

THE PATH TOWARD MAGNETIC FUSION ENERGY DEMONSTRATION AND THE ROLE OF ITER

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Abstract: ITER is a major step in fusion research. It marks the transition of 50 years of research on “exploring the physics of plasmas” to a new phase that will focus on “exploring the physics of fusion”. Yet, ITER is not sufficient to enable a transition to fusion energy demonstration (DEMO). Fusion Nuclear Science and Technology (FNST) development is the most difficult challenge remaining in the practical realization of fusion as a practical energy system. FNST development requires DT plasma-based testing facilities in which the main loading conditions of the fusion environment can be simulated in a volume sufficient to study integrated and component scale phenomena. FNST testing in fusion facilities prior to DEMO can be classified into three stages:

Stage I: Fusion “Break-in” and Scientific Exploration

Stage II: Engineering Feasibility and Performance Verification

Stage III: Component Engineering Development and Reliability Growth

Requirements on the key parameters and features of fusion facilities for FNST development have been derived based on analysis of FNST issues, phenomena, performance goals, and engineering scaling laws.

Analysis of the ITER design and operating conditions show that ITER can be successfully utilized to satisfy the objectives of Stage I. However, a new dedicated facility is required to perform Stages II and III. Such a facility is called either a Volumetric Neutron Source (VNS) or Component Test Facility (CTF). A very important requirement that must be satisfied in order to realize a technically practical and self-consistent scenario toward DEMO is that the fusion power of CTF must be <150 MW. This requirement is derived from analysis of tritium consumption in ITER and CTF and the projected tritium supply from CANDU-type facilities and other fission reactors. A small-size, low fusion power CTF can be obtained in a low-Q tokamak plasma with normal conducting magnets.

1. Introduction:

Fusion has great potential to be a sustainable energy source with no emission of greenhouse or other polluting gases. However, fusion development has taken a relatively long time. When the viability, practicality, and economic competitiveness of fusion will be demonstrated is an open question. Our success in realizing practical fusion in the 21st century will depend in large measure on our understanding of the enormous engineering challenges that a fusion energy system involves and addressing them in an extensive

R&D program, including the construction and operation of the appropriate facilities in a timely manner.

Fusion development from 1950 until today can be characterized as “exploring the physics of plasmas.” Fusion is now entering a new phase that can be generally called “exploring the physics of fusion.” This phase may take about 20 years with the primary research activities focused on the construction and operation of ITER, under construction by an international consortium in Cadarache, France, and the National Ignition Facility (NIF) being constructed by the US in Livermore, California. ITER and NIF will investigate the physics of burning fusion plasmas in magnetic and inertial fusion, respectively.

The most challenging phase of fusion development will most likely be the R&D on Fusion Nuclear Science and Technology (FNST). This phase will aim at developing the nuclear components surrounding the plasma, which are exposed to an extreme environment of high surface and volumetric heating, intense radiation fluxes, strong 3-component magnetic field, and many thermal/chemical/mechanical/electromagnetic interactions. Nuclear components are located inside the vacuum vessel where tolerance for failure is low.

There are five pillars of a fusion energy system: *1-Confined and Controlled Burning Plasma, 2-Tritium Fuel Self-Sufficiency, 3-Efficient Heat Extraction and Conversion, 4-Safe and Environmentally Advantageous, 5-Reliable System Operation.* FNST plays the key role in all the last four pillars, i.e. 2-5. Yet, FNST has not yet received the priority and the resources needed in the world fusion program. The blanket is a central component of FNST. Yet, no fusion blanket has ever been built or tested. There exist no facilities that provide the necessary environment for meaningful testing of the fusion nuclear components.

ITER will provide the first fusion nuclear environment in which blankets can be tested and data relevant to FNST obtained. While testing in ITER provides very important information on FNST, it is severely limited. Development of FNST will require a new facility designed specifically to test and develop fusion nuclear components. This type of facility for fusion nuclear science and technology is often called CTF (Component Testing Facility) or VNS (Volumetric Nuclear Source).

2. What is Fusion Nuclear Technology?

Fusion Nuclear Technology (FNT) includes all components from the edge of the plasma to the toroidal field coils, i.e. First Wall/Blanket, vacuum vessel and shield components, and other plasma interactive/high heat flux components (divertor, r.f. antennas/launchers/waveguides, diagnostics). These components are illustrated in a vertical cross section of a tokamak reactor in Fig.1. Other components coupled to and affected by the nuclear environment include Tritium Processing Systems, Instrumentation and Control Systems, Remote Maintenance Components, and Heat Transport and Power Conversion Systems. Many technical areas are essential to FNT; for example, neutronics, materials, thermomechanics, thermofluids, magnetohydrodynamics, safety, solid mechanics, radiation effects and chemistry.

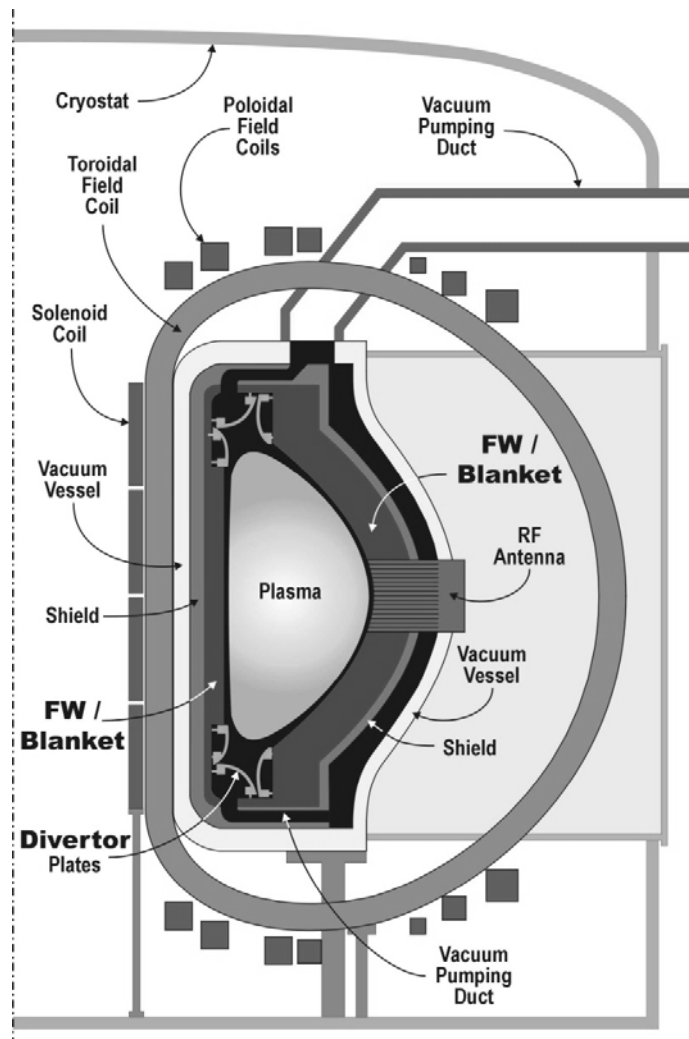


Figure 1: Vertical Section of a Tokamak Reactor that shows the fusion nuclear components

FNT components, particularly the blanket/first wall/divertor must operate safely and reliably in a harsh environment. Yet, no fusion blanket has ever been built or tested. Blanket systems have many possible designs, materials, and configurations. Many blanket concepts have been proposed worldwide, see Table 1, each having its own balance of feasibility and attractiveness issues. Only after stages of fusion environment testing can an informed down-selection be made. The large number of concepts and wide range of issues are best screened by utilizing the resources and the ingenuity of the world's FNT programs.

Table 1: Blanket concepts proposed by ITER Parties for ITER testing [5]

Concept	Acronym	Materials	Proposing Party
Helium-Cooled Ceramic Breeder	HCCB	RAFS Structure Be multiplier, Ceramic breeder (Li_2TiO_3 , Li_4SiO_4 , Li_2O) Helium coolant and purge	EU, KO, CN, (JA,US, RF, IN)* *Supporting Role
Water-Cooled Ceramic Breeder	WCCB	RAFS structure Be multiplier, Ceramic breeder (Li_2O) Water coolant, He purge	JA
Helium-Cooled Lead-Lithium	HCLL	RAFS structure Molten Pb-17Li breeder/multiplier Helium coolant	EU, CN
Dual-Coolant Lead-Lithium	DCLL	RAFS structure SiC flow channel inserts Molten Pb-17Li breeder/coolant Helium coolant	US, CN (EU, JA, IN)* *Supporting Role
Helium-Cooled Molten Lithium	HCML	RAFS structure Lithium breeder Helium coolant	KO
Self-Cooled Lithium	Li/V	Vanadium alloy structure Insulator barrier (e.g., AlN) Lithium breeder/coolant	RF
Lead-Lithium Ceramic Breeder	LLCB	RAFS structure Dual coolant Lead Lithium and Helium Dual breeder Lead Lithium and Ceramic	IN

3. ITER and Test Blanket Module (TBM)

ITER is a tokamak, in which strong magnetic fields confine a torus-shaped fusion plasma. It will be the first fusion reactor to create more energy than it uses. The objectives set out for ITER are basically two: 1) programmatically, to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes; and 2) technically, to demonstrate extended burn of DT plasmas, with steady state as the ultimate goal; to Integrate and test all essential fusion power reactor technologies and components, and to demonstrate safety and environmental acceptability of fusion. Breeding blankets represent one of the major technological breakthroughs required from passing from ITER to the next step, usually called DEMO, a demonstration reactor able to furnish electric power to the grid. For this reason, among the technical objectives of ITER it is specifically stated that “*ITER should test tritium breeding module concepts that would lead in a future reactor to tritium self-sufficiency and to the extraction of high-grade heat and electricity production.*”

Test Blanket Modules (TBMs) inserted in ITER represent a principal strategy by which ITER will provide the first experimental data on the potential of fusion as an energy source. TBMs are essential to answering two critical questions about fusion as an energy source: “*Can tritium be produced in the blanket at a rate sufficient to supply tritium to fuel the plasma?*” and “*Can heat be extracted from the blanket, simultaneously with tritium breeding, at temperatures high enough for efficient electricity generation?*” This is why successful TBM experiments in ITER represent an essential step on the path to DEMO in all the ITER Parties’ fusion development plans. A *principal mission* of the ITER Test Blanket Module (TBM) Program is to develop, deploy, and operate ITER TBM experiments that provide unique experimental data on, and operational experience with, the integrated function of blanket and first wall (FW) components and materials in a true fusion environment. This data is essential for validation of the scientific understanding and predictive capabilities; demonstration of the principles of tritium self-sufficiency in *practical* systems; development of the technology necessary to install breeding capabilities in next-step machines; and providing the first integrated experimental results on reliability, safety, environmental impact, and efficiency of fusion energy extraction systems.

The overall ITER operational plan through the first ~10 years is preceded by one year of integrated commissioning of in-vessel components. The 10-year plan includes 2.5 years of initial H-H operation; a brief D-D phase; and an approximately six-year-long D-T phase. During the D-T phase, typical operating conditions for the TBMs include an average FW surface heat flux of 0.27 MW/m^2 (during a plasma pulse), a neutron wall load of 0.78 MW/m^2 (during a plasma pulse), and a pulse length of 400 s (or longer) with a duty cycle of 22% (or higher). These parameters are used in the conceptual designs of Parties’ TBMs. Other important conditions of ITER that allow for meaningful integrated testing of blanket components and material systems include a strong magnetic field (~ 5 T) of the same order as in power plants, and off-normal plasma events such as disruptions, ELMs, VDEs, *etc.*

Three 1.75 m wide \times 2.2 m high equatorial ports have been allocated by ITER for TBM testing. Test modules must be recessed 50 mm from the nominal surface of the first wall of the ITER shielding blanket in order to reduce plasma-wall interaction effects,

including the maximum disruption energy load (0.55 MJ/m^2 over 1-10 ms). Correspondingly, a 2 mm beryllium protection layer on the FW is requested.

Each TBM is supported by a water-cooled steel frame that has a thickness of 200 mm on each side of the TBM and a backside shield behind each TBM. The TBM is inserted from the plasma side into the frame and supported from behind by attachment to the backside shield block with flexible supports. Each frame can hold two vertically or horizontally oriented TBM backside shield pairs. This combined unit is known as the TBM port plug, and provides a standardized interface with the ITER basic structure, including thermal insulation of the basic machine from the TBM. The port plug is inserted through the bioshield and into the port as a single unit.

Each TBM system includes several associated sub-systems, such as coolant loops, tritium management equipment, a liquid breeder loop (in liquid breeder TBMs), instrumentation packages and control systems, and safety systems. These sub-systems will need to interface with the ITER facility and services, including remote handling equipment, the hot cell facility, the ITER standard cooling system, the HVAC, diagnostic, and control and safety systems, each with its corresponding operational procedures and limitations. Any equipment and interfaces necessary for a particular TBM will have to match the space and services available at each test port.

Three blanket options, in which liquid metal MHD plays an important role in determining blanket performance, have been proposed for testing in ITER. They are a helium-cooled PbLi (HCLL), a dual-cooled PbLi (DCLL), and a dual-function PbLi (DFLL) blanket concept. The common MHD problems among the three concepts relate to the MHD flow distribution for complex flow elements including toroidal manifold flow distribution, contractions/expansions in poloidal plane, and MHD velocity profile in electrically-coupled multiple ducts. In the HCLL blanket, liquid metal circulation is primarily required for tritium removal. Larger flow rates are desirable in order to keep the tritium permeation losses low. A specific MHD question on the HCLL concept addresses the coupled effect of the MHD velocity magnitude and profile on alleviating the tritium permeation problem. The basic idea of the DCLL blanket is to use helium to remove all heat deposited in the blanket structure (including the surface heat flux on the first wall), and a flowing, self-cooled, PbLi alloy breeder to remove nuclear heat generated in the breeding zone – at a high temperature for efficient power conversion. The DCLL concept consists of PbLi channels contained within a helium-cooled structure made of reduced activation ferritic steel (RAFS). A unique MHD problem for this particular concept relates to the effect of natural convection on the MHD flow and temperature distributions. Both DCLL and DFLL concepts require the use of an insulator such as SiC/SiC flow channel insert (FCI) for pressure drop and thermal loss control. Such a FCI performs two important functions: (a) the FCI thermally insulates the PbLi so that its temperature can be considerably higher than the surrounding structure, and (b) the FCI also provides electrical insulation between the PbLi flow and the thick, load-bearing RAFS walls to reduce the MHD pressure drop to a manageable level, even in high magnetic field regions. MHD related R&Ds have been identified under the IEA collaborative efforts, including toroidal expansion and toroidal manifold MHD experiments.

In addition, it is necessary to ensure that the TBMs are compatible with the tokamak operation. Several issues driven by the interaction of the test blanket module and the magnetic field that must be characterized and investigated during the hydrogen plasma operation phase including:

- interference of the test modules with plasma confinement, including the effects of ferritic/martensitic steels on the ITER magnetic confinement fields;
- operation of the test modules, diagnostics, and supplementary equipment in a strong magnetic field;
- test module structural loads and corresponding responses owing to surface heat flux on the test module first wall during normal plasma discharges, and including spatially non-uniform heat fluxes, for instance, from plasma MARFES;
- test module structural loads and corresponding responses during tokamak startup and shutdown, including transient events like plasma disruptions; and
- material erosion and transport from the test module first wall and the necessity of using a beryllium protective layer (current requirement is for a 2 mm Be layer).

These issues also present challenging opportunities for the PAMIR Community.

4 . Framework for FNT development

The technical foundations for the fusion nuclear technology development path to DEMO are based on many previous technical studies led by the US and other countries over three decades. Examples of references that provide the technical basis are References [1], [2], and [3]. These comprehensive studies concluded that blanket development is one of the key components on the critical path to DEMO. The major elements of the proposed blanket development path to DEMO are illustrated in Fig. 2. They are:

Base R&D activities with nuclear and non-nuclear experiments in *non-fusion* facilities; and modeling and computer simulations

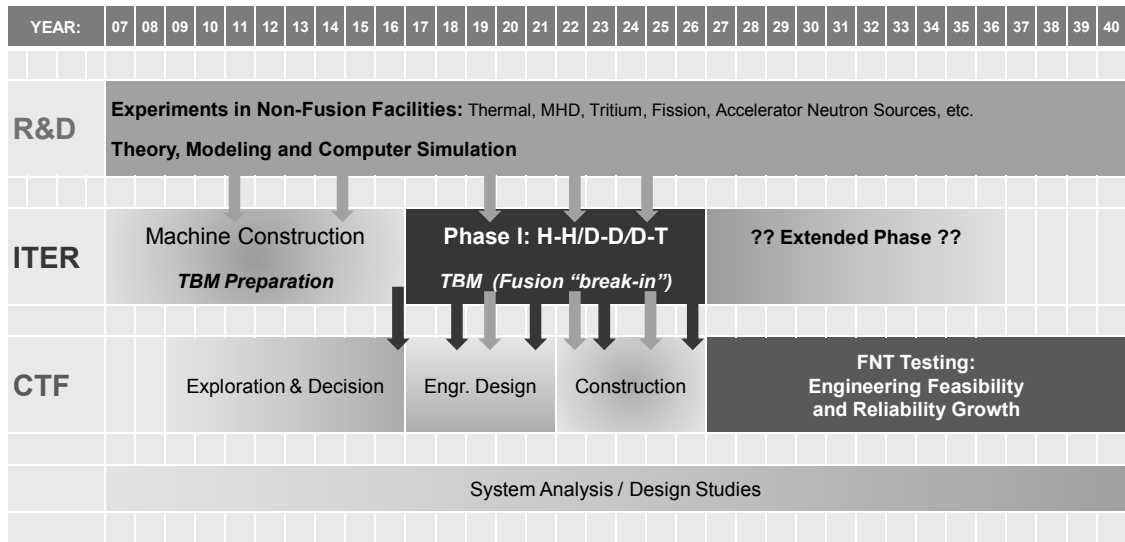
Testing Blanket Modules (TBM) in ITER during Phase 1 of operation

Continuous transfer of information from ITER TBM and base R&D into the refinement of blanket designs and the construction of blanket test modules, and possibly breeding blankets, in CTF

Testing in CTF that addresses the engineering development and reliability growth of blankets to a level sufficient to design, construct and operate full breeding blankets in DEMO.

It is important to understand the relationship and incremental role of each of these elements. A detailed description is given in reference 6.

Major Activities and Approximate Timeline for Fusion Nuclear Technology Development



Based on FESAC 2003 Panel, but with:

- Timeline shifted by 2 years to adjust for current ITER schedule
- Additional year added to CTF Design and Construction Phases

Arrows indicate major points of FNT information flow through ITER TBM

Figure 2: Major Activities and Approximate Timeline for FNT Development

These main FNT development path elements are made up of many progressive R&D activities, as illustrated in Fig. 3. Note that tests in non-fusion facilities are limited to single-effect and some multiple-interaction tests. Fusion tests are needed to cover several multiple-interaction tests, integrated tests, and component tests.

In partial analogy to experience from technology development in other fields, we propose that testing and development of FNT (primarily the blanket) in fusion facilities proceed in three stages: (I) initial fusion environment "break-in"; (II) engineering feasibility and performance verification; and (III) component engineering development and reliability growth, as illustrated in Fig.4.

Types of experiments, facilities and modeling for FNT

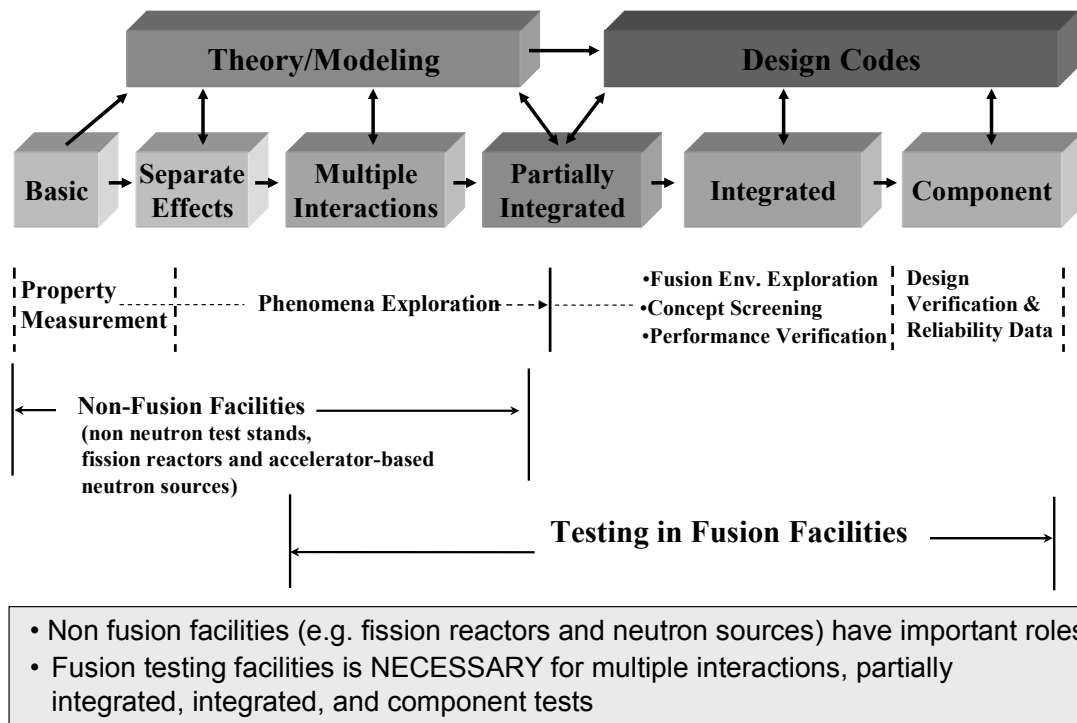


Figure 3: Types of Experiments, Facilities, and Modeling for FNT

We note again that FNT components such as the blanket have never been tested before in any fusion facility. Therefore, the Stage I testing should be focused on calibration and exploration of the fusion environment, including uncovering unexpected synergistic effects and testing experimental techniques and diagnostic tools (e.g. how to measure and collect data, interpret and extrapolate results, and include the effects of the fusion environment on instrumentation tools). Part of the Stage I fusion environment exploration is screening a number of candidate design concepts. Only a limited number of concepts are tested in Stage II, which aims at engineering feasibility and performance verification. Modules with a representative size should be used in this stage to ensure that all the key aspects of subsystem interactions are tested. Results of tests in Stage II should permit selection of a very small number of concepts, but selection of a single concept is too risky, prior to performing reliability growth tests in Stage III. Stage III tests focus on true engineering development where actual prototypical components are tested and an aggressive design/test/fix iterative program is instituted. The extensive reliability testing required to achieve blanket availability goals is one of the primary reasons why blanket testing determines the critical path for FNT development.

The role of ITER TBM is to provide the Stage I testing needs, while the CTF mission is to perform the testing required in Stages II and III.

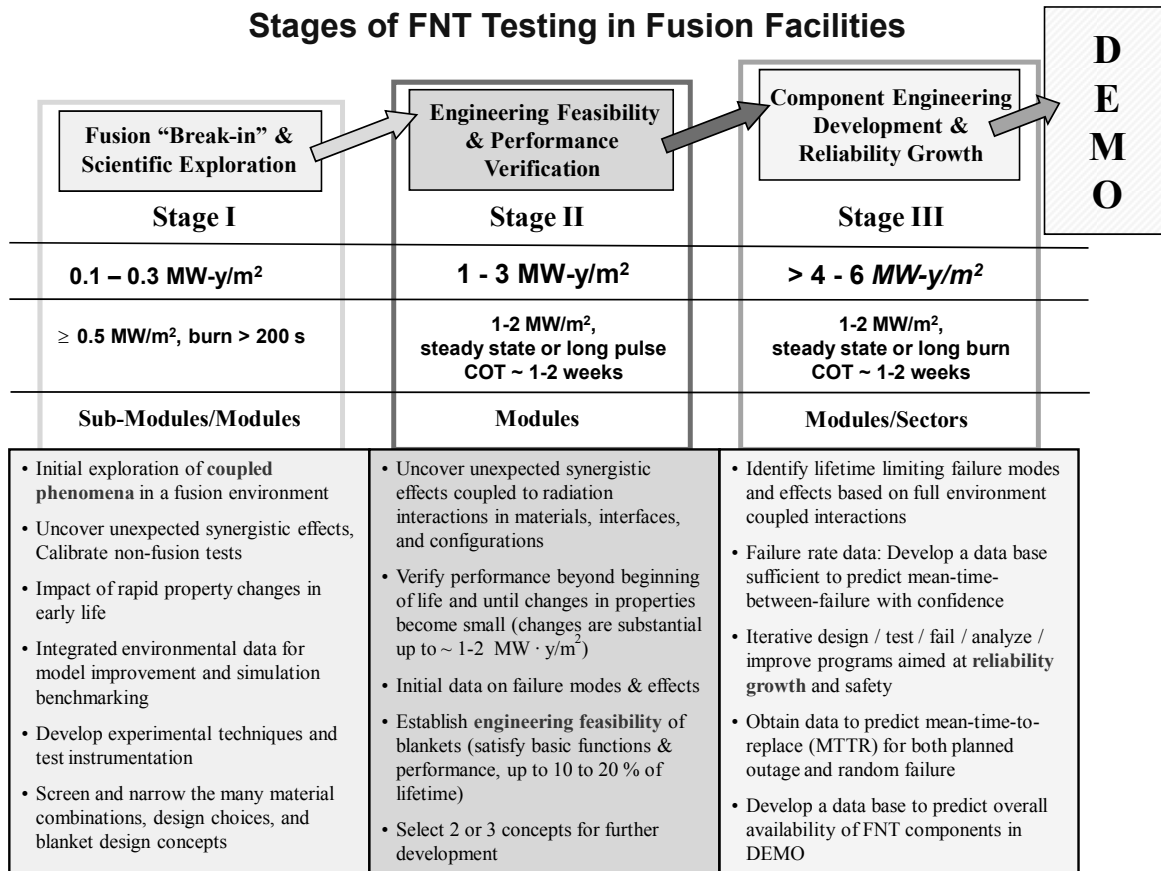


Figure 4: Stages of FNT Testing in Fusion Facilities

5. DEMO Goals

DEMO requirements are a strong driver for the need for such an FNT development path, as described above. Previous system and planning studies provide general goals and features of DEMO. All studies and planning activities conclude that the DEMO must achieve tritium self-sufficiency. Another conclusion is that at least one option must be validated for each component prior to construction of DEMO. The goal of fusion R&D plans around the world is the operation of a demonstration power plant (Demo), which will enable the commercialization of fusion energy. The target date is typically 20-40 years from now. Early in its operation the Demo will show net electric power production, and ultimately it will demonstrate the commercial practicality of fusion power. It is anticipated that several such fusion demonstration devices will be built around the world. In order for a future fusion industry to be competitive, the Demo must:

- a) achieve tritium self sufficiency; b) be safe and environmentally attractive;
- c) extrapolate to competitive cost for electricity; d) use the same physics and technology as the first generation of competitive commercial power plants to follow; and
- e) achieve availability of ~ 50%, and extrapolate to commercially practical levels.

The most difficult and time consuming stage in FNT development is expected to be the “reliability growth phase.” Prior studies, *e.g.* Refs. [1] and [4], have shown that the availability of the blanket system must be higher than 88% to meet a Demo target availability goal of 50%. Since the time to replace blankets is long (weeks), the Mean-Time-Between Failures (MTBF) must be long to achieve such a high availability target goal. Current assessments, again see *e.g.* Ref. 1, show that (A) the MTBF for a single blanket module must be considerably longer than its fluence lifetime, and (B) the required blanket system MTBF is longer than what is achievable based on extrapolations from other technologies. Therefore, an aggressive reliability growth program needs to be pursued for the blanket, which will require a large testing area and long testing time to achieve a reasonable confidence level. This is one of the major objectives of CTF. Early data from R&D and ITER TBM should help screen blanket concepts in order to allow CTF to focus quickly on engineering development and reliability growth testing of a very small number of blanket concepts (preferably two).

6. Conclusions

Fusion nuclear components must operate safely and reliably in a harsh environment. No fusion blanket has ever been built or tested. Hence, their integrated function and reliability are by no means assured. ITER presents the first opportunity to test blanket materials and components in an actual fusion environment after many years of research, development and design in domestic programs. ITER test blanket module (TBM) testing represents a critical step toward establishing the principles of tritium self-sufficiency and energy extraction – on which the feasibility of deuterium-tritium fusion energy production relies. The role of ITER TBM is to provide the Stage I Fusion Break-in testing needs. The CTF mission is to perform the testing required in Stages II and III.

Fusion Nuclear Science and Technology (FNST) development is the most difficult challenge remaining in the practical realization of fusion as a practical energy system. The cost of R&D and the time to DEMO and commercialization of fusion energy will be determined largely by FNST.

7. References:

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