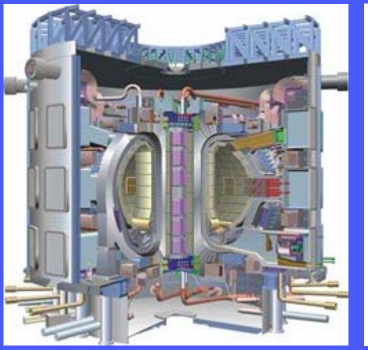
WORKSHOP ON THE ROLE OF THE ITER TBM
IN FUSION NUCLEAR TECHNOLOGY DEVELOPMENT
ORNL, MAY 30 – JUNE 1, 2007

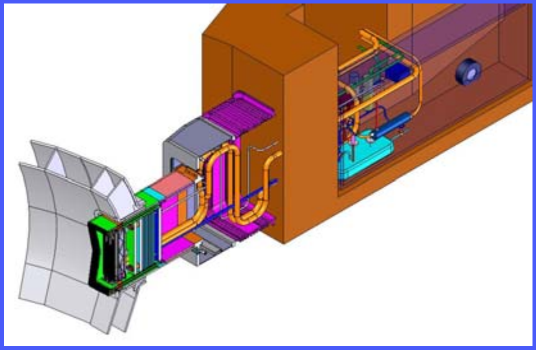
ANSWERS TO SPECIFIC TECHNICAL, PROGRAMMATIC, AND LOGISTICAL QUESTIONS

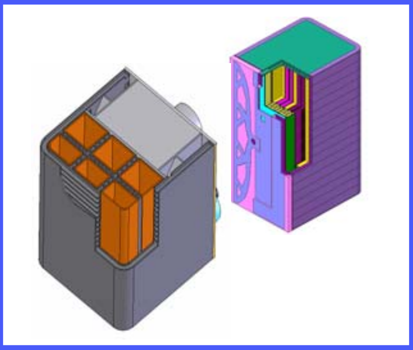
BY:

**M.A. ABDOU, N.B. MORLEY, A.Y. YING, C.P.C WONG, R. KURTZ, M. SAWAN,
B. MERRILL, Y. KATOH, S. MALANG, M. YOUSSEF, S. SMOLENTSEV, D.K. SZE**

AND THE US ITER TEST BLANKET MODULE TEAM







KEY CONTRIBUTORS:

**M.A. ABDOU, N.B. MORLEY, A.Y. YING, S. SMOLENTSEV, S. SHARAFAT, M. DAGHER,
M. YOUSSEF, K. MESSADEK - UNIVERSITY OF CALIFORNIA, LOS ANGELES**

C.P.C. WONG, D. SONN, C. BAXI - GENERAL ATOMICS

T. MANN, Y. KATOH, B. PINT, S. ZINKLE, P. FOGARTY - OAK RIDGE NATIONAL LABORATORY

R.J. KURTZ - PACIFIC NORTHWEST NATIONAL LABORATORY

B. MERRILL, P. SHARPE, P. CALDERONI, D. PETTI - IDAHO NATIONAL LABORATORY

R. NYGREN, M. ULRICKSON, T. TANAKA - SANDIA NATIONAL LABORATORY

M. SAWAN, G. SVIATOSLAVSKY - UNIVERSITY OF WISCONSIN

R.S. WILLMS - LOS ALAMOS NATIONAL LABORATORY

S. REYES - LAWRENCE LIVERMORE NATIONAL LABORATORY

D.K. SZE - UNIVERSITY OF CALIFORNIA, SAN DIEGO

S. TOURVILLE, S. MALANG, A. ROWCLIFFE - CONSULTANTS

TABLE OF CONTENTS

Introduction

This report contains responses to a series of questions formulated to elucidate the benefits of US TBM testing in ITER, as well as the cost and risk of such a program. These questions were distributed to the TBM team by the director of the Virtual Laboratory for Technology (VLT) on May 15, 2007. A workshop on the role of ITER TBM in fusion nuclear technology (FNT) development in the US will be held at ORNL on May 30 – June 1, 2007. The workshop will be attended by US TBM Team members, a panel of nuclear/fusion technology experts, and Department of Energy officials. The responses to the questions given herein will be discussed in detail. A draft consensus report on the findings of the expert panel with respect to the answers of the US ITER TBM team to the questions is expected at the end of the meeting with final report to be provided to the VLT by June 13, 2007. The purpose of these panel findings is to aid the US Department of Energy in developing a US TBM policy before the July Interim ITER Council Meeting this July in Tokyo.

Panel Members

David Petti, INL, Chair (david.petti@inl.gov)
Nermin Uckan, Executive Secretary, (uckanna@ornl.gov)
Said Abdel-Khalik, GIT (said.abdelkhalik@me.gatech.edu)
John Haines, ORNL (hainesjr@ornl.gov)
Richard Mattas, ANL, Retired (mattes@anl.gov)
Farrokh Najmabadi, UCSD (najmabadi@fusion.ucsd.edu)
Lou Qualls, ORNL (quallsal@ornl.gov)
Ron Parker, MIT (parker@psfc.mit.edu)
John Sackett, INL (johnflyer@riversdbs.net)
Ned Sauthoff, USIPO (sauthoffnr@ornl.gov)
Steve Zinkle ORNL (zinklesj@ornl.gov)

Questions Related to Fusion Nuclear Technology Development

Note: The series of 18 questions are answered consecutively below. Each question is stated first as posed, and followed by the answer prepared by the US TBM team. Note that there is duplication and overlap in the questions. This is why in the answers to some questions references (with hyperlinks) to other questions are provided.

Question 1.

What, in detail, is the fusion nuclear blanket development path to DEMO (including a Component Test Facility (CTF))?

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). 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, safety, solid mechanics, radiation effects and chemistry.

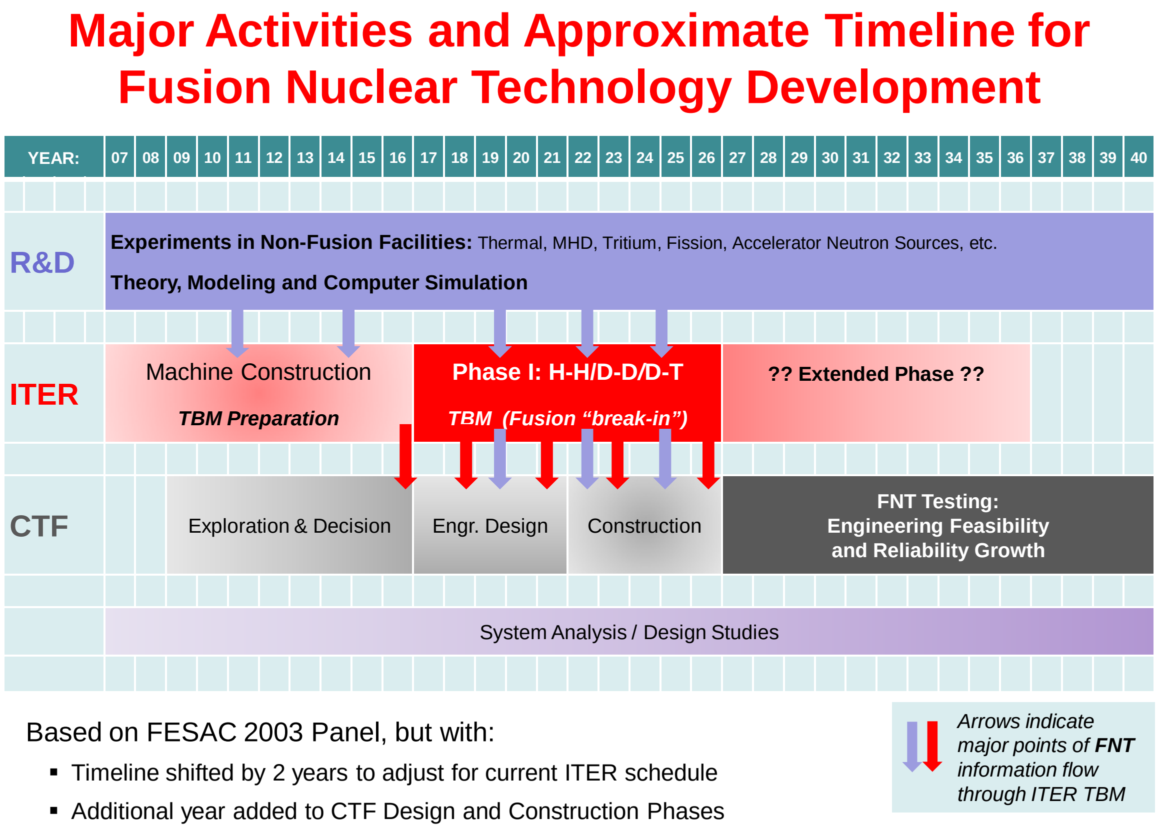
FNT components (primarily the FW/Blanket, as discussed here) must operate safely and reliably in a harsh environment. Yet, no fusion blanket has ever been built or tested. Blanket systems have many possible designs, materials, and configurations as shown in Table 1-1. Many blanket concepts have been proposed worldwide, see Table 1-2, 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 1-1: Many *blanket concepts* proposed worldwide based on the selection from many possible material combinations and configuration options

Material or Configuration	Options
Structural Materials	Reduced Activation Ferritic Steel Alloys (including ODS), Vanadium Alloys, SiC Composites, Austenitic Steel Alloys
Coolant Media	Helium, Water, Liquid Metal Alloys, Molten Salts
Breeder Media	Lithium-Bearing: Ceramic Breeders (Li_4SiO_4, Li_2TiO_3, Li_2O); Liquid Metal Alloys (Li, PbLi, SnLi); Molten Salts (FLiBe, FLiNaBe); Varying enrichments in Li-6
Neutron Multiplier Materials	Beryllium, $Be_{12}Ti$, Lead alloys
MHD/Thermal Insulator Materials	SiC composites and foams, Al_2O_3, CaO, AlN, Er_2O_3, Y_2O_3
Corrosion and Permeation Barriers	SiC, Al_2O_3, others
Plasma Facing Material	Beryllium, Carbon, Tungsten alloys, others
HX or TX Materials	Ferritic Steels, Refractory Alloys, SiC, Direct Gas Contact
Blanket Configurations	He or Water Cooled Ceramic Breeder/Be; Separately Cooled, Self-Cooled, Dual-Coolant LM or MS
Ceramic Breeder Configurations	Layered, Mixed, Parallel, Edge-On (referenced to FW)
Liquid Breeder Configurations	Radial-Poloidal flow, Radial-Toroidal Flow, others
MHD/Thermal Insulator Config.	Flow Channel Inserts, Self-Healing Coatings, Multi-Layer Coatings
Structure Fabrication Routes	HIP; TIG, Laser and E-beam Welding; Explosive Bonding; Friction Bonding; Investment Casting; and others

Table 1-2: Blanket concepts proposed by ITER Parties for ITER testing [1-5]

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



Based on FESAC 2003 Panel, but with:

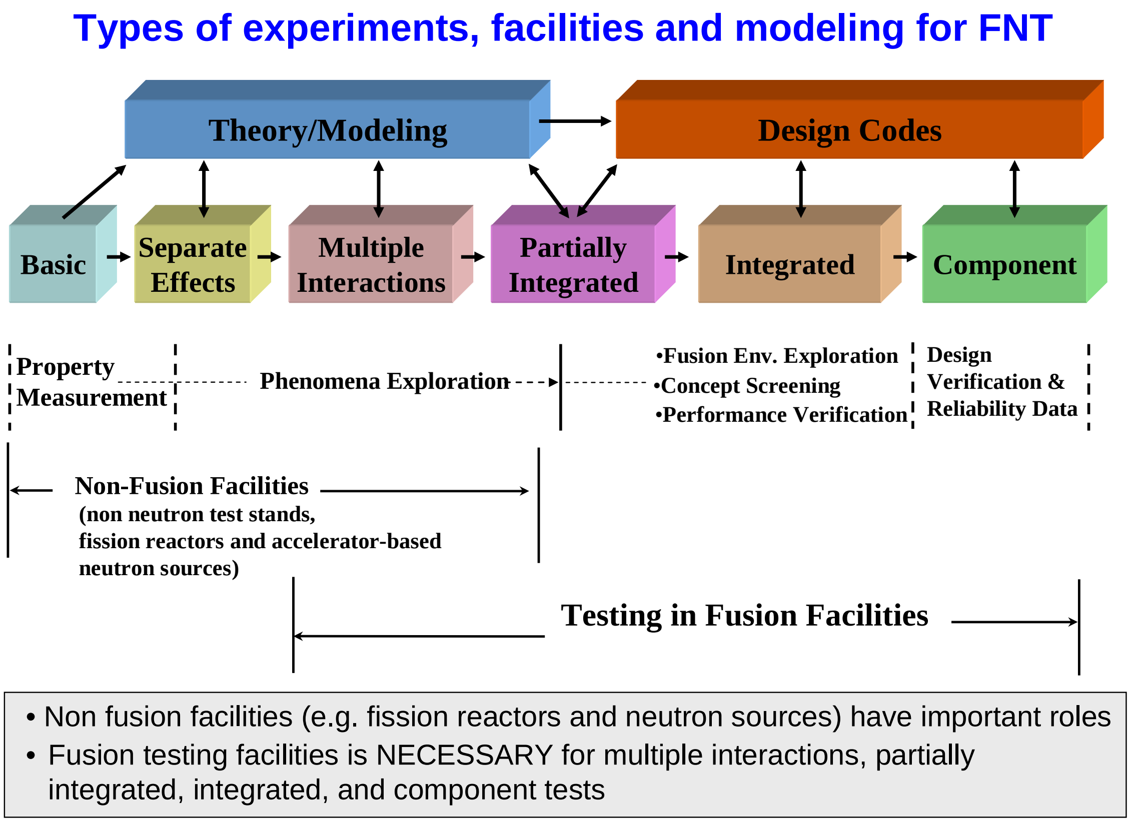
- Timeline shifted by 2 years to adjust for current ITER schedule
- Additional year added to CTF Design and Construction Phases

Figure 1-1: Major Activities and Approximate Timeline for Fusion Nuclear Technology Development

1.1 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 3 decades. Examples of references that provide the technical basis are References 1-1, 1-2, and 1-3. 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. 1-1. They are:

1) Base R&D activities with nuclear and non-nuclear experiments in *non-fusion* facilities; and modeling and computer simulations
2) Testing Blanket Modules (TBM) in ITER during its Phase 1 of operation
3) 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
4) 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.



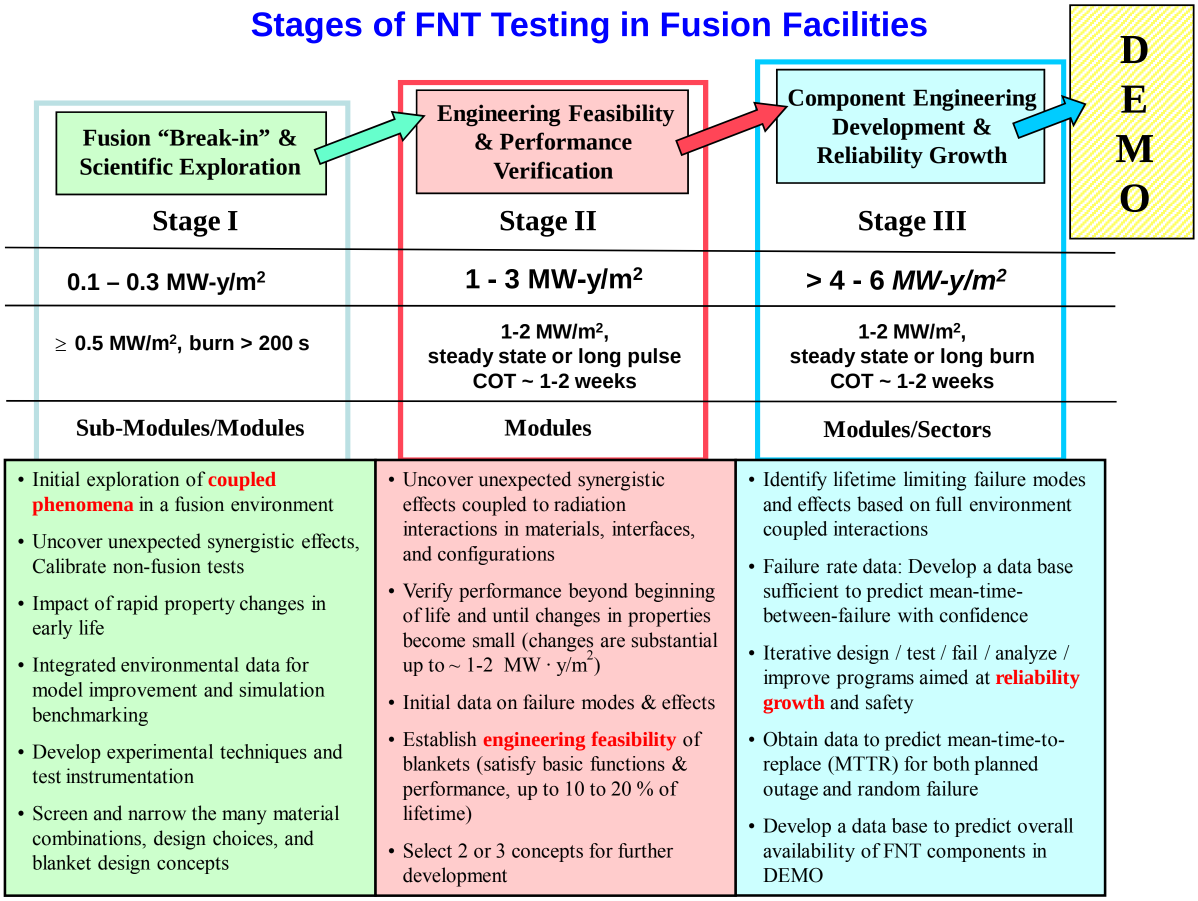
- Non fusion facilities (e.g. fission reactors and neutron sources) have important roles
- Fusion testing facilities is NECESSARY for multiple interactions, partially integrated, integrated, and component tests

Figure 1-2: Types of Experiments, Facilities, and Modeling for FNT

It is important to understand the relationship and incremental role of each of these elements. A detailed description is given in the response to Question 3, where this information was specifically requested.

These main FNT development path elements are made up of many progressive R&D activities, as illustrated in Fig. 1-2. 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. 1-3. (Some analogy can also be made between these stages and the three stages often used in fusion plasma confinement physics; namely, concept exploration, proof of principle and performance extension.)



Stage I	Stage II	Stage III
Fusion "Break-in" & Scientific Exploration	**Engineering Feasibility & Performance Verification**	**Component Engineering Development & Reliability Growth**
0.1 – 0.3 MW-y/m^2	**1 - 3 MW-y/m^2**	**> 4 - 6 *MW-y/m^2***
≥ **0.5 MW/m^2, burn > 200 s**	**1-2 MW/m^2, steady state or long pulse COT ~ 1-2 weeks**	**1-2 MW/m^2, steady state or long burn COT ~ 1-2 weeks**
Sub-Modules/Modules	**Modules**	**Modules/Sectors**
• Initial exploration of **coupled phenomena** in a fusion environment • Uncover unexpected synergistic effects, Calibrate non-fusion tests • Impact of rapid property changes in early life • Integrated environmental data for model improvement and simulation benchmarking • Develop experimental techniques and test instrumentation • Screen and narrow the many material combinations, design choices, and blanket design concepts	• Uncover unexpected synergistic effects coupled to radiation interactions in materials, interfaces, and configurations • Verify performance beyond beginning of life and until changes in properties become small (changes are substantial up to ~ 1-2 MW · y/m^2) • Initial data on failure modes & effects • Establish **engineering feasibility** of blankets (satisfy basic functions & performance, up to 10 to 20 % of lifetime) • Select 2 or 3 concepts for further development	• Identify lifetime limiting failure modes and effects based on full environment coupled interactions • Failure rate data: Develop a data base sufficient to predict mean-time-between-failure with confidence • Iterative design / test / fail / analyze / improve programs aimed at **reliability growth** and safety • Obtain data to predict mean-time-to-replace (MTTR) for both planned outage and random failure • Develop a data base to predict overall availability of FNT components in DEMO

Figure 1-3: Stages of FNT Testing in Fusion Facilities

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 the 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.

1.3 DEMO Goals

DEMO requirements are a strong driver for the need for such an FNT development path, as described above. Previous US system and planning studies and the FESAC Plan for Development of Fusion Energy in 2003 [1-4] 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. Below are relevant quotes from the FESAC 2003 Plan:

> The goal of the plan is operation of a US demonstration power plant (Demo), which will enable the commercialization of fusion energy. The target date is about 35 years. 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 US fusion industry to be competitive, the US Demo must:
>
> a. be safe and environmentally attractive,
> b. extrapolate to competitive cost for electricity in the US market, as well as for other applications of fusion power such as hydrogen production,
> c. use the same physics and technology as the first generation of competitive commercial power plants to follow, and
> d. ultimately achieve availability of ~ 50%, and extrapolate to commercially practical levels. [1-4]

The most difficult and time consuming stage in FNT development is expected to be the "reliability growth phase." Prior studies, *e.g.* Refs. 1-1 and 1-4, 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. 1-1, 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).

1.4 Conclusions

Blanket 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 and technologies 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.

References

1-1. "Results of an International Study on a High-Volume Plasma-Based Neutron Source for Fusion Blanket Development," Fusion Technology, 29: 1-57 (1996).

1-2. "Technical Issues and Requirements of Experiments and Facilities for Fusion Nuclear Technology" Nuclear Fusion, 27, No. 4: 619-688 (1987).

1-3. "A Study of the Issues and Experiments for Fusion Nuclear Technology," Fusion Technology, 8: 2595-2645 (1985).

1-4. "A Plan for the Development of Fusion Energy: Final Report to FESAC," (March 2003).

1-5. "US ITER Test Blanket Module (TBM) Program, Volume I: Technical Plan and Cost Estimate Summary," UCLA-FNT-216 (2007).

Question 2.

What are the important phenomena that are believed to drive the behavior of the fusion blanket (and hence underlie the strategy outlined in question 1)? What are the relative time scales for these phenomena and are there important coupled or integrated effects that should be considered? Are there separable effects?

FW/Blanket modules accept energy in the form of a surface heat flux (SHF) consisting of particles and radiation from the plasma, and a volumetric heat deposition coming from the neutrons incident on the first wall (*i.e.* neutron wall load (NWL)) that produce nuclear reactions, secondary neutrons, charged particles, gamma rays, and thus local heating in the blanket materials. The thermal energy from these sources is transferred to a FW/Blanket coolant(s) which is used to produce electricity in a thermal conversion cycle, and tritium is produced by nuclear reactions in lithium-bearing ceramics or liquids present in the blanket system for just this purpose.

2.1 Nuclear Heating and Tritium Production

Nuclear reactions in fusion blankets lead to several important phenomena that impact the fusion blanket. Neutrons and secondary gamma rays are absorbed leading to the generation of volumetric nuclear heating that varies in magnitude and profile depending on the blanket design. The relative contribution from neutrons and gamma rays is important since it impacts the synergistic effects between volumetric heating and neutron induced effects (radiation damage, gas production, tritium breeding, lithium burn-up, *etc.*). The local nuclear heating and production rate for tritium tracks essentially instantaneously with the neutron flux. Existing diagnostics for measurement of neutron flux, spectrum, heating, and tritium production, can acquire many measurements in the span of 1 to 2 seconds. Short pulse lengths and low fusion power are, in fact, desirable to keep damage in the diagnostics to a minimum and accuracy high. Such measurements can be best performed during the short bursts of D-T shots planned during (and immediately following) the ITER D-D phase.

Some typical nuclear time constants given expected ITER parameters are tabulated below.

• Neutron slowing down time in blanket • Plasma neutron flux measurements • Response time of typical active neutron and tritium diagnostics in TBM	< 1 ms
• Conservative estimate for on-line measurements	< 1 s

2.2 Thermal Transport and Fluid Flow Phenomena

The fusion energy is not deposited uniformly in the blanket, but instead will have strong spatial variations, falling off strongly with distance from the FW. Heat transfer processes (conduction, convection and radiation) are strong drivers of blanket behavior due to the fact that temperatures of the blanket materials, and temperature gradients, influence strongly many material properties (thermal conductivity, yield strength, tritium solubility, viscosity and gas density, etc.), structural load (thermal stress), and blanket behavior (corrosion and compatibility, tritium permeation and release, etc.). Convection couples the heat transfer very strongly to the fluid flow phenomena in the FW/Blanket coolants including turbulence, flow development, flow distribution between parallel channels, and MHD effects in liquid metal coolants like PbLi.

This dominant effect of the thermal state of the blanket on most other phenomena of interest makes the study and understanding of Thermo-Fluid-Mechanical effects in blankets one of the key goals in ITER TBM. Effective testing requires a similar distribution of heat sources to a fusion blanket including the simultaneous surface heat flux and volumetric heating with a characteristic deposition profile. No avenue, other than fusion environment testing, can produce this desired thermal loading condition. Other fusion conditions such as strong magnetic fields with realistic gradients are also needed to reproduce the conditions influencing the fluid mechanics and thermal state of the FW/Blanket.

Heat transfer and MHD/fluid mechanics can be effectively studied in ITER conditions where size of the test vehicle, typical surface and volumetric heat loads, magnetic fields, and initial irradiation effects are all present in the D-T phases. Decoupled studies of FW helium coolant heat transfer, and MHD fluid mechanical effects in liquid metal flows, can be pursued in the H-H phase to gain initial insight into typical blanket phenomena prior to more coupled-environment tests in the later D-T phases.

Typical time scales for various thermal and fluid flow phenomena (given ITER TBM sizes and conditions) are given below and indicate that achievement of near steady state thermal conditions is expected in ITER TBMs during typical 400 s pulsed operation. Acquisition of temperature, pressure, flow rate and velocity measurements can be taken rapidly and repeatedly during both the initial transient period at the beginning of the pulse through achievement of steady-state conditions. Thermalization time constants may be further controlled and improved by tailoring of coolant and purge inlet temperatures and flow rates during dwell times to promote favorable heat transfer.

• Establishment of SHF and NWL heating profiles • Helium coolant transit time • MHD current response and Joule dissipation	< 1 s
• Conduction through 5 mm RAFS or PbLi • MHD velocity profile formation • Structure bulk temperature rise	<10 s
• Conduction through 5 mm SiC FCI or Ceramic Pebble Bed (k=1) • PbLi transit time • Simulation of accident conditions	< 100 s

2.3 Structural Response

The structural responses of FW/Blankets are also an important class of issues that affect strongly the integrity, reliability, and safety of a fusion energy system. Primary stresses on the blanket structure come from pressurized coolants, the weight of the blanket element, and any electromagnetic forces present due to currents induced in the materials or magnetic permeability of the structure itself during normal and transient conditions, such as disruptions. Secondary stresses due to thermal expansion and temperature gradients also profoundly contribute to the stress state of the structure. The stresses will continuously redistribute during stages of startup-shutdown, quasi steady-state operation, and unplanned transients in the plasma or blanket (*e.g.* loss-of-coolant/flow-accidents). In addition, the presence of flaws or defects remaining after pre-service nondestructive examination or induced during service will produce highly localized stresses that may cause unexpected deformation or fracture.

The response of TBM components and structures to these stresses will depend upon the mechanical properties of materials (yield strength, ductility, fracture toughness, creep strength, fatigue resistance, etc.) which are strongly influenced by operating temperature and temperature variations, the microstructure produced during initial fabrication and subsequent heat treatments, adsorption of impurities from coolants or as a result of transmutation due to nuclear reactions, effects of radiation damage, *etc*. All these factors can be simultaneously achieved in ITER TBM experiments. Deformations (strains) can be measured under different fluid, mechanical, thermal, and plasma operating conditions; providing important information for validating structural mechanics simulations for improved future blanket designs.

Response to fast transients like disruptions will also be essentially instantaneous. Testing TBM response to disruptions and the coupled effects of RAFS structure/plasma interactions are key goals of ITER TBM in the H-H phase. These goals are important to establish the resistance and limitations of the experimental designs, materials, and fabrication methods prior to nuclear experiments in the later D-T phases.

Longer time constant phenomena like thermal creep, fatigue, and ceramic thermal sintering will accrue over many ITER pulses and will be more difficult to interpret than instantaneous deformations, but post-test nondestructive and destructive examination (i.e. post irradiation examination, or PIE) of TBMs will provide insight on the performance of critical components and structures susceptible to these degradation mechanisms. The ability to perform failure mode analyses and other PIE without the need for hot-cells is an advantage of testing during the H-H phase.

Integrated blanket response to irradiation-induced creep and sintering and other high fluence and long time constant mechanical effects should be considered beyond the scope of ITER TBM testing and must be treated ultimately in a steady-state fusion testing facility such as a CTF.

• Thermal expansion response time • Disruption or VDE time	< 1 s
• Low Cycle Fatigue	>100 h
• High Cycle Fatigue • Thermal Creep	>1000 h

2.4 Tritium Transport and Inventory

Recovery of tritium once it is produced in the blanket is highly design concept dependent. Liquid breeders rely on the circulation of the liquid to bring the bred tritium to some external permeator or extractor that removes it (with some efficiency) from the breeder. Ceramic breeder systems circulate a purge gas through porous beds of ceramic breeder material in the blanket itself. In both cases purge and liquid breeder transit times are relatively short, and tritium concentrations can be measured in the various output streams – purges and coolants.

The release of tritium from ceramic breeders, and the permeation of tritium through RAFS structures are both strongly dependent on the temperature of the materials and surface conditions (*e.g.* oxidation layers) so tritium transport and inventory are strongly coupled to the thermal-fluid phenomena already described. Using all this information together with predictions and measurements of tritium production, a picture of tritium transport and permeation can be constructed and compared against coupled system simulations. PIE of breeder and structural materials in TBMs following exposure can help quantify tritium inventories in various materials and components following long operation.

While long time constants for diffusion through RAFS walls and tritium release from ceramic breeders might limit to some degree the study of this issue in TBM experiments, still it is expected that a significant amount of useful information for validating tritium transport models will be obtainable from such measurements during integrated TBM experiments in ITER D-T phases. Certainly even qualitative information on complex tritium control issues will be useful for further blanket development.

• Ceramic Breeder purge gas transit time	< 10 s
• DCLL PbLi transit time	<100 s
• Tritium diffusion time through 5 mm RAFS (500 C)	40 mins
• Steady state tritium inventory in typical ceramic breeder (800 C) • Steady state tritium inventory in typical ceramic breeder (500 C)	< 1 hour < 10 hours

2.5 Mass Transport and Corrosion/Erosion

Dissolution of metallic and ceramic materials into a liquid coolant, erosion of wall material by a high speed helium coolant, or localized attack and cracking due to radiation-induced segregation are processes that take considerable time, much longer than a single pulse in ITER. However, corrosion limitations for PbLi in particular are restrictive and highly dependent on temperature. Corrosion mass transport and redeposition are also expected to be a blanket safety and maintenance concern due to the movement of radioactive or hazardous transmutation corrosion products into the support systems outside the fusion blanket itself.

Considering the long operation time of the ancillary coolant loops supporting ITER TBM, measurements during and after experimental campaigns are expected to give good qualitative information concerning mass transport in blanket systems. Blanket temperatures will vary, but generally will be kept hot during long operation periods. Measurement of chemical and radioactivity outside the TBMs, i.e. in the heat and tritium transport systems and other ancillary equipment, can be used to construct an online picture of corrosion mass transport. PIE of the TBM and external loop components (via in-situ ultrasound, interchangeable witness coupons and inserts, scrape samples, *etc.*) will be used to shed more light on mass transport behavior by identifying points of preferential corrosion, erosion or redeposition sites in particular designs and systems.

2.6 Radiation Response

Radiation damage affects structural materials, breeding and neutron multiplying media, diagnostic and electronic materials, including insulator materials through degradation processes that include hardening, embrittlement, phase instabilities, segregation, precipitation, irradiation creep, volumetric swelling, helium embrittlement, and radiation-induced changes in thermal and electrical properties. The temperature and dose (dpa, or flux × time) regimes where these damage processes produce significant material property changes are shown in the table below – and while not intended as firm limits, give an indication of when a damage mechanism may measurably degrade the material.

While TBM experiments in ITER experience relatively low neutron fluence (~1 dpa in Phase 1) compared to estimated lifetimes of materials for FW/blanket systems, still no blanket materials have ever been irradiated with fusion spectrum neutrons even to a dose comparable with that anticipated in ITER. Even the very early effect of fusion spectrum, not to mention the synergistic effects with complex loadings and fields, provide valuable information for screening FW/blanket design concepts, materials selection, and fabrication technologies.

Some very important beginning-of-life effects, especially in embedded diagnostics and ceramics will likely occur in ITER D-T TBM experiments. Instantaneous changes in electrical conductivity of ceramics can occur as soon as a neutron flux is present. In addition, saturable irradiation swelling and thermal conductivity property changes of SiC Flow Channel Inserts for the DCLL will be 70% complete by 0.3 dpa – achievable in multiple sequential TBMs during the first 10 years of ITER operation. The impacts of these changes on thermofluid/MHD performance of the TBMs will lead to a measurable response. Similar effects in ceramic breeders are also expected.

Hardening and embrittlement in RAFS are not expected in this dose range at operating temperatures > 350°C. There is a possibility of radiation-induced segregation that may cause phase instabilities or environmentally assisted corrosion. Close attention to these effects should be paid in the destructive testing and examination phase following TBM removal from ITER.

Middle and end-of-life reliability growth experiments with significant irradiation damage effects in metals require much higher fluence and must be pursued in a high-flux neutron source such as IFMIF and in module and component scale testing in another fusion facility such as a CTF.

Damage Phenomenon	Temperature Range, Fraction of Melting Temp.	Dose Range, dpa
Volumetric Swelling / Thermal Conductivity Changes (SiC)	<0.4	≥0.01
Hardening & Embrittlement	<0.3	≥0.1
Phase Instabilities	0.3 – 0.6	>1
Irradiation Creep	<0.45	>10
Volumetric Swelling (RAFS)	0.3 – 0.6	>10
He Embrittlement	>0.5	>10

2.7 Surface heat and particle flux effects on first wall material

FW/Blanket systems will by definition have plasma exposure on the first wall, which is the source of the surface heat flux. There is also the possibility of helium and hydrogen implantation, as well as plasma driven tritium permeation into the FW coolant, due to impingement of energetic ions or charge exchange neutrals on the FW. The presence of Be armor on the TBM, and the mandated 50 mm recession from the ITER shielding blanket first wall, may mitigate these effects somewhat, but will not eliminate them. TBM could potentially have a plasma material interaction, experimental mission in addition to anticipated passive observation of Be erosion and PIE on helium and hydrogen implantation effects. The distinct advantage of the TBM in this regard is its frequent replacement during the various phases of ITER operation.

2.8 Summary

A main purpose of ITER TBM is to study coupled effects in fusion FW/Blankets and to look for unexpected synergistic effects. A summary table of phenomena and testing issues was prepared in Ref. [2-1]. This table is useful to see the breadth of issues, and is reproduced here.

Structure

- Changes in properties and behavior of materials
- Deformation and/or breach of components
  - Effect of first-wall heat flux and cycling on fatigue or crack growth-related failure
  - Magnetic forces within the structure (including disruptions)
  - Premature failure at welds and discontinuities
  - Failure due to hot spots
  - Interaction of primary and secondary stresses and deformation
  - Effect of swelling, creep, and thermal gradients on stress concentrations (e.g., in grooved

Coolant/structure interactions

- Mechanical and materials interactions
  - Corrosion
  - Mechanical wear and fatigue from flow-induced vibrations
  - Failure of coolant wall due to stress corrosion cracking
  - Failure of coolant wall due to liquid-metal embrittlement
- Thermal interactions
  - MHD effects on first-wall cooling and hot spots
  - Response to cooling system transients
  - Flow sensitivity to dimensional changes

surfaces)

- Failure due to shutdown residual stress
- Interaction between surface effects and first-wall failures
- Self-welding of similar and dissimilar metals

- Tritium permeation through the structure
  - Effectiveness of tritium permeation barriers
  - Effect of radiation on tritium permeation
- Structural activation product inventory and volatility
- Hermiticity of SiC

Coolant

- MHD pressure drop and pressure stresses
- MHD and geometric effects on flow distribution
- MHD insulating coating fabrication, integrity, and in situ self-healing
- Stability/kinetics of tritium oxidation in the coolant
- Helium bubble formation leading to hot spots
- Coolant/purge stream containment and leakage
- Activation products in Pb-Li
- Liquid-metal purification

Breeder and purge

- Tritium recovery and inventory in solid breeder materials
- Liquid breeder tritium extraction
- Temperature limits and variability in solid breeder materials
  - Temperature limits
  - Thermal conductivity changes under irradiation
  - Effect of cracking
  - Effect of LiOT mass transfer
- Breeder behavior at high burnup/high dpa
- Coolant/coatings/structure interactions

Solid breeder/multiplier/structure interactions

- Solid breeder mechanical and materials interactions
  - Clad corrosion from breeder burnup products
  - Strain accommodation by creep and plastic flow
  - Swelling driving force
  - Stress concentrations at cracks and discontinuities
  - Thermal expansion driving force
- Neutron multiplier mechanical interactions
  - Beryllium swelling (swelling driving force in beryllium)
  - Strain accommodation by creep in beryllium
  - Mechanical integrity of unclad beryllium
- Thermal interactions
  - Breeder-structure and multiplier-structure interface heat transfer (gad conductance)

General blanket

- D-T fuel self-sufficiency
  - Uncertainties in achievable breeding ratio
  - Uncertainties in required breeding ratio
- Tritium permeation
  - Permeation from breeder to blanket coolant
  - Permeation from beryllium to coolant
  - Permeation characteristics at low pressure
- Chemical reactions
- Tritium inventory
- Failure modes and frequencies
- Nuclear heating rate predictions
- Time constant for magnetic field penetration for plasma control
- Blanket response to near blanket failures
- Assembly and fabrication of blankets
- Recycling of irradiated lithium and beryllium
- Prediction and control of normal effluents associated with fluid radioactivity
- Liquid-metal blanket insulator fabrication, effectiveness, and lifetime
- Tritium trapping in beryllium

References

2-1. "Results of an International Study on a High-Volume Plasma-Based Neutron Source for Fusion Blanket Development," Fusion Technology, 29: 1-57 (1996).

Question 3.

As part of the blanket development roadmap, explain the incremental role of ITER and any other testing that would be required to qualify blankets for use in CTF (and eventually DEMO) including:

- **R&D to insert a blanket in ITER**
- **Results from ITER operation, given its current performance characteristics**
- **R&D needed prior to CTF (if any)**
- **Initial operation of blanket in CTF**

A detailed description of the blanket development roadmap is given in response to Question 1. Some of this material is referenced here. In brief, the R&D required for blanket testing in CTF includes: a- "ALL" the R&D required for inserting TBM in ITER, and b- additional R&D and more aggressive testing. The most cost effective approach to satisfying these additional R&D and testing needs for CTF is to conduct TBM experiments in ITER supplemented by R&D in out-of-pile facilities, enhanced simulation capabilities, and design activities.

3.1 R&D to insert a blanket in ITER

R&D utilizing existing fission and/or out-of-pile facilities to prepare to insert a blanket module in ITER is designed to obtain a fundamental database; gain understanding of basic, separate- and some multiple-effect phenomena; and/or develop and verify predictive capabilities – all in areas critical to practical blanket development and operation. The products of this R&D (data, understanding, and predictive capability) are required to advance US blanket concepts and capabilities to the degree necessary to begin fusion environment testing, whether in ITER and/or CTF. The R&D should be as extensive as necessary in order to balance the costs and risks of complex tests in the ITER fusion environment. The minimum set of activities to prepare for and advance to ITER TBM testing is described in detail in response to Question 4.

3.2 Results from ITER TBM operation

TBM testing in ITER is designed to provide stage I fusion "break-in" experience and scientific exploration of blanket performance and response in the complex, multi-field fusion environment. The role of TBM testing in the overall development pathway is to provide for:

- Initial exploration of **coupled phenomena** in a fusion environment, including: uncovering unexpected synergistic effects, calibrating results from non-fusion tests, and providing data for model improvement and simulation benchmarking
- Assessing the impact of rapid property changes in early life
- Development of fusion environment experimental techniques and test instrumentation

- Screening and narrowing the many material combinations, design choices, and blanket design concepts

A more detailed description of specific testing strategy and goals, taking into consideration the strengths and weaknesses of the ITER device and environment, is given in detail in response to Question 14. However, we point out here for emphasis that a unique feature of ITER is the strength and distribution of the magnetic field and the high plasma current. In these areas, the similarities between ITER and DEMO are much larger than between potential CTF concepts and DEMO, since CTF must be a driven, small size, small power device. These features affect blanket phenomena, such as response to disruptions and MHD flow and heat transfer. This means that the confidence level in the functioning of breeding blankets would be considerably lower without TBM tests in ITER.

3.3 R&D needed prior to CTF

The blanket development pathway (as illustrated in Figure 1) depicts the need for continued R&D efforts in parallel with ITER TBM experiments. Such R&D is necessary to explore technical areas required for CTF blanket testing and ultimate blanket development that either (A) can not be explored in ITER, (B) are more effectively studied in other facilities, and/or (C) advance the predictive and analysis capabilities needed for blanket systems design. Examples of such R&D efforts include development of high temperature PbLi/FCI experiments to explore the mechanisms for pushing for high DCLL outlet temperature, development of materials for FCI and ceramic breeders with improved properties, exploration of medium fluence radiation damage effects and material properties for CTF and DEMO materials, continued development of advanced simulation codes validated with ITER TBM and basic R&D data, and even more in depth exploration in out-of-pile facilities of interesting or unexpected phenomena uncovered in TBM experiments.

3.4 Initial Operation of Blankets in CTF

With TBM accomplishing the goals of the fusion break-in (Stage I in Fig. 1-3), the CTF role will be to establish the “Engineering Feasibility and Performance Verification” (Stage II) and “Component Engineering Development and Reliability Growth” (Stage III). One of the principal objectives of Stage II is to establish engineering feasibility of blankets, which is defined as satisfying the basic functions and performance up to 10 to 20% of lifetime. The principal objectives of Stage III include an aggressive series of Test, Analyze and Fix iterations to improve the reliability of only a select few (at most 3) blanket concepts in meeting the demanding reliability requirements of a fusion DEMO. Stage II and Stage III goals are described in detail in Fig. 1-3. Such testing in Stages II and III will be the key to qualifying blankets for DEMO.

There are several interesting and unanswered questions related to the vision for CTF that will affect strongly the R&D and testing strategy on CTF. One such question is when CTF will be required to have full-coverage breeding blanket (in addition to testing ports) to achieve tritium self-sufficiency (or nearly so). This depends on (A) the level of fusion power in CTF, (B) the device availability achievable in CTF, (C) whether ITER second phase will be conducted and has "priority" over the world tritium supply. ITER second phase will essentially require most of the world tritium supply, except for about 5 kg. If CTF has fusion power of greater than 100 MW, then there is barely enough tritium to operate CTF for less than 1MW.y/m^2, beyond which CTF must produce its own tritium, i.e. has full breeding blanket. TBM testing in ITER plus additional parallel R&D will reduce the risk of constructing such full breeding blanket that functions out-of-the-box at an acceptable level (depending on how positive the results of TBM tests are). Without ITER TBM, the risk of installing a full breeding blanket on CTF is judged to be extremely high. US collaboration with the other ITER Parties on ITER TBM will also be essentials to reduce the risk. Should preparatory R&D and testing in ITER show for instance the US concept, DCLL, to be infeasible or unattractive, then the US may have to begin investing in another concept , most likely one of the approximately 10 TBM concepts to be developed and tested by the other ITER Parties.

Assuming that TBM is successful and a base breeding blanket can be built on CTF, advanced concepts (*e.g.* higher performance, higher temperature DCLL) can be tested in special "ports" similar to ITER.

Questions Related to ITER TBM and its role in FNT development

Question 4.

What are the current types of experiments planned in the R&D leading up to the TBM? Do they capture the important phenomenological coupling identified as critical to blanket behavior? Why or why not? Where is this R&D being carried out? Are there any collaborative programs in this area in the IEA or bilateral agreements?

R&D tasks that have been identified for ITER TBM development [4-1] directly contribute to important design and fabrication route decisions; address TBM safety issues and reliability risks in ITER; and/or are needed to understand, operate, and analyze US TBM experiments in ITER, particularly in the H-H phase[1].

4.1 Description of needed R&D for US TBM

As illustrated in the response to Question 2, the interacting phenomena in TBMs will be complex. Understanding and interpreting results will require expertise in many areas that come from a strong base R&D program. In addition, the safety and reliability requirements of ITER will be demanding, and significant R&D remains to be done before any TBM will be qualified and accepted for installation in ITER. The largest R&D category identified here is the development of fabrication technologies for the construction of the TBMs having reduced activation ferritic steel structures with complex geometry and with an integrated beryllium-armored first wall. Other significant R&D items are: SiC flow channel insert development; fundamental studies of LM-MHD, helium flow, and heat transfer behavior; and solid breeder pebble bed thermomechanics, temperature control and performance.

Table 4-1 provides a brief description of each of the main TBM R&D categories. These R&D tasks represent only the most critically needed research over the next ten years that are directly needed to prepare for, qualify, diagnose and usefully operate both DCLL and HCCB TBMs. It is noted that this R&D is assumed to be complimented by R&D efforts internationally, especially in the EU and Japan where research on PbLi and Ceramic Breeder blankets with RAFS have been strongly supported. Examples of such valuable international R&D include the portions of RAFS fabrication and irradiation programs that have been shared; ceramic breeder fabrication, irradiation, and characterization experiments; and PbLi compatibility and corrosion, tritium extraction and irradiation experiments.

It should also be noted that significant engineering analysis is also planned as part of the TBM engineering design to address many issues, for example TBM electromagnetic and structural

---

[1] Note that later TBMs will have some R&D activities

Table 4-1: Minimum set of TBM R&D Categories and their Main Goals

TBM R&D Areas	Main Purpose
Thermofluid MHD	Obtain experimental database on key MHD flow elements affecting operation of the TBM for which there is little/no existing data • Poloidal PbLi channel distribution manifolds. Data needed to allow design of manifold elements controlling PbLi flow distribution • FCI effects on pressure drop and heat transfer. Data needed to determine pressure drop and heat transfer characteristics for basic SiC FCI and near FCI joints, pressure equalization holes, and flaws in order to set FCI and SiC design requirements Obtain verified predictive capability for PbLi flow and heat transfer with extrapolation to ITER conditions. Code and model developments and verification activities using existing and new (above) experimental data in order to determine operational conditions in TBM
SiC FCI Fabrication and Properties	Obtain experimental database on the essential properties of SiC for FCIs (conductivities, strengths, failure modes, etc.) resulting for various proposed fabrication techniques. • Develop testing procedures and apparatus • Produce and characterize 2 generations of samples Develop technical specifications and prototypes of preferred FCI materials and fabrication techniques. Validate low dose irradiation resistance and properties of FCI.
SiC/FS/PbLi Compatibility & Chemistry	Improve experimental database on compatibility of materials used in the DCLL TBM system: static and flowing compatibility at 550ºC (and above where possible) especially to determine any dissimilar material effects between, e.g., FS and SiC. Evaluate material samples and mockups used in flowing thermofluid MHD integrated testing experiments. Establish recommendations for material temperature limits and effects.
RAFS Steel Fabrication Development and Materials Properties	Develop material specifications and oversee fabrication of mockups for partially integrated mockup testing. Obtain experimental database on HIP and Investment casting fabrication of RAFS samples and mockups, including dimensional tolerances and mechanical properties. Develop detailed database on primary fabrication route (HIP or IC) using TBM-like RAFS samples and mockups, including dimensional tolerances and mechanical properties, for process and material qualification with ITER. Develop joining procedures, test methodology and obtain experimental database of joint samples for TBM, including mechanical properties and effects of low dose irradiation, for process and material qualification with ITER. Develop procedure and standard samples for validation of NDE testing methods for final TBM qualification with ITER.
Be Joining to RAFS for FW Armor	Develop proposed attachment or coating techniques for Be joining to RAFS as required by ITER for all TBMs.

	Develop test procedures, test samples, and obtain preliminary experimental database of mechanical and thermal properties of joints for candidate joining methods. Test initial irradiation resistance of the joint. Prepare and test small and medium scale mockups for testing high heat flux testing facility for thermal cycle resistance. Optimize joining procedures
PbLi/H_2O H2 Prod	Obtain an experimental database and correlation for the percentage of reacted Li during PbLi/Water reactions under projected ITER accident conditions using most appropriate PbLi/water contact modes.
He Flow & Manifolds	Obtain experimental database and simulation verification for key helium flow issues affecting safe operation of the TBM, particularly the flow distribution in proposed manifold designs
Ceramic Breeder Thermomechanics	Obtain experimental database and fitted constitutive equations for thermo-physical properties of ceramic breeder packed pebble beds under thermal and mechanical loads typical of the various phases of ITER. Verification of simulation tool for large-scale pebble bed thermomechanics analysis, and definition of initial mechanical loading conditions during packing assembly
Tritium Control and Recovery Predictive Capability	Development and experimental verification of predictive capability for the tritium permeation in configurations relevant to HCCB and DCLL designs including • the establishment of a database of material properties such as D/T solubility and permeability at lower pressure regimes (<100 Pa) under flow conditions; and • the experimental investigation of the effect of isotope swamping and velocity profile on the permeation rate • tritium extraction from PbLi using vacuum permeator system with various materials and gas conditions • tritium extraction from He using candidate technologies for He cleanup (TBD) Definition and experimental verification of purge gas composition and flow conditions for the candidate ceramic materials within which the permeation rate from the pebble bed to the helium coolant is acceptable
Breeder Pebble Knowledge Base and Proc. Specs	Evaluation of the on-going breeder pebble fabrication R&D in EU and JA as a pebble material source for the US. Utilization of US capabilities where cost effective.
Diagnostics and Instrumentation	Develop/modify existing diagnostic transducers including insulation/attachments to TBM, high temperature, deployment in packed beds, tokamak magnetic field compatibility, neutron/gamma irradiation, and small size. Typical transducers include thermocouples, strain gauges, hall sensors, current coils and voltage probes, pressure sensors, etc. Identify and test nuclear field diagnostics for the D-D phase TBM
Integration of Predictive Capabilities (Virtual TBM)	Develop integrated management tool software package and database aiming at the capability to simulate critically coupled physical phenomena including thermo-fluid MHD, thermal-hydraulic, nuclear, thermo-mechanic, mass transfer Provide needed capability to simulate from CAD models and understand effects of design and condition changes.

analysis including resistance to disruption forces. Developing and utilizing the various predictive capabilities helps provide insight into coupled phenomena and ultimately will allow the extension of ITER TBM results design blankets for future fusion devices and ultimately DEMO.

4.2 Phenomena Coupling

As part of the R&D effort, representative "partially-integrated" tests will be needed on scaled mockups (see Fig 1-2). This testing is to follow successful single and multiple effects tests in many areas and is designed to capture as much as possible integrated structural, thermal, and flow behaviors prior to ITER TBM testing. Three main partially-integrated tests are considered necessary before the initiation of TBM fabrication.

> **Mockup FW heat flux testing** – The objective of this test is to thermally load a helium-cooled TBM mockups (both DCLL and HCCB) with a simulated FW heat load in a succession of pulses characteristic of ITER operation. Acceptable helium flow characteristics, structural temperatures and deformation, and failure modes will be verified. An additional goal of this test is to develop additional experience with high temperature helium coolant loops and test any non-standard He flow loop components.
>
> **PbLi flow and heat transfer test** – The objective of this test is to verify the DCLL MHD PbLi pressure drop, flow distribution, heat transfer, and initial chemical compatibility characteristics in an integrated mockup containing all the geometric and material elements of the first TBM. The following elements will be included: inlet/outlet manifolds and FCIs, parallel poloidal channels and FCIs, helium cooled divider plates and walls, and coaxial PbLi inlet/outlet pipes and FCIs. An additional goal of this test is to address safe handling and practice preheating and uniform filling of the TBM with PbLi, as well as testing of any non-standard PbLi flow loop components.
>
> **Pressurization tests** – The objective of this test is to test the response of a prototype mockups (both DCLL and HCCB) to pressurization by the helium coolant and to mimic a breach of helium into the PbLi portion of the TBM. A certain over-pressurization (a factor of 1.25 is specified in the TBWG ITA Report) could be required, depending on final ITER acceptance test requirements.

Such mockup experiments are designed to capture to the maximum extent possible the phenomenological coupling identified as critical to blanket behavior in Question 2. But the absence of spatially varying nuclear heating and beginning-of-life irradiation effects is a key limitation that can only be overcome by nuclear environment testing, such as in ITER.

4.3 R&D Performers

R&D tasks have not been assigned to specific performers in the technical plan. It was assumed that the base program facilities and people will be utilized whenever possible to save on costs and to develop lasting expertise. SBIRs can also play a role. For the partially integrated tests described above, cost estimates were based on modifying the Plasma Materials Test Facility (PMTF) at the Sandia National Laboratory and the Magneto-Thermofluid Omnibus Research (MTOR) Laboratory at UCLA.

4.4 Existing International Collaboration related to TBM R&D

There are many international collaboration programs, such as the IEA and TITAN US-Japan agreements, which have been set up to resolve some key fusion nuclear technology issues. Results from most of these collaborations will provide input to TBM design and development.

The on-going international collaborations, such as IEA collaboration, have been working together for a long time to solve many of the key issues for the fusion blankets and most results are relevant to TBM needs. The IEA collaboration includes: IEA safety, IEA material, IEA solid breeders, IEA liquid breeders – and all will generate important results for the different type of TBM's. It is important that we urge the redirection of some of the efforts more directly toward near term TBM applications.

The recently signed TITAN collaboration is focused on the interaction among irradiation, tritium and magnetic field. This effort will be most useful for the TBM applications. Major effort will be directed toward the blanket tritium system, focused on the PbLi system, MHD effects, and irradiation/tritium synergism. Those will be some of the key problems we will face in blanket design activities.

International collaboration on FNT is essential to reduce the cost and risk involved with the TBM design and development.

References

4-1. "US ITER Test Blanket Module (TBM) Program, Volume I: Technical Plan and Cost Estimate Summary," UCLA-FNT-216 (2007).

Question 5.

What will we learn from an ITER TBM in the overall context of FNT development that we could not possibly learn either by testing in existing plasma/fission devices for neutronic and plasma effects supplemented with other separate effects testing?

The most important key phenomena driving blanket behavior (see Question 2) that require replication in fusion nuclear component experiments are: (A) neutron effects (radiation damage, tritium and helium production), (B) bulk heating (nuclear heating in a significant volume), and (C) non-nuclear conditions (e.g. magnetic field, surface heat flux, particle flux, mechanical forces, operation temperature). Definitive testing for decisive resolution of synergistic issues requires all three of these important loading conditions of the fusion environment, and test articles with prototypical materials and interactions/interfaces among all the physical elements of the components and their support systems. ITER presents the first opportunity to test blanket materials and components in an integrated fusion environment, including spatially-dependent volumetric heating, and 3-component magnetic field with gradients, a large test volume, and a vacuum environment. The TBM will provide the first opportunity to develop detailed and realistic engineering designs; and to construct and test a blanket module in a true fusion environment. This will be the first learning experience with a breeding blanket at high temperature in the integrated fusion environment.

The roles (see Question 3) and goals (see Question 14) of ITER TBM tests are described in detail elsewhere. Successful TBM experiments in ITER will provide an experimentally-validated scientific basis to embark on the engineering development of the tritium breeding blanket and its integrated plasma-facing first wall. What we will learn by testing in existing plasma/fission devices for neutronic and plasma effects is limited mostly to single environmental conditions and some multiple effect/multiple interaction experiments (as shown in Fig. 1-2). While valuable, such tests are not able to simulate integrated conditions. Parameter space between the ITER-TBM and existing plasma and fission devices will be presented in the following. Accelerator devices are included also for completeness. It can be concluded that in the overall context of FNT development, the parameter space covered by ITER-TBM cannot be accomplished by existing plasma devices and is a necessary extension from fission and accelerator driven devices.

5.1 Plasma devices

In operating plasma devices like DIII-D, C-Mod and NSTX with DD discharges, both neutrons and tritium are produced. For a DD reaction, equal numbers of 2.45 and 14.1 MeV neutrons are produced. As shown in Table 5.1, when compared to the ITER TBM module operating in the D-T environment, existing plasma devices produce neutrons and tritium at rates several orders of magnitude lower, with a plasma pulse length much shorter. Correspondingly, the plasma discharge time and neutron fluence will also be much lower. Therefore, neutron and tritium production from existing plasma devices will have little value in the overall context of FNT development, except in the awareness and impacts on safety operational procedure of respective existing plasma devices.

Existing plasma devices can contribute to the design and operation of ITER TBM. They are in the areas of startup and shutdown, operation in a tokamak environment, handling of transient events like ELMs and disruption, and plasma facing material selection with effects from erosion/redeposition. Experience in these areas will be applied to the design of ITER TBM, but due to very limited available space or volume in existing plasma devices and lower plasma current and field strength (with impact on disruption load), testing value would be limited.

Table 5.1: Comparison between ITER TBM and US large tokamaks

	ITER TBM	DIII-D	C-Mod	NSTX
Max. neutron flux, n/cm^{2}s (14.1, 2.45 MeV and lower energy neutrons)	4.7x10^{14*}	2.8x10^{10}	1x10^{8}	3x10^{8}
Tritium production rate, ci/m^{2}s	1.25x10^{-2*}	1.8x10^{-7}	1x10^{-11**}	
Discharge time, s	400	5	2	1000
Major Radius, m	6.2	1.88	0.74	1.0
Plasma Current, MA	15	3	2	1
First wall material	Be	C	Mo/SS	C
First wall erosion rate, ~ave. to max., nm/s	TBD	TBD***	0.03 to 20	

*at 500 MW fusion power pulse (for TBM tritium is produced in the breeder)

** no beam driven neutrons

***Will be measured with the MiMES (This is a mid-plane evaluation system in DIII-D, where material samples can be inserted to measure the erosion and re-deposition of different materials. Initial experiments are planned for the later part of 2007.)

Another possible existing plasma device that might serve as a test bed to address issues that are relevant to FNT is the EAST superconducting tokamak in China. The intention there was to construct a reduced size test port (compared with an ITER TBM half-port) to perform some tests on field errors, sustaining disruptions and liquid metal MHD effects for liquid metal breeder designs. However, it should be noted that the plasma current and field strength (and other performance parameters) of EAST is still much lower than that of ITER. The experimental data from testing in EAST can be used to bench mark modeling results for projection to ITER operation. But, testing in EAST can only be used to enhance the projection of performance in ITER. Still, the need for the testing in reactor relevant plasma characteristics with a module size adequate to simulate the resultant forces caused by plasma disruption can not be fully addressed. KSTAR has roughly similar limitations and possible utilization as EAST. It must be noted that installing a test module on a plasma device like will require: (A) essentially all the R&D identified for ITER TBM, and (B) construction of test modules and ancillary equipment. Testing in a plasma device like EAST or KSTAR should be considered only as part of the R&D to prepare for the ITER TBM, to reduce risk but at added costs.

5.2 Fission Reactors

Fission reactors provide neutrons in a moderate volume and are thus suitable for many single and multiple effect experiments. The capabilities of the two high-flux fission reactors available in the USA as well as the High Flux Reactor (HFR) at Petten, the Netherlands are summarized in Table 5-2. Note that a TBM is much larger in size. Fission reactors provide neutrons in a limited volume and are thus suited to some FNT experiments such as tritium release characteristics or tritium inventory associated with a breeder material. For example, the EXOTIC irradiation experiments in the HFR have been designed to investigate tritium release properties, tritium residence time, and mechanical stability of the fabricated ceramic breeder pebbles at different levels (up to DEMO) of Li burn-up. Similar experiments with PbLi alloys, called LIBRETTO, have also been performed.

However, testing in fission reactors suffer from serious limitations including small test volume and lack of other fusion-related conditions, such as relevant radiation damage parameters, surface heat flux, and magnetic field effects. For example, there is no fission reactor operating now anywhere in the world that can provide a test location with ≥ 15 cm equivalent circular diameter at a fast neutron flux equivalent to 1 MW/m^2 wall loading (~$5x10^{14}$ n/cm^2s of E>0.1 MeV neutron spectrum). This size limitation makes it difficult to evaluate the synergistic effects present in multiple-variable tests. Another set of problems arise from the difference between the fission and fusion reactor neutron and secondary gamma-ray spectra. These differences lead to difficulties in simulating the magnitude, profile, and time-dependent behavior of reaction rates such as helium and tritium production, as well as power density and atomic displacements. Despite these limitations, fission reactor testing is suitable for some multiple effect tests that are needed to establish the Proof of Principle for certain designs. An example is an in-pile pebble bed assembly (PBA) irradiation experiment which was recently completed at HFR to study the effect of neutron irradiation on the thermomechanical behavior of a ceramic breeder pebble bed while achieving DEMO-representative temperatures with defined thermomechanical loads.

5.3 Accelerator based neutron sources

Accelerator based neutron sources produce neutrons in a volume that is smaller than typical fission reactors. Deuterium-Tritium accelerator sources produce 14 MeV neutrons, but are limited by target fabrication and cooling considerations to neutron fluxes that are orders of magnitude lower than that in a fusion reactor with 1 MW/m^2 neutron wall load. Examples of these facilities are the FNS at JAEA and FNG at ENEA, Frascatti. FNS and FNG have been used extensively for neutronics experiments aimed at validation of codes and data and identifying uncertainties in calculated nuclear parameters. A total of 26 experiments have been performed between 1984 and 1998 under the US-JAERI collaboration using the FNS 14 MeV point source.

However, these facilities limited neutron intensities (<~10^{13} n/s) as shown in Table 5-2 and result in very low neutron flux even at small distances from the target (~$3x10^{10}$ n/cm^2s @ 5 cm) that is more than 5 orders of magnitude lower than flux at the first wall of fusion reactors. The lifetime of the target is generally limited to <100 h resulting in extremely low fluences. The flux profile, spectrum, and gradient in these devices are not prototypical of conditions in fusion blankets. The low flux level cannot yield nuclear heating and reactions at rates that allow engineering tests other than neutronics tests. These facilities can be used for verifying the prediction capability of present codes and databases for tritium production in solid breeder (or liquid breeder) to help assess the tritium self-sufficiency issue and to generate safety factors for design purposes. Results showed consistently that calculations tend to overestimate the experimentally measured tritium production rate by up to ~20%. Additionally, irradiation of various samples for low-activation tests and updating/verification of our current dosimetry and activation/decay heat databases can be performed at these facilities along with studies on neutron and gamma ray shielding. Part of the D-T fuel cycle pertaining to tritium production in solid breeders (or liquid breeders) can be tested in these facilities and contribute to the overall feasibility study for these concepts. However, “Concept Exploration” to verify tritium self-sufficiency cannot be undertaken in these facilities. All integral neutronics experiments performed to date have been limited to simple configurations of materials. The low neutron flux level does not permit testing of prototypical, highly heterogeneous blanket configurations.

Table 5-2: Capabilities of Operating Fission Reactors Available for Blanket Tests

Reactor	Location	Reactor Power (MW)	Fast Flux, E>0.1 MeV (n/cm^{2}s)	Irradiation Capsule Diameter (cm)	Nuclear Heating (W/g)	Core Height (cm)	Comments
HFIR-RB “-target	ORNL	85 85	4.4x10^{14} 1.1x10^{15}	4.0 3.3	12 46	50 50	In-situ test capability
ATR-ITV “–I holes	Idaho Falls	250 250	4.5x10^{14} 3.0x10^{12}	2.5 12.5	~20 1.5	122	In-situ test capability
HFR	Petten, The Netherlands	45	2.92x10^{14}	14.5		60	Shutdown imminent

Table 5-3: Comparison of the Irradiation Parameters for ITER-TBM, D-T neutron RTNS-1, FNS, FNG

Facility	Location	Power (MWe)	Total neutron flux (n/cm^{2}s)	Irradiation Volume	Nuclear heating (W/g)	Concept Maturity	Comments
ITER-TBM	3 ports in ITER	500 fusion	4.7x10^{14}	0.484 x 1.66 x ~0.3 m^3 for DCLL ~ 1/3 of the above for HCCB	8 w/cc in FS 18 w/cc in PbLi	Conceptual for ITER	Present discussion topic
D-T neutron RTNS-1	US		1x10^{12} n/s	~0.5 cm^3; low flux regions 1 m x 1m		Operating	Existing facilities (~400 keV D)
FNS (350 keV D source, 20 mA)	JAEA, Japan		3x10^{11} to 5x10^{12}	Mock-up 1x 1x 0.8 m	limited	Operating	neutronics, nuclear data base, tritium production and shielding experiments
FNG (300 keV, ~ 20 mA)	Frascati, Italy		5x10^{11}	Mock-up 1x 1x 0.7 m	limited	Operating	ITER shielding experiments, tritium production measurements

Question 6.

Consider FNT development for DEMO with and without ITER. Which of these options is better technically? Which is cheaper? Is some combination of both the best? What are the incremental risks to ITER operation of the TBMs?

Analysis of benefits, costs, risks, and schedule shows that TBM testing in ITER Phase 1, combined with CTF, clearly provides the best approach. ITER is "real" with construction preparation underway. ITER will be an *existing* facility. It should be used in conjunction with R&D in non-fusion facilities and theory/simulations to advance the engineering science and FW/blanket knowledge base to a level sufficient to support the development of blankets for testing in CTF. This allows CTF to be more effective technically and economically in developing the fusion nuclear technology required for DEMO on a timely basis.

As shown in the answer to Question 1, FNT development in fusion facilities has three stages: (I) initial fusion "break-in" in the fusion environment, (II) engineering feasibility and performance verification, and (III) component engineering development and reliability growth (illustrated in Fig. 1-3). These stages have requirements on testing parameters and plasma operation (see Question 1). The ITER environment is well suited for TBM tests to accomplish Stage I, initial fusion "break-in", allowing CTF to be designed for and, immediately upon D-T operation, begin addressing stages II and III. If this Stage I is not performed in ITER TBM, it will have to be performed in CTF resulting in increased costs, risks, and delayed DEMO. Key points are as follows:

- ITER already has been designed with capabilities, worth billions of dollars, for testing TBMs, both in hardware and the fusion DT environment capabilities it offers.

- Exactly the same R&D and qualification testing for ITER TBM will be needed for CTF. ***But in ITER costs can be shared with international partners.***

- TBM in ITER saves at least 2-3 years in CTF operation (see Question 7 that follows). This is a huge cost savings when given a CTF operating cost of ~$200 million per year. (TBM does NOT pay for operating costs of ITER. ITER operation costs are already paid for, and shared internationally, independent of TBM)

- In addition to the many technical objectives to be achieved by ITER TBM (see answer to Question 1, Question 14, and other questions), ITER will be used for initial concept screening of the many blanket designs from the 7 parties. Spending years in CTF doing concept screening will cost hundreds of millions of dollars in operating costs as well as costs to do the R&D and qualification testing for many more concepts than the one or two the US will do for TBM (again, see Question 7).. CTF should be used for engineering development and reliability growth on the very limited number of concepts that look most promising following screening in ITER

- Experience in safety and licensing of ITER TBM will be essential to the licensing of CTF (see response to Question 9).

- Because of the critical issue of limited external supply of tritium (almost all the world supply of tritium will be used by an ITER extended phase), CTF could potentially be required to produce essentially all its tritium and therefore must install its own breeding blanket. Without ITER TBM, the risk of installing a full breeding blanket in CTF is judged to be extremely high. TBM testing in ITER, plus additional parallel R&D, will substantially reduce the risk of constructing such a full breeding blanket to achieve an acceptable operational level. US collaboration with the other ITER Parties on ITER TBM will also be essential to reduce the risk. Should preparatory R&D and testing in ITER show for instance the US concept, DCLL, to be infeasible or unattractive, then the US may have to begin investing in another concept, most likely one of the roughly 10 TBM concepts to be developed and tested by the other ITER Parties.

- TBMs will be required to present a minimal risk to ITER safety and operation, or they will not be accepted. Details of potential risks are given in the response to Question 15. But even if the US is not involved in TBM, it is a certainty that other parties will be fielding TBMs. Having the US involved in TBM testing will allow the US to work towards minimizing any potential risks to the ITER machine or operation schedule.

In summary, a combination of ITER TBM and CTF is the best technical option and the most cost effective, and has lower risks compared to ITER TBM alone, or CTF alone.

Question 7.

Would testing in ITER reduce the cost of overall FNT development because of the potential for collaborations with other parties while with a non-ITER testing program, the US may have to go alone for the most part?

Including TBM testing in ITER in the fusion nuclear technology (FNT) development plan (see response to Question 1 for FNT plan details) is a cost-effective, time saving approach for a number of reasons, as described below.

A staged approach to development of first-wall/blanket (FW/B) technology for DEMO is essential to ensure that robust blanket concepts are identified that meet performance goals and achieve high reliability. The first stage involves low-fluence testing of a large number of blanket concepts to screen and narrow the many material and design choices. More extensive testing is performed at the second stage to intermediate fluence levels. In the third stage, mature blanket concepts are tested to higher fluence levels to produce comprehensive component reliability and safety information.

Since all of the most promising blanket concepts will be tested in ITER, participation in this project provides the US with a cost effective way to accomplish the first stage of FW/B development because it avoids the need to independently screen blanket concepts in another fusion device such as CTF. It also affords an opportunity, through international collaboration, to share the R&D burden for TBM development. The potential savings associated with international collaboration was recently estimated in a formal planning and costing activity [7-1]. Finally, since the operational costs for ITER are already covered, and shared by all seven Parties, the major incremental costs for the US to test TBMs in ITER would be construction of test articles, performance and analysis of experiments, and post irradiation nondestructive and destructive examination (PIE).

The proper role of the CTF is to perform engineering and reliability growth studies on a few of the most promising blanket concepts that emerge from the screening phase. Screening in ITER increases the likelihood that blanket designs capable of breeding tritium will be available at the beginning of CTF operations, thus ensuring tritium self-sufficiency for this machine. If the mission of CTF is expanded to include screening, then the total cost for FW/B development will significantly increase because CTF operational costs, estimated at $200 M/y [7-2], must be included and an appropriate supply of tritium must be obtained. In addition, the overall time to develop successful blanket concepts will likely increase with a non-ITER strategy because a commitment to design and build CTF has not been made.

References

7-1. "US ITER Test Blanket Module (TBM) Program, Volume I: Technical Plan and Cost Estimate Summary," UCLA-FNT-216 (2007).

7-2. "Results of an International Study on a High-Volume Plasma-Based Neutron Source for Fusion Blanket Development," Fusion Technology 29 (1996) 1.

Question 8.

Is testing in ITER a necessary condition before committing to some future device where tritium breeding will be critical from the very beginning (i.e. DEMO)?

The risk of proceeding to a device requiring tritium breeding, without the testing experience and knowledge gained from ITER, is judged to be unacceptably high. This is made evident by considering Fig. 8-1, which shows that the operation of ITER (through a second phase) will exhaust the tritium resources available for fusion, whether we participate in ITER TBM testing or not. There is no practical external source of tritium for fusion energy development beyond ITER. Hence, all subsequent or additional fusion devices (CTF, DEMO) have to be either very small power or breed their own tritium.

Testing blankets in ITER will help verify the technological conditions for attaining tritium self-sufficiency in future fusion devices. Testing in ITER with TBMs having their own integrated loops and systems for tritium breeding, tritium processing, and heat extraction will provide information that allow better determination of the minimum required TBR. In addition, testing in ITER will provide information that will help better define practical blanket design parameters (*e.g.* FW thickness, structure content, and coolant conditions) that impact tritium breeding. It is also obvious that for the testing of TBMs in ITER the consumption of tritium is already accounted for.

If we were not to participate in testing in ITER, blanket testing and assessment will have to become an early phase requirement of CTF, and thereby lengthen the operation of CTF, which also means additional consumption of tritium in competition with ITER. One could envision a possible program on CTF where the US performs initial fusion break-in and screening on four blanket concepts in four different sectors of CTF. We will have to go thru the HH phase, DD phase, low and high performance DT phases, similar to the TBM program in ITER. These tests will then help us to decide on what would be the best blanket option for the full coverage self-sufficient blanket in CTF for the second 10 years of testing. It is reasonable to assume that the initial testing would take 10 years, similar to ITER. If we make the following additional assumptions:

- Fusion power of CTF is 100 MW
- Only half of the first 10 years is operated at full D-T power
- During the DT power operation, the availability of CTF is 30%
- Half of the consumed tritium could be supplied by the blankets being tested.

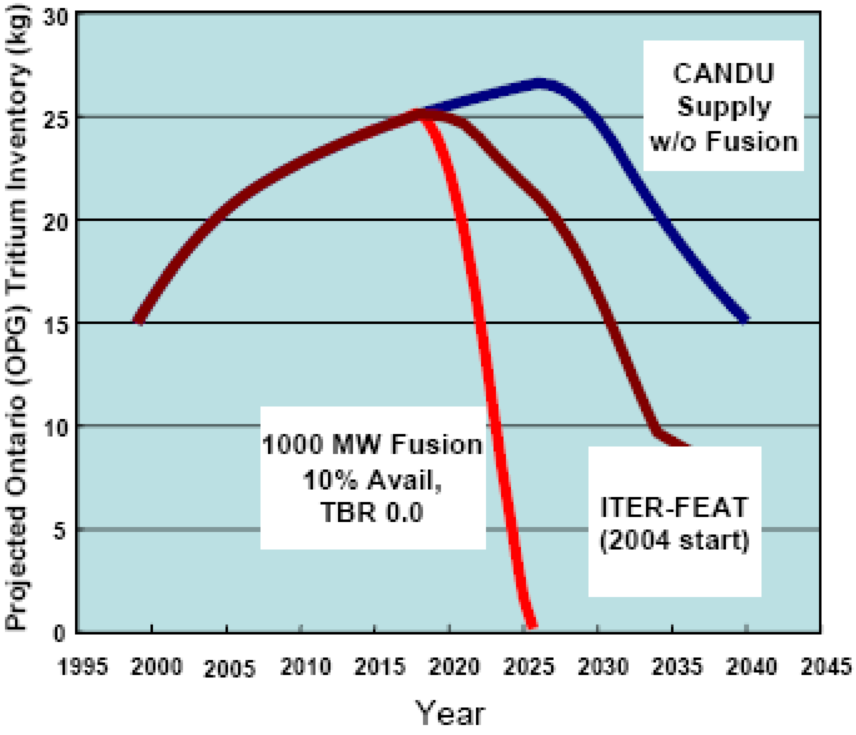


Figure 8-1: Projected tritium inventory and consumption, 55.8 kg of tritium will be consumed per 1000 MW fusion reactor per year, and the maximum tritium inventory from CANDU production is 27 kg.

the net consumption of tritium for the testing and selection of the blanket would be about 4.2 kg at a likely cost near half a billion dollars. Note that some recently proposed preliminary designs for CTF have fusion power significantly larger than 100MW, and will have even higher tritium consumption and cost. Collaboration in ITER TBM also gives the US access to the R&D and testing results of other ITER Parties blanket development programs. This information sharing not only reduces the risk and cost associated with providing tritium for a device like CTF, but it also reduces the total R&D and testing time that the US would have to invest in order to screen blanket concepts before they could advance to CTF testing.

Question 9.

Given the complexity of the blanket and potential regulatory aspects, would the US be at a significant disadvantage in defending the safety case of facilities beyond ITER (CTF and DEMO) if the US did not field an ITER TBM since the US database may not have the most prototypic conditions? (This assumes that the US does not get access to data from other TBMs because of Intellectual Property Rights or proprietary considerations)

The answer to this question depends on what materials are used to construct and cool the CTF structure and whether CTF will merely consume tritium or will have to produce the tritium it will consume. If CTF uses water cooled stainless steel and only consumes tritium provided by external sources, like ITER does, then the licensing and operational experience gained from ITER will directly translate to CTF. Even in this case, though, one of the benefits to the US of testing TBMs in ITER would be to lessen the effort required for CTF testing blanket approval.

If in contrast, the CTF is constructed using helium-cooled RAFS (or similar) then the US will be at a very distinct disadvantage.

Furthermore, since ITER will consume most of the tritium available in the public sector (see response to Question 8), and it is therefore likely that CTF will have to produce much of the tritium it will consume, the US will be at a significant disadvantage by not having participated in the ITER TBM program because the most likely blanket candidates for a CTF breeding blanket are the TBM concepts being tested in ITER. Even though these components are only test modules, the ITER International Organization (IO) is applying for licenses for theses TBMs at the same time and by the same process that they are using to apply for the license to operate ITER. The information required by the French Authorities in licensing a TBM is the same information that is required for licensing ITER, and would be the same information required for licensing a CTF breeding blanket. This means that the successful licensing, operation, and maintenance of the TBMs and their Ancillary Equipment Units (AEUs) are very valuable in providing information and support for licensing a CTF that breeds tritium (although the issue of increased fluence on structural components integrity will still have to be addressed by irradiation testing in non-fusion neutron sources).

With regards to licensing a DEMO, this depends on whether the US builds a CTF. As stated above, if the US builds a CTF, the ITER TBM experience is useful to lessen the effort for licensing the CTF blanket. If the US does not build a CTF, then the only feasible way to license DEMO would be on the basis of the experience of licensing and operating a prototypical breeding blanket in a prototypical fusion environment, e.g., the ITER TBM program, plus non-fusion material irradiation testing in a facility like IFMIF to gain material integrity information at the neutron fluence that DEMO blankets will experience.

A comparable question to ask is what are the safety benefits to the US of the TBM program which could not be obtained by existing non-fusion testing? There are three areas that can be advanced by the TBM program. The first is blanket reliability, which has an impact on public and worker safety. While the bulk heating for the TBM (neutron wall loading of 0.8 MW/m^2) is lower than a CTF or DEMO (1-3 MW/m^2 and 3 MW/m^2, respectively), the FW surface heat flux, fluid and structure temperatures, structure thermal gradients, fluid pressures, fluid velocities, magnetic fields, and disruption forces are very comparable to CTF or DEMO. The major disparities between ITER TBMs and a CTF are in the integrated wall load experience accumulated at the test modules and the number of thermal cycles. The integrated wall load for the ITER TBM is very low (~0.1 $MW.y/m^2$ during the first 10 year of ITER operation compared to that of CTF and DEMO of about 6 and 10 $MW.y/m^2$ respectively). But the number of thermal cycles for a TBM (~6000) is larger than that of blanket modules in a CTF. The successful operation of over 6000 thermal loading cycles, combined with numerous disruptions will have a significant impact on demonstrating early-life blanket reliability to a Regulator. While these phenomena could be studied by separate effects testing in non-fusion tests, the integral real world effect of the combined phenomena is the best indicator of reliability and can not be studied in any other existing facility.

The second area is worker radiation exposure. During DT operation of the TBM, the TBM and PbLi AEU will become radioactive. The radioactivity in the AEU that is of concern is 210-Po, 203-Hg, 203-Pb and radioactive deposits from TBM structural corrosion. 210-Po is a highly toxic radioactive substance. In fact, it is more than 105 times more toxic than tritium. Fortunately, only 1.8 Ci of 210-Po will be produced over the lifetime of the AEU so accidental releases will not be hazardous to the public, but maintenance procedures will have to be developed for both hands-on and remote cutting and capping of the AEU during TBM replacement that provide worker protection from this substance, in particular ventilated tents. In addition, the TBM corrosion product deposits and activated PbLi (203-Pb) inside the components of the AEU will produce a gamma radiation field that must be shielded by Pb in order to allow maintenance of the AEU. These maintenance procedures and the techniques developed to reduce worker dose will be highly beneficial to the licensing process of CTF and DEMO.

The third area is tritium accountancy and safety. Because a DEMO using a DCLL breeding blanket may require a refractory metal alloy heat exchanger (V, Ti, or Nb alloys), in order to keep the tritium inventory in the heat exchangers and the permeation from the PbLi cooling loops into the confinement building at manageable levels, very aggressive PbLi tritium extraction techniques (efficiency > 80%) and tritium diffusion barriers will have to be developed. There is some theoretical evidence that suggests that the separation technique adopted for the ITER TBM could be effective for application to CTF and DEMO. There is also some experimental evidence that permeation barriers composed of aluminum or aluminum oxide bonded to steel pipe or heat exchanger tube walls could reduce the permeation rate by several orders of magnitude below that of the pipe or tube wall alone. The TBM and AEU will provide a unique test apparatus for testing permeation barriers in a fusion radiation environment.

Question 10.

If the US decides not to pursue a TBM, what strategy is recommended in the near term to assure the US has a credible fusion nuclear technology program (e.g. collaborate with one or more of the other TBM teams, go it alone, leverage fission research where appropriate)?

If the US decides not to pursue its own TBM, then there are several options to consider. But whichever option is selected, it is important to note that a "credible" fusion nuclear technology program will in any event require the performance of the R&D activities as laid out in the responses to Questions 4 and 13. The role of this R&D and analysis, as pointed out in Question 3, is to advance the US capabilities to understand and build a practical blanket for fusion, whether it is first tested in ITER or CTF.

It is the opinion of the US TBM team that in the event that the US does not pursue its "own TBM", the US must still remain involved in the ITER TBM testing program in consortium with other parties. ITER TBM represents a unique and critical opportunity that for many reasons must not be missed:

- It is the first facility that will have a true fusion environment, worth billions of dollars. It is the only "real" facility with construction started. ITER should be considered an "existing facility" that should be used to advance a credible US Fusion Nuclear Technology Program (much like a fission reactor, but *without* paying for operating costs).
- ITER is realistically the only facility with a real fusion environment that will be available for testing during the time frame of ITER's first 10 year of operation.
- Collaboration with international partners on ITER TBM is a unique feature that realistically is not likey to be available under any other framework for international collaboration on FNT, at least in the framework of the next 15-20 years. This collaboration can result in huge savings for the US and access to R&D and TBM testing information on many FW/Blanket concepts.

We present below for your information two scenarios from the US TBM Technical Planning and Cost Estimate report [10-1, Chapter 6] (referred to below as the Report), starting from the baseline scenario and proceeding to Low Cost Range scenario. A new, even lower cost scenario is presented in the response to the following Question 11.

10.1 Scenario 1 (Report Baseline Scenario)

As a point of reference, we briefly describe the "baseline" cost scenario as analyzed by the US TBM team in the Report. In this scenario, the US pursues two concepts with different strategies and different leadership roles. The US will develop nearly *all critical* technologies and systems needed for these concepts.

- DCLL
    - TBM ITER half-port size with all necessary ancillary equipment (He loops, PbLi loop, System integration)
    - US pursues DCLL alone (with some accounting for known areas of international collaboration)
- HCCB
    - One-third of a half-port submodule and 1/3 share of ancillary equipment (He loop, System integration)
    - US pursues in consortium in a supporting role, and capitalizes on R&D sharing with US DCLL and international partners
- Project Support Costs typical of US DOE Project

The total cost is $114M over the next 10 year period and includes costs to: perform fundamental R&D ($41M), design and analysis of practical test blanket systems including scaled mockup testing in non-fusion facilities ($40M), TBM unit and ancillary system hardware fabrication ($10M beginning ~2012), and DOE project style administration and contingency ($23M).

Notes:

1- Some of these R&D tasks are being performed already under the base program (in areas such as Plasma Chamber, Material, Safety, and PFC) and SBIR efforts

2- This highest cost scenario should be considered unlikely given recent negotiations in TBWG. ITER has three ports, and therefore can test only 6 TBMs while the number of Parties is 7.

3- This scenario was examined in detail in the Report, per agreement with DOE on the scope of a possible TBM at that time (2006). It is provided here for reference. Costs of other scenarios are largely inferred from this detailed estimate.

10.2 Scenario 2 (Low Cost Range Scenario)

This scenario was analyzed in the Report as characteristic of a "Low Range" (but there are lower cost scenarios as discussed in Question 11). In this scenario, the US still pursues 2 concepts both in consortium, but with different leadership roles. The US develops *selected* critical technologies and systems required by these blanket concepts.

- DCLL
    - TBM ITER half-port size, all necessary ancillary equipment (He loops, PbLi loop, System integration)
    - US pursue DCLL in consortium with international partners, with the US as the *lead* party. The US performs roughly 50% of the R&D and fabrication, 60% of the TBM engineering design, 75% of the safety analysis)
- HCCB (no change over previous scenario)
    - One-third of a half-port submodule and 1/3 share of ancillary equipment (He loop, System integration)

  - US pursues in consortium in a supporting role, and capitalizes on R&D sharing with US DCLL and international partners
- Project Support Costs typical of US DOE Project

The total cost is $79M over the next 10 year period and includes costs to: perform fundamental R&D ($24M), design and analysis of practical test blanket systems including scaled mockup testing in non-fusion facilities ($27M), TBM unit and ancillary system hardware fabrication ($6M beginning ~2012), and DOE project style administration and contingency ($22M).

Notes:

1- Some of these R&D tasks are being performed already under the base program (in areas such as Plasma Chamber, Material, Safety, and PFC) and SBIR efforts.

2- This scenario has lower cost than the reference and should be considered the most likely upper cost scenario given recent negotiations in TBWG. Proposed rules by TBWG require that each TBM be pursued by a consortium of interested international parties, with one party as the "lead party". In this scenario the US takes the leadership role on DCLL and pays about 50% of the total cost (the other two or more parties share the other 50%)

3- Some activities will necessarily be performed by partners, the US will have access to, but not necessarily a domestic capability in all areas.

In summary, it is essential that the US be involved in ITER TBM. There are a number of lower cost options, other than the scenario where the US pursues its own TBM. To lower the cost, the US can be involved in a consortium with other parties. If the US is not willing to assume leadership of the DCLL concept, then it should consider a "support role" at a more modest cost. Regardless of whatever option is selected for US participation in ITER TBM, the US should maintain a strong base program on FNT and pursue the R&D identified for the TBM.

References

10-1. "US ITER Test Blanket Module (TBM) Program, Volume I: Technical Plan and Cost Estimate Summary," UCLA-FNT-216 (2007).

Question 11.

Given the cost of TBM, could you identify the lowest cost option possible that US could pursue and attain most/all of the benefits? Since such an option would probably mean substantial collaboration with one or more ITER parties, what could be proposed?

There are several options with lower cost than the reference case presented in the US TBM Report. We select two cases here to illustrate the general features of such lower cost options.

11.1 Case A (Optimal Case): Part of a consortium with US lead on one concept (DCLL)

This is similar to Scenario 2 in Question 10 (and detailed in the US TBM Report [11-1, Chapter 6]). In this scenario the US reduces cost by forming a consortium of 3 or 4 parties for the US-favored TBM concept, DCLL, but the US maintains the leadership of the consortium. A lead party is expected to pay roughly 50% of the cost. On the solid breeder design, HCCB, the US contributes only a submodule as part of a consortium led by another party. The US will not pursue a "port master role".

The total cost for this case is $79M over the next 10 years, including escalation and contingency. Note that some of the R&D tasks included in this cost are being performed already under the base program (see details under Scenario 2 of answer to Question 10).

This case A is judged to be optimum, because it lowers cost through utilization of international collaboration to a greater extent, via the consortium. Yet the US reaps nearly full benefits and maintains a leadership on the US-favored concept, the DCLL. Hence the US has greater influence on R&D priorities, TBM design, and testing strategy.

Case A is achievable because: 1) recently proposed rules by TBWG require that each TBM be pursued by a consortium of interested international Parties, with one party as the "lead Party", 2) there is consensus among all Parties that the US is amply qualified to lead a concept, and 3) there are other parties who already expressed interest in participating in DCLL. As an example, the EU has formally indicated great interest in being a "support Party" on a DCLL consortium led by the US. Similarly, Japanese universities expressed strong interest in a supporting role in a US-led consortium.

11.2 Case B: Part of a consortium but with the US as a "Supporting" Party

In this scenario, the US pursues 2 concepts as a *supporting partner* in a consortium with international partners (2 or more parties). Another Party, not the US, will serve as the lead party and pay the larger share, but will also set many of the design and R&D priorities.

- DCLL
  - US is a supporting Party and provides FCI test elements, diagnostics, and ¼ share of ancillary systems. The US supports engineering design and some modest fabrication effort for H-H or D-D phases, and capitalizes on R&D sharing with international partners
  - US considers the option of designing and fabricating a full DCLL TBM for the high duty D-T phase using fabrication technology developed in HCCB (below)
- HCCB
  - US pursues in consortium in a supporting role, and capitalizes on R&D sharing with international partners
  - US focuses its structural engineering design and fabrication R&D on this small one-third of a half-port submodule for the H-H phase and low duty D-T phase. US contributes 1/3 share of ancillary equipment (He loop, System integration)
- Project Support Costs typical of US DOE Project, but on smaller hardware investment

The total cost is very roughly estimated at ~$44M over the next 10 year period and includes costs to: perform fundamental R&D ($21M), design and analysis of practical test blanket systems including scaled mockup testing in non-fusion facilities ($10M), TBM unit and ancillary system hardware fabrication ($4M beginning ~2012), and DOE project style administration and contingency ($9M).

Case B has modest cost and is achievable within the proposed rules by TBWG. In this case the US will play a supporting role while another Party will take the leadership responsibility. Some activities will necessarily be performed by partners; the US may have access to, but not necessarily develop a domestic capability in many areas. Being not in the driver's seat, there could be additional risks and hidden cost not accounted for in our previous planning.

Case B has very modest cost, but not all the benefits of Case A. However, if cost is a dominant factor in the US decision to participate in TBM, then this Case B offers vast benefits compared to the US being out of the ITER TBM program altogether.

11.3 Required Actions

In either case, if the US selects one of these options, the US should move quickly to identify and negotiate with the potential consortium members in order to secure the best terms and identify the tasks on which the US should focus its R&D and expend its resources. Moving forward with establishing favorable consortium agreements was a key recommendation of the US TBM Program Review ([11-1, Appendix C]) conducted in August 2006. It is also essential that the US expresses now its intent to participate in the ITER TBM program in order to preserve US rights and claims to the testing space.

References

11-1. "US ITER Test Blanket Module (TBM) Program, Volume I: Technical Plan and Cost Estimate Summary," UCLA-FNT-216 (2007).

Question 12.

Will this type of design lead to a breeding blanket design for DEMO that will survive disruptions and other potential physics phenomena?

Design of the TBM and its potential response to disruption is answered in a sub-section of Question 15. Please refer to that as background for the following answer.

For the DEMO design, the general design approach for the blanket structural supports could be similar to the TBM, in terms of locating the supports at the strong back side of the blanket in the region of the shield and/or attached to strong components. For the DEMO design there will be a general push to make the frontal area of the blanket as large as possible in order to reduce the structural fraction and ensure tritium self-sufficiency. Therefore, the handling of disruption would become an additional trade-off factor in determining the acceptable module frontal dimension with adequate supports and insulation at the back of the blanket. Furthermore, it is expected that the more severe location for the blanket to withstand disruption would be at the upper and lower outboard of the chamber and inboard locations. At these locations a DEMO blanket could potentially have smaller frontal dimensions, which could mean smaller integrated mechanical loads, but also increased structural fraction. However, we know that a large fraction of the tritium breeding will be contributed from modules around the outboard location of the tokamak. This could potentially compensate for the smaller modules at the other locations.

Therefore, tritium breeding ratio of a commercial tokamak reactor will have to be assessed with the consideration of tolerance to disruption. This should be demonstrated by future integrated assessment of a DEMO and will be aided by disruption and tritium breeding data from ITER TBM and other sources.

ITER Specific Logistic Questions

Question 13.

Describe the current state of each technology area for the US TBM design and its readiness relative to the requirements necessary to qualify the ITER TBM. Explain how the R&D leading to ITER will advance the technology readiness far enough to enable the US to take advantage of testing on ITER. What are the technical risks associated with the R&D that could prevent the US from being successful in launching its TBM on ITER?

R&D activities to prepare the US to qualify its TBM modules and ancillary systems, and to be able to design and understand meaningful TBM experiments in ITER, were detailed under the response to Question 4. These R&D activities fall into categories where advancement is needed because either:

1. There was little need and too little emphasis placed on these areas in the science-based technology program over the past years (*e.g.* industrial fabrication with RAFS, nuclear and high temperature diagnostics, helium flow distribution in manifold systems, tritium extraction for PbLi at low partial pressure, *etc.*)
2. Certain fundamental behavior of the blanket concepts are still unknown due either to the difficulty of the issue, or the recent evolution of the concept (*e.g.* SiC Flow Channel Insert Development, MHD behavior of PbLi with FCIs, cycling effects on ceramic breeder pebble bed dimensional stability)
3. ITER requirements and qualification specifically demand it (*e.g.* mockup testing in partially-integrated simulation facilities, H_2 generation, Be armor joining to RAFS, *etc.*)

The status of technical needs in each R&D area was previously summarized in Table 4-1. The R&D identified is considered the minimum set needed for the US to address ITER requirements and prepare for TBM experiments in ITER assuming significant benefits gained from international R&D programs in the EU and Japan. Examples of such valuable international R&D include the portions of RAFS fabrication and irradiation programs that have been shared; ceramic breeder fabrication, irradiation, and characterization experiments; and PbLi compatibility and corrosion, tritium extraction and irradiation experiments.

It is certain that performing the proposed R&D and working closely with interested partners internationally will drastically improve the US readiness for qualifying and performing ITER experiments, as well as make positive advancements necessary for the US to build and test systems in a later CTF (or similar) device. However, there still remain risks that the US will not be successful in qualifying its experimental hardware, particularly given the delay in initiating the needed efforts. Three main categories of technical risks were evaluated for the proposed US TBM development plan [13-1].

- Deliverables do not qualify and so are not accepted for deployment in ITER

- Deliverables will fail during operation, jeopardizing ITER operation or availability and subsequent TBM qualification, acceptance, and deployment
- Deliverables will not meet their operational goals, and so jeopardize their experimental mission and subsequent TBM deployments

TBM technical designs must be evaluated first to minimize risks that could threaten the compatibility of the TBMs with tokamak operations. It is probable that the US will have to present a portfolio of test results and analyses, making a clear case for qualification, prior to receiving ITER approval to install the US TBMs and systems. This establishes the structural integrity; interaction with normal tokamak magnetic operation, including startup and shutdown; and the ability to withstand transient events like ELMs and disruptions as the highest priorities for evaluation in the TBM technical risk assessment for the H-H phase deliverables. Analysis has to be performed to convincingly demonstrate that the TBMs will be able to withstand these loads, including the disruptions (see response to Question 15). R&D activities, laboratory and sub-module tests, prototype and integrated mockup tests, and analysis by verified predictive capabilities have been specifically formulated to address the above risks for the H-H phase and the subsequent D-D and D-T phases.

The primary technical risks associated with the H-H phase TBMs are mostly associated with the development of the required RAFS fabrication technology that can produce a TBM within US design specifications, that will pass all qualification testing and safety requirements, and that meets schedule deadlines for deployment in the ITER H-H phase. Ancillary coolant loop systems are based to a large degree on available commercial technology, and there appears to be sufficient time in the schedule for their design, development, and fabrication. However, there is concern that these systems will have a limited testing time prior to operation in ITER, and so H-H phase break-in tests serve an important role.

Many secondary risks, including SiC FCI development and robustness, uncertainty in the PbLi MHD predictive capability and experimental database, uncertainty that compatible diagnostics can be developed, *etc.* could potentially lead to failure in meeting H-H phase experimental mission and design goals. Such a failure could in turn jeopardize subsequent D-D and D-T phase TBM deployment and performance.

The strategy for dealing with these assorted risks include: (a) beginning RAFS fabrication, SiC fabrication, and thermofluid MHD R&D early, supported by detailed analyses in the corresponding engineering design activity, and (b) the inclusion of a prototype and other partially integrated mockup experiments in order to test the fabrication specifications, diagnostics, and operating conditions against ITER qualification requirements in time to influence the final design and TBM fabrication.

References

13-1. M.A. Abdou et al. “US ITER Test Blanket Module (TBM) Program, Volume I: Technical Plan and Cost Estimate Summary,” UCLA-FNT-216 (2007). Chapter 9.

Question 14.

How does the TBM program fit within the ITER Technical Objectives?

- **What are the critical technical issues to be answered with testing blanket modules on ITER, taking into account the performance characteristics of the current ITER design?**
- **What is the sequence of technical issues that will be investigated on ITER with different modules?**

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" [14-1]. ITER TBM is a prime example of the use of ITER to make progress towards fusion as a practical, safe, and reliable energy source.

The need to test breeding blankets in ITER has been recognized many times in the US planning efforts for ITER where calls are made to "Deliver to ITER for testing the blanket test modules needed to demonstrate the feasibility of extracting high-temperature heat from burning plasmas and for a self-sufficient fuel cycle" [14-2] as part of the OFES Strategic Plan, and "Participate in the [ITER] test blanket module program" to "Deploy, operate and study test blanket modules" [14-3] as part of the official DOE submission to Congress for ITER approval as prepared by the BPO. All ITER Parties have defined DEMO breeding blanket designs and are performing (or planning to perform) an R&D program leading to the fabrication of Test Blanket Modules, and to their installation and testing in ITER.

14.1 Critical FNT issues to be addressed by ITER TBMs

The unique conditions of ITER that allow for meaningful integrated, multi-field, multi-physics testing of blanket components and material systems include:

- large test ports (maximum height of TBM ~2 m, similar to the size of typical blanket modules in a future power plant);
- plasma exposure with typical plasma radiation, particle loads, startup and termination conditions;
- strong and spatially complex magnetic field (~5 T) of the same order as in power plants;
- typical off-normal plasma events such as disruptions, ELMs, VDEs, *etc*.;
- actual fusion neutron flux and energy spectrum as in power plants;
- prototypical ratio of gamma-ray heating to neutron heating;
- tritium production and nuclear volumetric heating in a large volume with spatial gradients;

- beginning of life radiation damage with spatial gradients
- strong confinement of radioactivity, allowing buildup of realistic tritium concentrations.

Major ITER testing objectives can be summarized as follows:

1) Validation of tritium breeding predictions through measurement of tritium production rates in the blanket and tritium concentrations in purge and coolant streams;
2) Validation of neutronics predictive capabilities (neutron flux, secondary gamma-ray flux, spectra for neutrons and gamma rays, nuclear heating rate, ratio of neutron to gamma heating);
3) Acquisition of data on the dynamic behavior of tritium recovery processes, tritium control, and tritium flow rates during periods of start up and short pulses when time-dependence is strong and over campaigns of many pulses where tritium oscillatory equilibrium concentrations are reached;
4) Validation of thermomechanical response and adequacy of the structure (including the thickness of first wall) of strongly heterogeneous, ferromagnetic, thin-wall breeding blankets in a fusion environment including vacuum, surface heat flux, spatially-dependent volumetric heating, and 3-component magnetic field with gradients – both under normal and off-normal operating conditions;
5) Quantitative characterization of the true thermal state (which is a leading driver of many other phenomena including structural response, mass transfer, etc.) of strongly heterogeneous breeding blanket concepts in response to fusion loading conditions including coupled heat transfer, thermo-mechanical, and fluid mechanical/MHD processes that govern the heat transport.

Specific physical phenomena driving blanket behavior were discussed in Question 2, where relevant time scales were provided that indicate the range of technical issues that can be addressed under ITER conditions. Such analysis shows that the above technical objectives of TBM can be realized with the performance characteristics of the current ITER design. Further blanket development beyond ITER TBM (e.g. in CTR) toward long time constant performance and high reliability and lifetime capability will be based in large part on the amount of confidence we will gain in our resolution and understanding of the aforementioned fundamental physical processes and performance issues.

It is also important to note that H-H testing has a very important role, as discussed in detail in Question 15.1. The ITER H-H phase provides the Partially-Integrated Testing (see Figure 1-2) for all fusion environment conditions except neutrons, and should be used to:

- perform integrated first wall helium cooling tests with the plasma heat flux to quantify helium flow and temperature distributions in non-isothermal complex flow elements of the TBM,
- measure PbLi MHD flow distribution and pressure drop in ITER operating magnetic fields environment with or without plasma current (different poloidal field configurations),

- Evaluate FCI and ceramic breeder integrity and response to MHD operation and pulse loads from disruptions,
- broaden of knowledge base on the ferro-magnetic effects of the TBM on the ITER confinement field and perform correction coils adjustment,
- perform initial adjustment of ancillary equipment behind the TBM and corresponding monitoring systems,
- test and adjust TBM diagnostics and integration with ITER CODAC and Fast Plasma Shutdown System,
- test and adjust all remote handling procedures,
- contribute to the safety portfolio for D-T phase ITER licensing including experimental TBMs.

14.2 Sequence of ITER TBMs

A number (3-4) of consecutive TBMs per blanket concept are currently planned for the first 10 years of ITER operation, each with a different technical mission and unique set of diagnostics designed to maximally utilize the ITER integrated fusion environment, while minimizing the technical development required (see table on following page for a more detailed description of a possible testing sequence). Studies of basic feasibility and operational issues are planned; as well as of exploration of phenomena and operational scenarios relevant to DEMO by using engineering scaling, and the control of coolants and flow rates. Maximum flexibility will be incorporated into the design of the TBMs and systems, to allow exploration of the largest set of parameters and conditions of interest for fusion. Quantitative data sets of in-situ TBM temperature distribution, structural strain and deformation, electric potential distribution (also related to PbLi flow rates and velocity profiles), pressure distribution, coolant chemical composition, tritium production, nuclear fields and spectra, and coolant temperature rise will be collected to meet scientific experimental goals. Additional material and component response data will be obtained by PIE of the structure, FCIs (DCLL only) and ceramic breeder and neutron multiplier (HCCB only) after the TBMs are removed from ITER. Analysis tools will be developed and used to interpret and correlate TBM data, and extrapolate it to subsequent experiments and future machines (e.g. CTF and DEMO) – forming an essential predictive capability.

It should be noted that a final decision on the number of TBMs must be evaluated in the future based on such factors as (1) the detailed optimized technical mission and design of each experiment, (2) any possibility to perform similar tests in collaboration with other parties, (3) availability of needed diagnostics with sufficient accuracy, (4) decisions on testing space and time allocations, (5) details of ITER operational scenarios not currently available, *etc*.

Table 14-1: Potential Sequence of TBMs and Their Experimental Goals

TBM	Experimental Goals	ITER Phase & Duration
1st -TBMs **EM / Structural**	• Establish testing capability, system performance baseline, and operation experience prior to D-T (nuclear) operation, including diagnostic and control system operation, heat transfer and thermal time constant measurements, etc. • Validate TBM structure, FCI (DCLL), and pebble bed (HCCB) response to EM/Plasma during normal operation and transient events prior to D-T phase • Perform initial studies of MHD effects in ITER fields, particularly flow distribution and pressure drop behavior (DCLL)	H-H for 3 years
2nd-TBMs **Nuclear Field/ Tritium Production**	• Establish neutron field measurements database for various types of ITER discharges and conditions • Measure tritium production rate (TPR), and nuclear heating rates • Validate FW He cooling at full load and determine FW tritium plasma driven permeation and implantation effects • Establish tritium processing capability prior to D-T operation	D-D + Early D-T for 2 years
3rd-TBMs **Thermofluid / MHD** **Thermo-Mechanical**	• Quantify the thermal and electrical insulation properties of the FCI and FCI failure modes and effects (DCLL) • Establish the PbLi flow behavior and resulting FCI and structure temperatures with nuclear heating and buoyancy/MHD effects (DCLL) • Study thermomechanical behavior of the breeder and beryllium particle beds on heat transfer and performance with nuclear heating (HCCB) • Study tritium transport and control through FCIs, RAFS, and Ceramic Pebble Beds, and PbLi and He coolant streams • Establish initial behavior of activation product generation, transport, and chemistry control in the PbLi coolant (DCLL) • Note: parallel submodules potentially utilized for various focused multi-effects studies	Low duty D-T for 2 years
4th-TBMs **Integrated**	• Investigate various scenarios for TBM operation, including synergistic effects of flow and FCI behavior on blanket temperature distribution • Investigate online tritium recovery and control from PbLi, CB purges, and He streams including ceramic breeder temperature window for tritium release • Investigate online PbLi and He coolant purification systems and corrosion product transport • Explore longer-term integrated operation of the system, including small accumulation of radiation damage in ceramics and RAFS joints regions	High duty D-T for 3 years

References

14-1. "Report from the re-established Test Blanket Working Group (TBWG) for the Period of the ITER Transitional Arrangements (ITA)," (September 2005). http://www.fusion.ucla.edu/ITER-TBM/Documents/TBWG_REPORT_for_ITA.pdf

14-2. "A Strategic Program Plan for Fusion Energy Sciences," (2004). http://www.ofes.fusion.doe.gov/News/FusionStrategicPlan.pdf

14-3. "Planning for U.S. Fusion Community Participation in the ITER Program," US BPO Energy Policy Act Task Group, (2006).

Question 15.

How does the TBM Program on ITER fit within the ITER operational plan?

- **What is to be gained with TBM on ITER prior to Deuterium-Tritium operation?**
- **What are the possible interferences of TBM experiments with the startup and operation of ITER? What are the incremental risks to ITER operation of the TBMs?**
- **Would it be possible to investigate preliminary issues (field errors, sustaining disruptions, etc.) on other facilities prior to installing modules on ITER?**
- **Are the present US designs for breeding blanket modules compatible with the disruptions expected in ITER? This is meant to go beyond will the present designs survive many disruptions in their midplane locations, and includes will breeding blanket modules of this type survive many disruptions if placed in any first wall location on ITER?**

The following contains an introduction to the answer of the main question. Additionally individual sub-questions are also addressed.

Through all the phases of ITER design activities, since it started 20 years ago until now, TBM plans and interfaces to ITER have been a joint activity among the ITER organization and the parties. The TBM program fits well within the ITER operational plan and is included in the official ITER schedule. Communication between national TBM organizations and the IO has been well established though the Test Blanket Working Group (TBWG) which consists of member of ITER IO and representatives of the Parties. Representation of ITER within TBWG has been on a high level and included, for example , the following:

- Director of Science and Technology, Dr. V. Chuyanov
- Chamber design group from Dr. K. Ioki
- Safety group from Dr. M. Iseli and Dr. JP Girard
- Remote handling group from Dr. A. Tesini
- Tritium group from Dr. M. Glugla

TBM operational phases and schedule, design specifications including test module, ancillary equipment and TCWS locations, TBM dimensions and frame support, and operational schedule, safety requirements and parameters were all specified and evolved with the IO.

These questions and issues are common to all the other Parties and are not unique to the US. They were addressed by the Parties and ITER IO within TBWG. The request for TBM testing during the H-H phase came from both the IO and the French team in charge of safety and licensing.

15.1 What is to be gained with TBM on ITER prior to D-T operation?

This question will be answered considering two different interpretations.

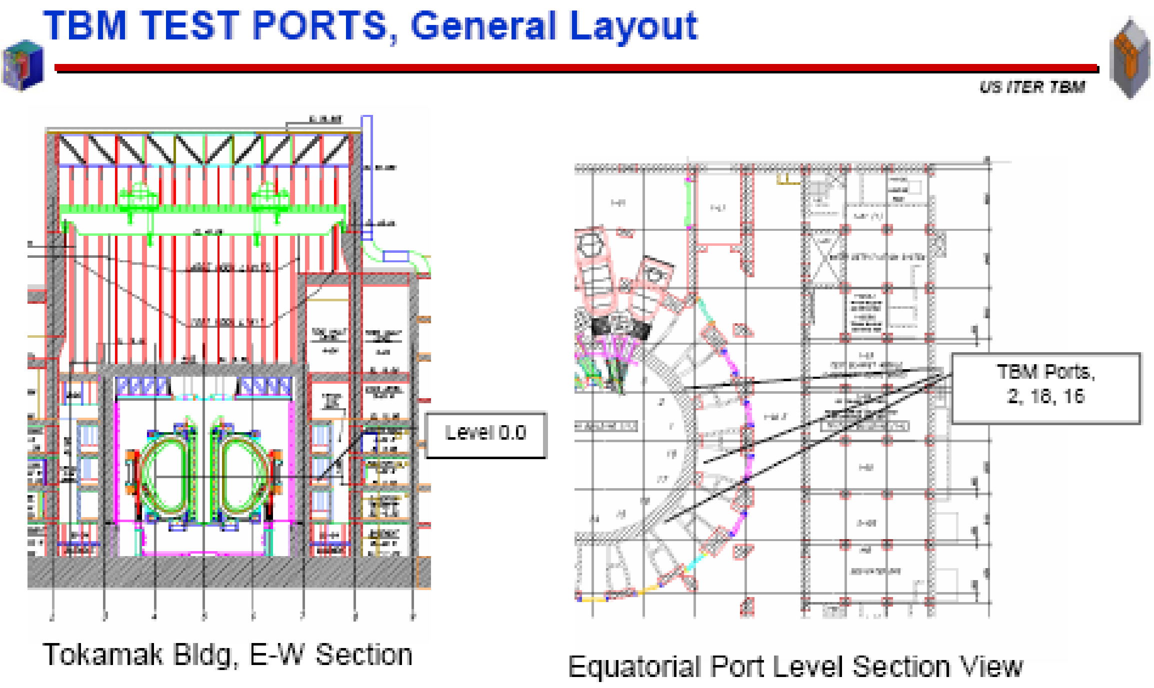
A. Reasons for ITER to install TBM during the H-H phase.
B. Benefits for TBM to be operated during the H-H phase.

A. As mentioned earlier, the request for TBM testing during the H-H phase came from both the IO and the French team in charge of safety and licensing. The reasons for ITER installing TBMs during the H-H phase of ITER, or prior to D-T operations include:

1. Ferritic steel (FS) is the preferred structural material for DEMO, and as shown in Fig. 15-1, the selected TBM test ports are not toroidally symmetric around the plasma chamber. With the insertion of FS test modules, field ripples and displacement will occur. Calculations have shown that the field ripples could be corrected with existing ITER correction coils. The total "3-mode" error field caused by the six typical TBMs in combination with NB magnetic field reduction systems and the coil joints, feeders, and terminals is 5×10^{-5}. This level of error fields and corresponding correction currents seems acceptable. The error fields will cause radial perturbation of the magnetic field lines near the limiters. The study performed has shown that maximum radial perturbation of the field lines along the limiters is less than 0.1 mm. However, the radial perturbation of the field lines can have a maximum deviation of -12 mm [15-1]. Impact from the radial displacement is unknown. Further assessment on the ferromagnetic effects of the TBM to the ITER confinement field is continuing. Therefore, it is prudent to verify and perform necessary field coil corrections adjustments during the H-H phase of ITER operation including startup and different operation scenarios of ITER. If necessary, minor hands-on adjustments can be made to ITER and/or to the TBMs prior to the D-T phase, after which, the metallic components will be activated. Any adjustment or maintenance close to the first wall after D-T discharges will need to be done remotely.

2. The demonstration that the TBM system can sustain disruptions, ELMs and MARF effects should also be done during the H-H phase of ITER to reduce the complexity and long duration of remote handling operations needed for TBM change-out if a failure occurs.

3. The TBM system, including the TBM, shield, water cooled frame, corresponding ancillary components behind the port plug and heat removal systems at the TCWS vault and associated piping, are very complicated engineering systems. In order to minimize the impact of the TBM system on ITER operation, it is again prudent to test out all the necessary systems (similar in many respects to the testing of components in the ITER basic device) before activation of the near first wall components and activation of the coolant like PbLi after the DT phase operation of ITER.



TBM TEST PORTS, General Layout

US ITER TBM

Tokamak Bldg, E-W Section

Equatorial Port Level Section View

Figure 15-1: TBM Test Ports layout in ITER

4. On the need for remote handling: for the DCLL TBM, after D-T operation begins, maintenance activities will require special procedures to limit mobilization of radioactive material. One of the more complicated TBM maintenance activities will be the replacement of a TBM. A detailed time estimate for replacing the DCLL TBM has been completed, and the replacement time is ~400 hours. The anticipated worker dose for this operation, after D-T operation begins, is ~5.5 p-mSv, which is more than a factor of two higher than ITER International Organization (IO) guidelines. It is important to verify that time estimates for all major maintenance activities are correct during the non-nuclear phase of ITER operation, and may be requested by ITER IO prior to TBM D-T operation for worker safety.

5. The Ancillary Equipment Units (AEUs) of the TBM are classified by the ITER IO as safety grade systems. Pressure, temperature, and flow sensors from these systems will tie directly into ITER's Fast Plasma Shutdown System (FPSS). It would be prudent to ensure that these systems are operating stably prior to D-T operation to avoid spurious signals being sent to the FPSS. This demonstration may also be required by ITER IO prior to TBM D-T operation.

B. Benefits from TBM operation during the H-H phase

The fundamental benefit from TBM operation during the H-H phase of ITER is the ease of maintenance and components adjustment before they are activated after a few D-T discharges. Otherwise, TBM and corresponding components located close to the inside of the biological shield will have to be done remotely or in the hot cell. Specific benefits can be listed:

- Initial adjustment of ancillary equipment behind the TBM and corresponding monitoring systems.
- Initial and gradual introduction and adjustment of the procedures for handling high melting point PbLi, including filling and draining of the material. During D-T operation, PbLi will be activated (as mentioned above).
- Ability for examination and adjustment of some TBM diagnostics.
- Practice and streamline the remote TBM change-out procedure (as mentioned above).
- Practice and streamline the procedure of working closely with neighboring half-port module.

There is also an experimental mission for the TBM that can be met during H-H phase operating conditions including studies of:

- Integrated first wall helium cooling tests, with the pulse plasma heat flux, such as helium flow and temperature distributions that can be quantified in complex flow elements of the TBM.
- PbLi MHD flow distribution and pressure drop in ITER operating magnetic fields environment with or without plasma current (different poloidal field configurations).
- FCI integrity and response to extended PbLi MHD operation and pulse loads from disruptions.

Such basic performance of the TBM is important to establish prior to proceeding to more demanding conditions in the D-T phases.

15.2 What are the possible interferences of TBM experiments with the startup and operation of ITER? What are the incremental risks to ITER operation of the TBMs?

The key possible interference with the startup and operation of ITER is the impact from the use of FS in the TBM test port (as mentioned above). This is also the key reason why there is such a strong preference is to performing all correction coil waveform adjustments during the H-H phase of ITER.

The other typical interference could be the failure of any of the six TBM half-port modules that could impact ITER operation. This is to be minimized by rigorous acceptance tests to be specified by ITER and demonstrated by parties at every stage of the TBM development, fabrication, and QA control.

Dummy TBMs will be designed and fabricated by ITER as a backup measure to replace damaged or unavailable TBMs, in order to minimize any negative impact to ITER operation. In general it is critical that all key systems of all TBMs be operated and tested with proven performance during the H-H phase of ITER in order to minimize adverse impacts to ITER startup and operation, and subsequent D-T operation.

15.3 Would it be possible to investigate preliminary issues (field errors, sustaining disruptions, etc.) on other facilities prior to installing modules on ITER?

With the operation of the EAST superconducting tokamak in China, and their intention of constructing a 1/2 size test port for ITER TBM pre-testing, it may be possible to perform tests on field errors and sustaining disruptions for both solid and liquid breeder concepts. Results from testing in EAST can provide a better experimental database for benchmarking modeling results for projection to ITER and DEMO operation. However, even with testing in EAST, results can only be used to enhance projections regarding the TBM performance in ITER, and to enhance our understanding of the issues. But still, the need for the testing during the H-H phase of ITER cannot be replaced.

In terms of EAST logistics, at least bi-lateral collaborations will need to be organized, and China at this time welcomes such possibilities. But as a practical matter, with the recognition such a unique testing possible by the seven ITER parties, the availability for testing will be limited and coordination will need to be done with consensus from EAST. Therefore, we will have to get commitment from EAST and to schedule the testing of our modules in a timely manner.

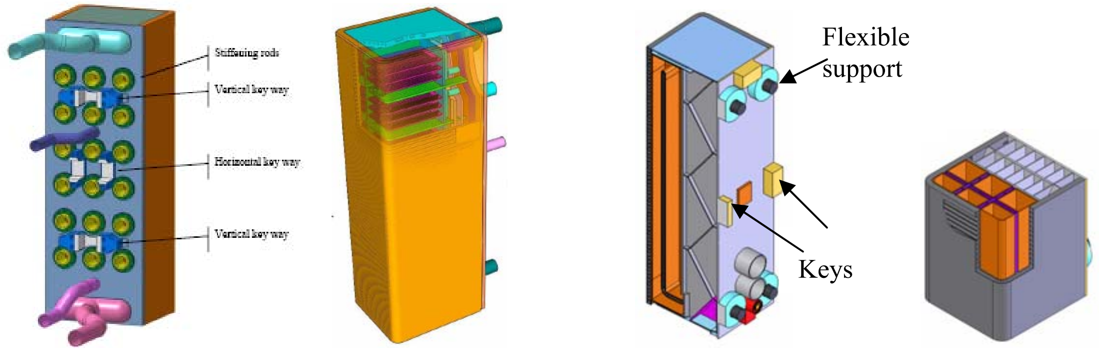
15.4 Are the present US designs for breeding blanket modules compatible with the disruptions expected in ITER?

TBMs in ITER will be required to demonstrate that they will be able to withstand ITER disruptions, or they will not be accepted. Due to resource limitation, we have initiated but not completed the disruption analysis on DCLL. Since the TBM concepts for the US DCLL and the European HCLL have similar geometric internal configuration and back support attachment scheme, we will report in the following, the more complete analysis performed on the HCLL design. Analysis has been done for the EU-HCLL (PbLi breeder) vertical half port module [15-2] and EU-HCPB (solid-breeder) horizontal half-port [15-3], which are essentially similar to our DCLL and HCCB designs, respectively, including the same type of first wall design details and U-shape configuration and similar internal structural designs (Fig. 15-1). For both EU concepts, a 10° slice of the tokamak including the double shell vacuum vessel, the TBM port, the frame and the TBM was used to model the surrounding structure and induced loads onto the respective TBMs. Analyses were performed for the individual half-port TBM and the assembly including the frame and two half-port TBMs. From the HCLL analysis, after analyzing 6 major plasma disruption events prescribed by IO, results show that the module can withstand the static loading of the worst disruption case. This is the case with fast main chamber disruption, in which the thermal quench occurs at the beginning of the event that develops immediately in a linear current quench of 40 ms duration followed at the end by a vertical displacement. It has been shown that the major EM load on the HCLL is the radial component of the moment due to induced currents at the end of the current quench. These loads never exceed 0.5 MNm. The loads, including induced current and the unlikely event of hallo current at the outboard mid-plane, can be reacted by four insulated keys and four insulated flexible supports at the back of the module which are attached to the shield (Fig.15-1). Static loads as a function of time on the keys and flexible supports are well within the primary and secondary loads allowable for the selected materials. In this case the HCLL TBM module, which is also filled with PbLi similar to our DCLL, is treated as a homogeneous conductor, and with the simplified assumption of behaving like a rigid body with a resistivity of 1.05×10^{-6} Ω.m. Summary of the reaction forces on the attachments is given in Table 15-1.

Table 15-1 Summary table of the reaction forces on the attachments of the EU-HCLL

Max. reaction force (MN)	Flex. attachment	Vertical keys (Horiz. forces)	Horiz. keys (eddy+halo) (Vertical forces)
Main disruption, 40 ms Linear current quench	Ra=0.045 (t=0.040s)	Rv=0.42 (t=0.036s)	Fz=-0.15 (t=0.036s)

Dynamic behavior of the module will be more difficult to analyze including details on gaps and tolerance and with radial direction forces. An alternative design approach is also being considered, which is to have the TBM and shield removed as one piece in the ITER hot cell in the vertical orientation. The TBM and the shield could then become a unit structure and could further reduce the impacts from induced and halo currents impacts due to disruption, and also allows the placement of the load reacting elements to possibly larger surface area, but still transfer the loads from the TBM to the shield than to the frame, which is attached to the vacuum vessel of ITER.



(a) (b) (c) (d) partial height

Figure 15-2: (a) and (b) EU-HCLL design, (c) and (d) US-DCLL design, both have the same external frontal dimensions, internally, both are filled with PbLi and high pressure He. (a) and (c) indicate back supports with keys and flexible attachments.

The above summary indicates that for the handling of disruption, there is minimum impact on the front part of the HCLL design, which is crucial to tritium breeding performance. The critical point for the design is the reacting loads on the attachments, which are located to the back of the breeding zone. For the DCLL design, with the poloidal flow of PbLi, when necessary, to be determined from our analysis, horizontal supports could be added to the module design, arriving at similar structural configuration as the HCLL, with minimum impact on the PbLi flow configuration and with reduced but still acceptable tritium breeding performance. This will have to be analyzed for DCLL. It should also be stated that in the handling of the thermal loading from disruption, most likely the Be front face of the TBM will be melted and vaporized, and the amount would be limited by vapor shielding effect. The thickness of Be vaporized will also limit the number of disruption that the TBM module can take. However, this will not have significant impact on the tritium breeding performance of the blanket, except perhaps the reduction in module life-time.

When the TBM is at a different poloidal location of the plasma chamber, the induced current impact will have to be re-assessed since the likelihood of disruption impact and halo current will be higher. In practice, details of the keys and flexible supports at the back will need to be re-designed and adjusted. Under the worst case condition, this could also impact the frontal dimension of the module in terms of acceptable integrated E&M loads. But the general configuration and material composition of the DCLL TBM is not expected to change significantly, and therefore, impacts on tritium breeding performance could be adjusted by corresponding changes in the radial depth of the modules and/or the enrichment of Li-6.

In general, when the back supports of the TBM module are designed properly, it is expected to be able to withstand many disruptions under static loading. The situation of dynamic loading will have to be assessed.

It can be observed that the analysis of disruption impacts to the TBM is very complicated but tractable. The analytical assessment has not been completed and should continue. The design direction of locating the support of the TBM to the strong back seems to be the right direction in order to minimize the impact from the handling of disruption to the tritium breeding performance of the TBM. On the other hand, there is no substitute for the experimental demonstration, and this increases the value of testing the TBM during the H-H phase of ITER.

References

15-1. V. Amoskov, A. Belov, V. Belyakov, E. Lamzin, N. Maksimenkova, B. Mingalev, S. Sytchevsky, “Error Fields from Test Blanket Modules (Approximation of Typical TBM), Version 2:29 March 2006, ITER_D_23DRLV, Efremov Institute, St. Petersburg, (2006).

15-2. DDD report for the EU HCPB TBM, version 0, TBWG report, (December 2005).

15-3. DDD report for the EU HCLL TBM, draft 1, TBWG report, (November 2005), also HCLL TBWG-17, 2006 and TBWG-18, 2007 presentations.

Question 16.

What are the difficulties with delaying the deployment of test modules on ITER until after it has achieved reliable operational modes several years into its operations?

- **Why can't the TBM program be considered part of the ITER research program and would only be considered when ITER had entered the nuclear testing phase of its research after it had met its burning plasma and steady-state objectives?**

16.1 Immediate need for TBM agreement

The TBM program must be treated separately from the definition of the physics research program because there is still hardware definition, design, and fabrication necessary before ITER can even operate. Currently, as part of the ITER agreement and procurement packages, there are 3 empty ports in the ITER machine with no hardware to fill them, nor party responsible for them. This situation has arisen because of the fact that the TBM program was treated separately and not adequately addressed. This must be remedied now.

Additional hardware in the forms of TBM support frames with integrated shielding, and dummy test modules are required to close the machine. Regardless of when the TBMs deploy (discussed in more detail below), this must be done to operate the machine.

Agreement among the parties on allocation of space to various concepts in ITER's 3 test ports will have impact on the ITER hardware interface. Furthermore, blankets to be tested in ITER still require R&D and fabrication of additional hardware, at the expense of the individual parties. It is not reasonable to expect them, including the US, to expend these resources without an agreed upon formula or framework as to if/when/how their TBMs will be tested. Having a defined plan will also allow parties to define collaborative agreements and work together on common issues and hardware from an earlier time – saving resources and reducing risk. In addition, it is prudent and cost effective to discover and include any TBM impacts on the construction of critical ITER hardware and facilities. These impacts, such as required piping, wiring, floor space, etc., will be less severe if included earlier.

16.2 Deployment Schedule of TBMs

Delaying the deployment of TBMs until after ITER has achieved some reliable operation mode and/or achieved its burning plasma and steady state objectives has never been considered by the parties, nor should it be. ITER principal objectives include TBM, and carrying out the TBM mission includes testing in the H-H and D-T phases.

Delaying the deployment of TBM deprives the TBM testing parties of the chance to do preliminary testing in the H-H and D-D phases. This testing (covered in detail in the response to Questions 14 and 15) is considered very important for a number of reasons. For the same general reasons that the physics program needs several years to learn to operate the machine, H-H TBM phase testing serves as a chance to slowly break in, condition, and learn how to operate TBMs, loops and control systems, without the added complications and risks of doing this testing in an activated machine. Licensing with the French regulators of experimental TBMs is likely to require such a demonstration period during the H-H and D-D phase. Also, if some later deployment time for TBMs is decided upon, reprogramming ITER plasma control to compensate for the presence of TBMs with different electromagnetic properties must be done, followed by a long period of TBM break-in testing. The result will be a significant retooling period that extends the operation of the machine and takes significant resources.

In addition, delayed deployment negatively affects the fusion nuclear technology development path as laid out in response to Question 1. Phase I ITER TBM testing allows a much earlier deployment of a CTF and ultimately DEMO machine, that tracks better with the physics development time-scales.

Integration of DEMO relevant burning plasma and DEMO relevant FW/Blanket technologies has been an important goal of the ITER research program since the beginning of ITER design activities two decades ago. This goal should continue to be maintained. TBM research over the first 10 years of ITER operation, just like the physics research program on ITER during that time, must remain flexible and will have to adapt to many exigencies, such as machine condition, plasma discharge sequences and schedules, status of various blanket R&D programs, results from prior TBM testing, domestic programmatic directives, and many others. It is considerably more useful, cost effective, and in the end less risky to adequately resolve the remaining international agreement issues regarding the TBM program implementation, and to begin the TBM testing in the H-H phase in concert with the physics development program

The interested reader is also referred to Question 18, where a similar question is discussed.

Question 17.

Is it conceivable to conduct a major program such as TBM on ITER with a limited number of collaborating parties?

- **How do you allocate time for experiments?**
- **How do you hold participating parties responsible for any damage or delay of ITER's main experiments?**
- **How do you keep ITER data from non-participating members?**

The difficulties and issues in such collaborations, with 7 parties, limited testing space, and many proposed modules have been recognized for a few years. The TBWG has initiated discussions and progress has been made. Presently, the recommendation for the three available testing ports is to assign port masters and concept leaders to oversee the coordination of the port interfaces and specific concept development and testing. IO has recently asked for guidance from the ITER Council on the assignment of leadership. The following reports the present progress and the status of development on this very important question.

17.1 How do you allocate time for experiments?

This problem is fully recognized by TBWG and the IO. Three items are being proposed for resolution by the ITER Council meeting in mid-July of 2007.

1. The framework for running the TBM programme (whether it should be a common understanding within the ITER Agreement, or a separate Arrangement);
2. The selection mechanism and criteria to be used for assigning TBM Leadership;
3. The rules needed to determine information sharing and Intellectual Property rights during TBM development and preparation.

The following are further details as reported by the IO [17-1]:

> 1. Status of the TBMs Ad Hoc Group's Deliberations
>
> 1.1 The test of DEMO-relevant breeding blankets is an ITER mission: "ITER should test tritium breeding module concepts that would lead in a future reactor to tritium self-sufficiency, the extraction of high grade heat and electricity production." The TBMs test programme in ITER is therefore a central element in the plans of all seven ITER Parties for the development of tritium breeding and power extraction technology.
>
> 1.2 For proper integration with ITER operations, the TBMs are to be installed and tested in ITER from the first day of H-H plasma operation. Therefore, the Parties

have officially requested that the ITER Organization (IO) includes TBMs and associated systems in the overall ITER licensing process.

1.3 Three equatorial ports in ITER are available for TBM testing, allowing up to six TBMs to be simultaneously installed and tested – two TBMs per test port. Taking into account the different operating parameters of ITER and DEMO, and in order to achieve the established testing objectives, for each of the six TBM types it will be necessary to design, manufacture and test several specific TBMs. Further time and space sharing between different TBM designs is not technically viable.

1.4 The TBMs will be installed in frames/shields made of the same materials as the basic ITER shield blanket but needing a specific design. The design is being performed by IO but the corresponding procurement is not included in the ITER costs. In order to operate ITER and to run the TBMs test programme, it is therefore necessary to allocate additional resources to procure six test port frames and corresponding shields, and six dummy TBMs (see corresponding cost structure in section 2).

1.5 To optimize the ITER testing capability and to test six independent TBMs, some changes in the ITER design are required. This implies a common cost to be determined by ITER and to be shared by all Parties willing to participate in the TBM programme.

1.6 The number of independent TBM concepts that can be tested by ITER is significantly smaller than the number of proposals for testing presented by Parties and in fact even smaller than the number of Parties. As a result, the testing can be done only by cooperation between the Parties.

1.7 The TBM test programme could be implemented under the ITER Agreement which should not require any change to the signed ITER Agreement. The TBM test programme should be implemented in the spirit of genuine partnership (as affirmed in ITER JIA). The organization of the overall TBM programme foresees each type of TBM having a responsible Party, called TBM Leader (legal details to be agreed). For each Test Port one of the responsible parties should play the role of a “Port Master” and ensure the coordinated operation and services for the two TBMs and associated systems installed in the port.

1.8 TBMs and associated systems are the responsibility of the Parties with ITER IO in a coordinating role, but are not part of the procurement identified for ITER construction. TBMs remain the property of the originating Parties. After dismantling and removing the TBMs from the ITER facilities, the TBM components and systems shall be taken back by the originating Parties under their responsibility. The sharing of information and Intellectual Property developed in the process of testing should be as defined in the ITER JIA.

> 1.9 Each Participating Party (or a Parties' Partnership for the TBM) shall bear the costs for development, construction, testing and operation of the TBM system. Qualification requirements, acceptance criteria and the testing programmes of the TBMs in the ITER facility should be developed to minimize risks, consistent with technical objectives and within the time schedule defined by IO.
>
> 1.10 All Parties are open to collaboration and to the establishment of Partnerships (bilateral and/or multilateral). For each TBM, the Partnerships' rules, legal obligations and mechanisms have to be defined by the Participant Parties.

Our recommendation is to follow through the above process with the goal of achieving the leadership role on DCLL and the development of HCCB while working very closely with other ITER parties on their proposed TBM concepts. We will have to decide on whether we would take an additional leadership role on becoming a port master, which would allow the control of ancillary and interface equipment.

17.2 How do you hold participating parties responsible for any damage or delay of ITER's main experiments?

The answer could be extracted from the quoted sub-sections 1.8 and 1.9 (of Section 17.1 above). On the other hand, specific questions posted in this form has not been answered explicitly. However, it could be interpreted as a joint responsibility from ITER and parties, with the best intention of satisfying all the design, stringent testing and operation criteria to be specified by IO. It is in the interest of the ITER IO as well as of any party participating in ITER blankets test that an extensive and comprehensive qualification program for any TBM, its anticipated test plan, and projected operation procedure, must be documented and presented to the ITER IO before a TBM and the corresponding ancillary systems can be installed. This is essential to minimize the risk to ITER operation, on availability and safety. We would recommend that the US strongly support the development of these stringent IO guidelines and TBM qualification procedures. Once these qualification rules are satisfied, the framework for liability can be developed following an approach similar to that developed for the procurement packages by the 7 parties for the basic ITER device.

17.3 How do you keep ITER data from non-participating members?

For the participating members, the following statements were issued by IO [17-1].

> Intellectual Property Rights Currently common understanding exists only for the sharing of information developed during the testing process. Agreement needs to be reached for the period during the development and preparation phases of the TBMs.
>
> Additional Question to be addressed by the IIC: What rules should be used to determine the sharing of information and Intellectual Property created in the

process of TBM development and preparations to testing before the actual testing is started?

As for the non-participating TBM members, we would assume that some safe-guards would be implemented for restricting access to technical information only to the participating members. This could become a common practice in ITER when significant investment has been put forward by participating parties on the TBM program.

References

17-1. Interim ITER Council Preparatory Meeting, IIC-2 Prep/3.5 rev.1, Marseille, 27-28 March 2007.

Question 18.

Is it feasible to suggest an international collaborative program on TBM development among the ITER parties without a defined ITER deployment plan, which can be worked out in the future, as will be done on many physics experiments on ITER?

As stated previously in the response to Question 16, questions regarding the implementation of the TBM program cannot be delayed until the definition of the physics research program because there is still hardware definition, design, and fabrication necessary before ITER can even operate. Currently, as part of the ITER agreement and procurement packages, there are 3 empty ports in the ITER machine with neither hardware to fill them, nor party responsible for them. This situation has arisen because of the fact that the TBM program was treated separately and not adequately addressed. This must be remedied now.

Additional hardware in the form of TBM support frames with integrated shielding, and dummy test modules are required to close the machine. The design, fabrication and responsibility for this hardware must be decided.

Blankets to be tested in ITER still require R&D and fabrication of additional hardware, at the expense of the individual parties. It is not reasonable to expect them (including the US) to expend these resources without an agreed upon formula or framework as to if/when/how their TBMs will be tested. Having a defined plan will also allow parties to define collaborative agreements and work together on common issues and hardware from an earlier time – saving resources and reducing risk. In addition, it is prudent and cost effective to discover and include any TBM impacts on the construction of critical ITER hardware and facilities. These impacts will be less severe if included early, and could include the inclusion of needed piping, wiring, floor space, *etc*.

The TBM program over the first 10 years of ITER operation, just like the physics program on ITER during that time, must remain flexible and will have to adapt to many exigencies, such as machine condition, plasma discharge sequences and schedules, status of various blanket R&D programs, results from prior TBM testing, domestic programmatic directives, and many others. However, in the case of physics research program, the basic machine has been designed and analyzed for many years, and provides sufficient flexibility for defining a particular test at a later point in time. This same state must now be established for the TBMs.