "warm start"). If the dwell time can be kept moderate (less than 100 ~ 200 s), then additional information may be obtained by providing a succession of uninterrupted pulses.

While the exact details of the testing program have not been specified yet, it is anticipated that testing will be carried out during continuous operating periods, followed by machine shut-down and possibly maintenance to the base machine. With an availability goal in the range of 10%, long periods of down time (up to several months) are expected. It is very desirable to complete a test campaign before a long shut-down, during which time the conditions within the test modules may be difficult to maintain. A more likely scenario is that these down times will be used for post-irradiation analysis of test modules and material specimens.

Continuous test periods of 1-2 weeks have been shown to be desirable and practical to achieve with the assumed device availability goal. Most important tests can be completed within this amount of time, and many of those with longer operating time requirements (such as corrosion and fluence effects) are not seriously affected by extended periods of down time.

5.2.2 Neutron Fluence

The fluence recommendation is based on a combination of the need to perform a sequence of concept performance tests, which take roughly 3-6 years at full power and high availability (~ 25%), resulting in 1-3 MW-yr/m^2 of fluence, and the desire to perform concept verification tests, which require activation of fluence-related phenomena, resulting in 3-5 MW-yr/m^2 of fluence. Table 7 provides a summary of fluence effects on blankets. These fluences are based on the exposure at the location of the test articles: the actual machine fluence required to obtain these exposures is higher, due to several reasons. For example, the existence of plasma facing components, first wall and multiple-containment structures for some tests reduces the neutron flux at the test module. Also, the current test strategy provides for extensive use of sequential testing in order to proceed from smaller size submodule performance tests to larger and more integrated module tests for concept verification.

The current operating scenario allows for a 8-year technology phase, with the possibility of an extended operation period under consideration. From a testing viewpoint, an extended phase of operation is needed to obtain the high fluences required for concept verification.

5.2.3 Neutron Wall Load

The minimum acceptable wall load depends primarily upon two factors. (1) Heat sources are directly proportional to the wall load. Most thermomechanical and tritium-related phenomena in nuclear components strongly depend on temperature profiles, which in turn are determined by the heat sources. (2) The ability to achieve adequate fluence exposure to test modules in a reasonable amount of time requires relatively high wall load and high availability.

Past studies suggest that a wall load in the range of 1-2 MW/m^2 is adequate for thermomechanical and tritium testing[8-10]. Useful testing at reduced wall load is made possible by altering the design and operating parameters of the test modules. Generally, bulk average temperatures are easy to maintain by varying the coolant speed and controlling the amount of heat removed through the heat exchanger. Temperature gradients within components can be obtained by changing the thickness of blanket elements. However, if sizes are changed by more than a factor of 2-3, new effects may arise and the overall geometry may become less representative of a real reactor component. Surface heating is an important aspect of thermomechanical performance, and care must be exercised to maintain prototypical ratios of surface to bulk heating.

TABLE 7 Summary of Fluence Effects on Blankets

- 0-0.1 MW-yr/m^2 (at test module)

  Some changes in thermophysical properties of non-metals occur below 0.1 MW-yr/m^2 (e.g., thermal conductivity)

- 0.1-1 MW-yr/m^2 (at test module)

  Several important effects become activated in the range of 0.1-1 MW-yr/m^2
  - Radiation creep relaxation
  - Solid breeder sintering and cracking
  - Possible onset of breeder/multiplier swelling
  - He embrittlement

  Correlation of materials data with fission reactors and 14 MeV sources can be done with 1 MW-yr/m^2

- 1-3 MW-yr/m^2 (at test module)

  Numerous individual effects and component (element) interactions occur here, particularly for metals, e.g.:
  - Changes in DBTT
  - Changes in fracture toughness
  - He embrittlement
  - Breeder burnup effects
  - Breeder swelling
  - Breeder/clad interactions

In summary, engineering scaling techniques are useful, particularly in simulating individual effects. However, the quality of the overall simulation is significantly degraded beyond a factor of 2-3 reduction in the wall load and surface heating.

The wall load required to attain the recommended fluence is difficult to specify, due to uncertainties in the achievable availability. To illustrate the need for high wall load and availability, Table 8 shows several options which would provide an accumulated exposure of 3 MW-yr/m^2 in 6 years.

TABLE 8 Wall Load and Availability Required to Reach 3 MW-yr/m^2 Goal Fluence in 6 Years

Wall Load (MW/m^2)	Availability
1	50%
1.5	33%
2	25%
2.5	20%

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