M. Abdou
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Need for Chamber/Material/PFC Communities to have Interactive Discussion on Required R&D and Development Pathways to Successful DEMO

- Renewed interest in Burning Plasma Experiment (e.g. at Snowmass, July 2002) has led to broader discussion in the fusion community about R&D pathways (facilities and schedule) to DEMO.

- There is an Opportunity here!
The purpose of this talk is to encourage the Chamber/Materials/PFC communities to start a process for discussions on the role of Chamber/PFC Technologies and Materials in fusion development from now to DEMO.

    - A suggestion for a meeting to start the process.

    - Summary information from previous studies as background to help start the process.

ITER-Based Development Path (from Snowmass 2002)

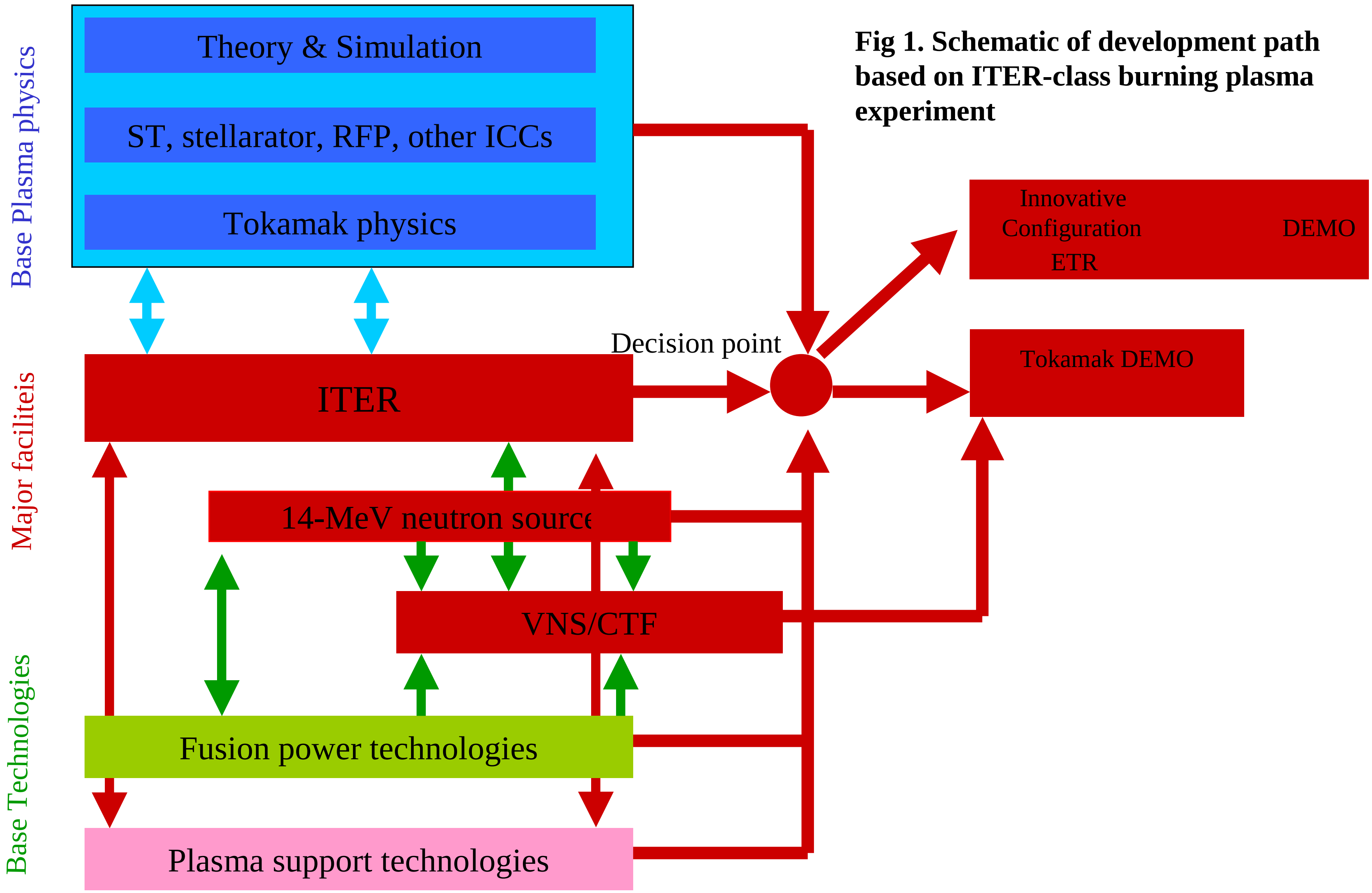

Fig 1. Schematic of development path based on ITER-class burning plasma experiment

- **This summary figure from the Snowmass 2002 community discussions is encouraging.**

- It has both IFMIF and VNS (CTF) parallel to ITER.
- It recognizes a decision point after ITER/IFMIF/VNS and prior to DEMO
- But there is still debate and questions (sometimes confusion) about the role and timing of these facilities.
- It is our responsibility in Chamber /PFC /Materials to reach & communicate a common understanding & definitions of the functions and interrelations of ITER/VNS/IFMIF.

<u>Suggestion for a Meeting</u>

- It would be very useful to have a 2-3 day meeting (around December/January) with 20-30 participants from the Material, Chamber, and PFC communities.

- Purpose of the Meeting

  Discuss what R&D is needed from now to DEMO in the Chamber/PFC/Materials areas.

  The needs should include roles and schedule of major facilities.
- To make the meeting productive I suggest we start by extensive summaries of findings and conclusions of previous studies.

Current Key Questions that are important to Chamber (materials, chamber technology, PFC)

1. How to achieve the goal of a successful fusion DEMO?
   (or, what are the pathways to a successful fusion DEMO?)

   - What non-fusion facilities are needed?
   - What are the fusion facilities needed?
   - Time Sequence for construction and operation of these facilities.

2. What technical work (R&D) should we do in the immediate future (next 2-5 years)?

"Personal Opinion"

The fusion technology community (including Materials, Chamber, and PFC) should make strong contributions to answering Question 1, but we should never forget that the question of "what to do in the IMMEDIATE FUTURE" must remain a HIGHER PRIORITY.

Reasons:
Development pathways will continue to be a subject of debate for many years to come (complex technical/programmatic issue, diverse community, large funds required make external/political events dominant in determining fusion policy).

- Fusion scientists and engineers must guard against "loss of time". We must continue to produce technical progress. This progress may indeed change our planned R&D pathways to DEMO.

Technology-Led Previous Studies relevant to Questions 1 & 2 (development pathways and immediate future R&D needs)

- **Blanket Comparison and Selection Study (BCSS)**
  - 1982 - 1984
  - Led by ANL; involved many U.S. organizations
  - Involved experts on materials, blankets, fusion systems

  Output

  - Identified leading material combination systems/blanket configuration.
  - Identified key issues and near-term R&D in non-fusion facilities.

- **FINESSE**
  - 1983 - 1987
  - Led by UCLA; involved many U.S. organizations; heavy international participation (scientists and engineers from Europe and Japan physically "on-site" working with U.S. experts).
  - Involved experts in materials, blankets, PFC, tritium, plasma physics systems, facilities.
  - Involved experts from other fields (fission, aerospace).
  - Involved universities, national labs (plasma physics and technology labs), and industry (heavy participation).

Technology-Led Previous Studies (cont'd)

FINESSE Approach (see Appendix B to this presentation)

- Unique approach designed to eliminate "politics" and "pre-determined bias"
- Started by identifying, understanding, and characterizing key issues
- It proceeded to determine the "testing issues"
- Then, the requirements and characteristics of facilities were identified
- Feasibility of performing tests in existing facilities were evaluated. Role of existing facilities and needed new facilities were defined
- Detailed R&D plans to provide data to construct the "first test module" in a fusion experimental facility were developed.
- Possible candidates for Fusion Technology Test Facility were compared (mirrors, various versions of tokamaks)

A STUDY OF THE ISSUES AND EXPERIMENTS FOR FUSION NUCLEAR TECHNOLOGY

OVERVIEW

BLANKET ENGINEERING

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The operating environment to be experienced by the nuclear components of a fusion reactor is unique and leads to a number of new phenomena and effects. New experimental knowledge is necessary to resolve many of fusion's remaining issues. Investigation of the required experiments reveals the importance of simulating multiple interactions among physical elements of components and combined effects of a number of operating environmental conditions. Some experiments require neutrons not only as a source of radiation damage effects but as a practical economical means for bulk heating and producing specific nuclear reactions.

The evaluation of required facilities suggests important conclusions. Present fission reactors and accelerator-based neutron sources are useful and their use should be maximized worldwide, but they have serious limitations. Obtaining adequate data for fusion nuclear technology over the next 15 years requires a number of new nonneutron test facilities in addition to the use of fission reactors. Experiments in the fusion environment will then be required for integrated tests and concept verification. The key nuclear needs for a fusion facility are 20 MW of deuterium-tritium fusion neutron power over 10 m^2 of experimental surface area with long (~1000 s) plasma burn and 2 to

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10 MW·yr/m² fluence capability. Fusion test devices with fusion power >100 MW are shown to be undesirable because of high cost and high risk. The analysis favors fusion devices that are able to operate at low total power and high power density. For fusion devices with large minimum power, e.g., conventional tokamaks, results indicate strong incentives for two separate test devices: one for plasma physics experiments and the other for fusion engineering research experiments.

I. INTRODUCTION

Fusion is one of a very limited number of options for a renewable energy source that can sustain an industrial society for a long period of time. Bringing the attractive potential of fusion into realization requires challenging advances in science and technology. Many critical advances are required in the area of fusion nuclear technology.

A fusion energy system consists of plasma, plasma support components (magnets, vacuum, auxiliary heating), and nuclear components. The primary functions of the nuclear components are

1. fuel generation and processing
2. energy extraction and conversion
3. radiation protection of personnel and components.

The primary nuclear components and other components affected by the nuclear environment are shown on Table I. Most of the world effort on fusion over the past three decades has focused on plasma physics research and plasma confinement experiments. The technical progress to date in plasma confinement has been excellent. Some progress has also been made in plasma-supporting technologies as needed for the plasma confinement experiments. In contrast, the resources devoted to fusion nuclear technology research and development (R&D) in the world fusion program have been very limited.

The promise of fusion is so great that a comprehensive and accelerated R&D program is necessary to permit a quantitative judgment of the potential of fusion as a viable, practical, and attractive energy source. Nuclear technology is a critical element in such a program since it has many of fusion's remaining unresolved issues. These issues relate to (a) feasibility, a primary acceptance criterion for the scientific and technological communities; (b) economics, a primary acceptance criterion for the utility industry; and (c) safety and environmental impact, a crucial acceptance criterion for the public.

The development of fusion nuclear technology is particularly challenging for several reasons.

1. The technical complexity of the issues poses a high degree of intellectual challenge requiring advances in several disciplines of science and engineering that are at the forefront of knowledge. These disciplines include materials science, chemistry, nuclear physics, thermodynamics, fluid mechanics, electromagnetics, magnetohydrodynamics (MHD), nuclear engineering, mechanical engineering, and chemical engineering.

2. Fusion nuclear development appears to be relatively expensive, primarily because neutrons are required in many key experiments.

3. Long lead times will be required to perform the necessary experiments and obtain an adequate data base.

4. New and sophisticated experimental facilities are required. Presently available experimental facilities provide important information, and there is a clear need to continue to use them. However, they are not sufficient to satisfy all the testing needs. In particular, the unique and complex fusion environment can be obtained only in a fusion facility. The characteristics, cost, benefits, and risks of such a facility require careful evaluation as part of the overall plan for fusion development.

Because of the importance of fusion nuclear science and technology, the U.S. Department of Energy/Office of Fusion Energy (DOE/OFE) initiated a new study[1] called FINESSE in November 1983. The general objective of FINESSE is to investigate the technical and programmatic issues in the R&D of fusion nuclear science and technology. The study is led by the University of California, Los Angeles and

TABLE I

Nuclear Components and Other Components Affected by the Nuclear Environment

Blanket
Shield
Plasma interactive and high heat flux subsystems
First wall
Impurity control
rf antennas, launchers, and waveguides
Tritium and vacuum systems
Instrumentation and control
Magnets
Remote maintenance
Heat transport and power conversion

SPECIAL TOPIC

TECHNICAL ISSUES AND REQUIREMENTS OF EXPERIMENTS AND FACILITIES FOR FUSION NUCLEAR TECHNOLOGY

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ABSTRACT. The technical issues, development problems and required experiments and facilities for fusion nuclear technology have been investigated. The results have been used to develop a technical framework for a test plan that identifies the role, timing, characteristics and costs of major experiments and facilities. A major feature of this framework is the utilization of non-fusion facilities over the next 15 years, followed by testing in fusion devices beyond about the year 2000. Basic, separate effect and multiple interaction experiments in non-fusion facilities will provide property data, explore phenomena and provide input to theory and analytic modelling. Experiments in fusion facilities can proceed in two phases: (1) concept verification and (2) component reliability growth. Integrated testing imposes certain requirements on fusion testing device parameters; these requirements have been quantified. The nuclear subsystems addressed in the study are: (a) blanket and first wall; (b) tritium processing system; (c) plasma interactive components; and (d) radiation shield. The two generic classes of liquid and solid breeder blankets have significant engineering feasibility issues, and new experimental data must be obtained before selection of an attractive design concept. Liquid metal blanket issues are dominated by problems related to momentum, heat and mass transfer, which can be addressed in non-neutron test facilities. Solid breeder blanket issues are, however, dominated by the effects of radiation, including heating, transmutation and damage, which can be reasonably addressed in fission reactors. The tritium processing uncertainties are primarily related to the control and recovery systems, and most can be addressed in existing and planned non-neutron facilities. A dominant feature of plasma interactive components is the strong interrelation to both plasma physics and nuclear technology. Required facilities include thermomechanical test stands and confinement devices with sufficiently long plasma burn. The radiation shield poses no feasibility issues, but improved accuracy of predictions will reduce design conservatism and lower costs.

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Some Key Conclusions from FINESSE

- FNT in a fusion environment will have a number of new phenomena and effects.
  - "Investigation of the required experiments reveals the importance of simulating multiple interactions among physical elements of components and combined effects of a number of operating environmental conditions. Some experiments require Neutrons not only as a source of radiation damage effects, but as a practical economical means for BULK HEATING and producing specific nuclear reactions."
- Non-fusion facilities (non-neutron test stands, fission reactors and accelerator-based neutron sources) are useful and their use should be MAXIMIZED worldwide.
  - But they have serious limitations.
- Experiments in the fusion environment will be REQUIRED for integrated tests, concept verification, and reliability growth.
- FNT fusion testing requires 20 MW of DT fusion power over $10m^2$ of experimental surface area with long (>1000s) plasma burn. [Note: Engineering scaling rules were also developed.]
- For fusion devices with large minimum power, e.g. tokamaks, results indicate strong incentives for TWO SEPARATE test devices:
  - One for plasma physics (burn) experiments
  - The other for fusion engineering research experiments

  [Note: Several design options for fusion engineering research facilities were proposed and compared by physicists and engineers.]

<u>VNS Studies</u>

<u>Historical Background</u>

- The subject of Fusion Engineering Research Facilities remained of considerable interest to physicists and engineers. (Several names, e.g. FERF, TDF,…)
- In the beginning of ITER-CDA (1988), there was discussion about 3 world facilities (ITER, VNS, IFMIF) in Europe, Japan, and the U.S.
- In 1991, Dr. Paul Reubet, the Director of JET (and later the Director of ITER-EDA) published a paper that advocated Fusion R&D pathways that involved 3 facilities (ITER, VNS, and IFMIF).
- In the beginning ITER-EDA (1992), Dr. Masaji Yoshikawa (President of JAERI) suggested the name of Volumetric Neutron Source (VNS) in order to avoid misunderstanding of it's mission relative to ITER (ITER tests superconducting magnet technology, plasma heating technology, etc.).
- In 1993, a group of 12 of the most senior physics and technology leaders of the U.S. fusion programs deliberated at several meetings and decided to make a proposal to Dr. Martha Krebs (New Director of ER) for the U.S. to take the lead on constructing VNS (with Japan and the E.U. building ITER). Dr Krebs was very supportive.

  - All of a sudden, one influential U.S. manager asked the group to halt the VNS discussion because it might negatively affect ITER.

- In early 1994, IEA decided to initiate a study on VNS. It was called HVPNS.

IEA Study on VNS
High-Volume Plasma-Based Neutron Source

- In early 1994, the International Energy Agency (IEA) initiated an international study on a High-Volume Plasma-Based Neutron Source (HVPNS) for fusion first wall/blanket development. [Based on request and approval by the official heads of the world fusion programs.]
- The study team included physicists, engineers, and material experts from Europe, USA, Japan, and Russia. [Abdou was asked to lead the study.] Many of these participants were leading experts on FNT testing and the key leaders of the ITER Technology Testing Program.
- The study followed an excellent technical approach, proceeding from key technical issues, to non-fusion facility tests, to requirements on fusion testing, to evaluating and comparing several development pathways.
- Perhaps the most important and long-lasting benefits of the study were 1) a real critical assessment of reliability/availability that revealed critical concerns and 2) discovering the critical role that reliability growth and availability will play in a fusion development pathway, and the type and schedule of facilities to reach successful DEMO.

Key Conclusions from IEA Study on VNS

(Please see the HVPNS article in Fusion Technology. Conclusions are on pages 38-40. The following pages are reproductions of parts of these conclusions.)

VIII.B Role (and Limitations) of Non-Fusion Facilities

Non-fusion facilities provide a cost-effective approach to performing single- and multiple-effect tests. Hence, they play an important role in providing basic data, screening of blanket concepts, and establishing the infeasibility of some blanket concepts, prior to performing the more complex and expensive fusion tests. However, the engineering feasibility of blanket components cannot be established prior to extensive testing in the fusion environment. None of the critical issues can be fully resolved by testing in non-fusion facilities alone. Non-neutron test stands, fission reactors, and accelerator-based neutron sources (including the D-Li source) are unable to simulate the multiple effects of the fusion environment, and they cannot provide adequate space to test articles with relevant material combinations, configurations, and dimensions.

VIII.D Blanket Failures and DEMO Availability

With regard to blanket failures and DEMO availability, the following can be stated.

1. Availability analysis reveals critical concerns in fusion power development; some of these concerns can be addressed by changes in blanket and machine design, but most must be addressed by extensive testing to realize the DEMO availabilty goals and to address critical questions concerning the practicality and economics of tokamak power systems. For a DEMO reactor availability goal of 50%, the blanket availabilty must be ~80%. The mean time to replace (MTTR) or recover from a failure and MTBF are the parameters that directly affect availability. Shorter MTTR lowers the required MTBF to achieve a given availability goal. For MTTR=3 months, the blanket MTBF must be >1.0 FPY; i.e., only one failure anywhere in the blanket is allowed for about every 1 yr of operation. For a blanket that has 80 modules, the corresponding MTBF per module is 80 FPY. These are very ambitious goals. Experience from non-fusion technologies shows that achieving such long MTBFs requires very extensive testing and development.

2. Some of the important conclusions regarding failure modes, failure rates, and reliability growth testing are:
   a. The capability of replacing the FW/B in as short a time as possible must be a design goal for fusion devices.
   b. Design concept selection and improvement for FW/B must aim at improving reliability (e.g. minimize welds, brazes, joints, and total tube length).
   c. A serious reliability/availability analysis must be an integral part of the design process.
   d. Research and development programs must be based on quantitative goals for reliability (type and number of tests, test duration, and prototypicality).
   e. Reliability growth/demonstration testing in fusion devices will be the most demanding, particularly on the number of tests and the time duration of tests (>10m^2 and ~6MW· yr/m^2 for blankets).
   f. Reliability testing should include identification of failure modes and effects, aggressive iterative design/test/analyze/fix programs aimed at improving reliability, and the obtainment of failure rate data sufficient to predict MTBF.

VIII.E ITER-ALONE SCENARIO

With regard to the ITER-alone scenario, the following can be stated.

1. As presently envisaged, ITER alone cannot satisfy the FNT fusion testing requirements listed earlier because of pulsed operation with a low duty cycle, low fluence, a short continuous operating time, low device availability, and a small number of blanket testing ports.

2. For the presently envisaged ITER strategy based on EPP with a fluence of 1 MW · yr/m^2 and 10m^2 (to be checked) of test area, blanket tests in ITER alone enable DEMO blanket concept performance verification but cannot demonstrate a blanket system availability in DEMO higher than 4%.

3. In addition to the high risk to DEMO, an ITER-alone strategy will result in long delays in the commitment to DEMO construction. The development schedule to DEMO becomes problematic.

VIII.F SCENARIOS with HVPNS

With regard to scenarios with HVPNS, the following can be stated.

1. A DEMO availability of >30% can be demonstrated by adding blanket tests in a HVPNS characterized by the following parameters: average neutron wall load of 1 to 2 MW/m^2, maximum neutron fluence ≥6 MW · yr/m^2, testing space at the first wall ≥10m^2, and device availability >25%.

2. Presentations made to the study participants during the phase I effort on candidate HVPNS concepts seem to show that an attractive design envelope for HVPNS exists. A small size (R<2m) tokamak with normal-conducting TFCs and a driven (Q ~ 2 to 3) steady-state plasma meets the FNT testing requirements with a capital cost expected to be <25% that of ITER. (The design of HVPNS was outside the scope of phase I. Presentations were made by volunteers from the United States, the European Union, and the Russian Federation. The study participants did not address the specifics of any design.)

3. An effective path to fusion DEMO involves two parallel fusion facilities: (a) ITER, to provide data on plasma performance, plasma support technology, and system integration, and (b) HVPNS, to test, develop, and qualify fusion nuclear components and material combinations and to demonstrate an acceptable MTTR for DEMO.

4. A testing strategy employing such an HVPNS would decisively reduce the high risk of initial DEMO operation with a poor blanket system availability and would make it possible, if operated parallel to ITER BPP, to meet the goal of DEMO operation by the year 2025.

VIII.F SCENARIOS with HVPNS (cont'd)

5. With an ITER/HVPNS strategy, blanket tests in ITER BPP are still very important for fusion scoping tests requiring lower fluence, short-term performance tests, and testing large blanket modules up to the size of a segment at low fluence.

6. The contribution of blanket tests in the presently envisaged ITER EPP to the reliability testing is very small compared with that obtainable in HVPNS. If HVPNS is operated parallel to the ITER BPP, several scenarios for better utilization of the ITER EPP can be envisaged and should be studied further. An example is the use of HVPNS testing information to construct a hot DEMO-type breeding blanket on ITER after the end of BPP to operate the second phase (EPP) of ITER in a pre-DEMO mode.

7. The parallel path strategy with ITER at large fusion power, low fluence, and VNS at low fusion power and high fluence reduces the tritium consumption and external supply problem to an acceptable level.

8. A scenario with HVPNS parallel to ITER (BPP) provides cost savings in the overall R&D toward DEMO compared with an ITER-alone strategy. The near-term cost burden is small in the context of an international fusion program with HVPNS and ITER sited in two different countries.

<u>Key Points from IEA-HVPNS Conclusions</u>

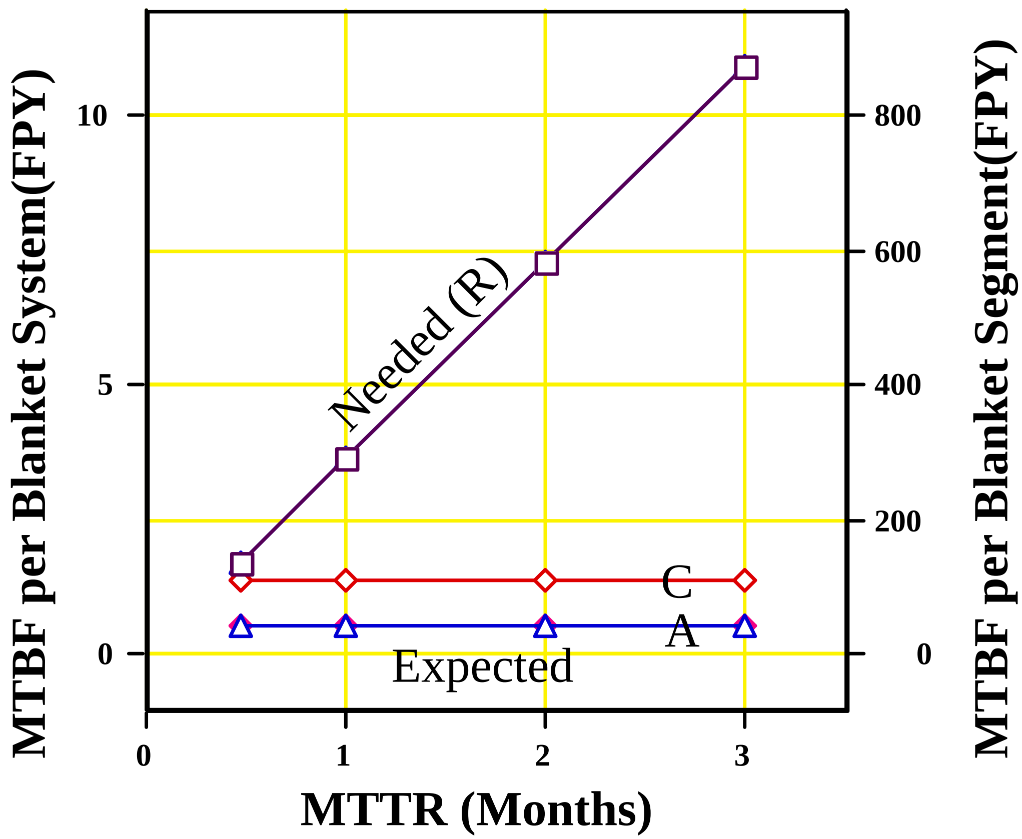
- Non-Fusion Testing is important, cost effective.
- However, extensive blanket testing in a FUSION DEVICE is REQUIRED

  "The engineering feasibility of blanket concepts cannot be established prior to extensive testing in the Fusion Environment."
- Availability analysis reveals critical concerns in Fusion Power Development.
- Reliability growth/demonstration testing in fusion devices will be the most demanding, particularly on the number of tests and time duration of the tests.
- Reliability testing should include identification of failure modes and effects and aggressive iterative design/test/analyze/fix programs
- An ITER alone scenario (with blanket tests only in ITER) can <u>not</u> demonstrate blanket availability in DEMO higher than 4%.
- HVPNS is required prior to DEMO
- HVPNS parallel to ITER actually reduces the overall R&D cost toward DEMO compared with an ITER-alone strategy.
- Timely HVPNS "reduces the tritium consumption and external supply problem in fusion development pathways to an acceptable level.
- Attractive design options for HVPNS exist.

R=Required

A = Expected with extensive R&D
(based on mature technology and no fusion-specific failure modes)

C = Potential improvements with aggressive R&D



The reliability requirements on the Blanket (in current confinement concepts that have long MTTR > 1 week) are most challenging and pose critical concerns. These must be seriously addressed as an integral part of the R&D pathway to DEMO.

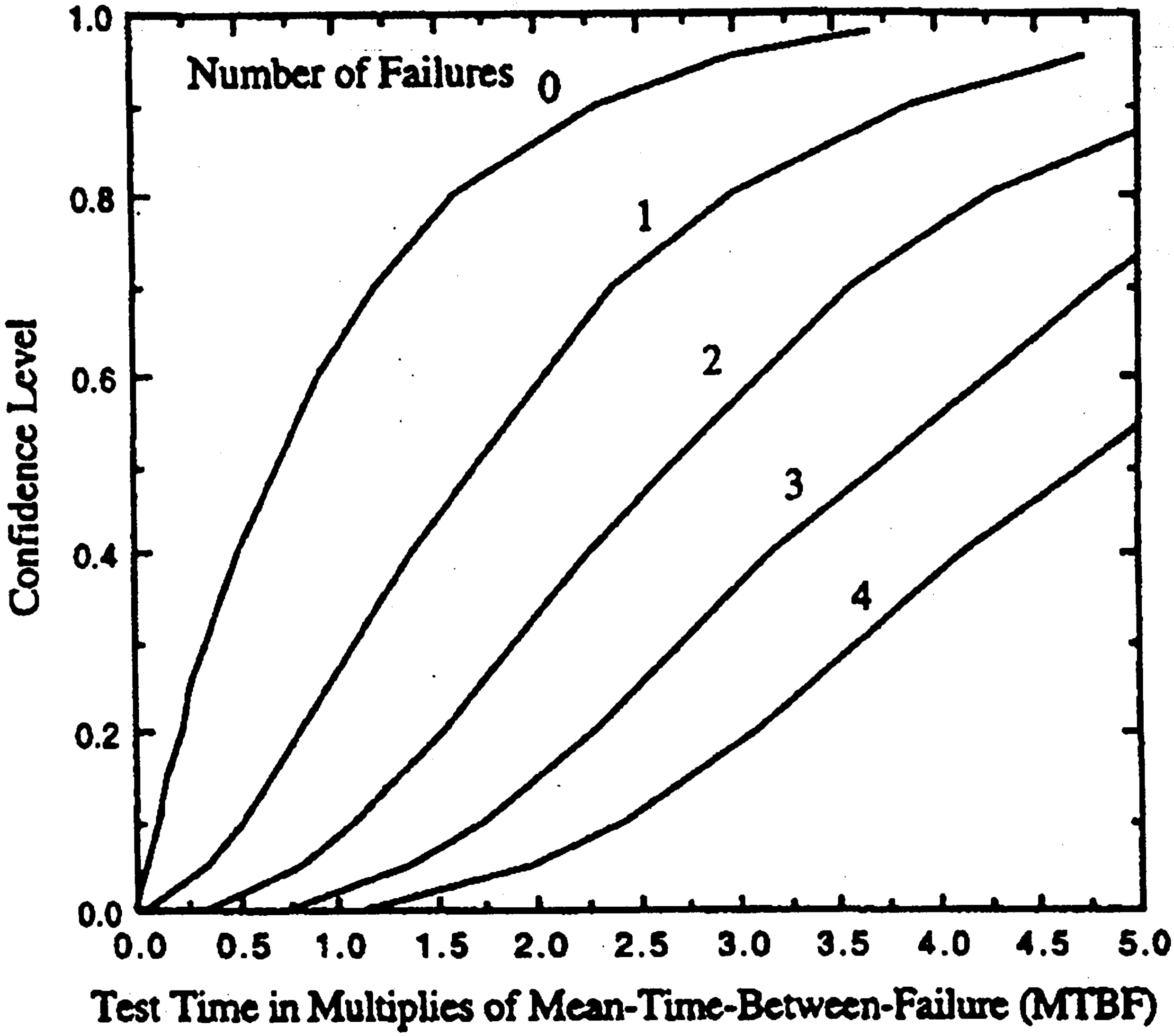


Fig. 7. Upper statistical confidence level as a function of test time in multiples of MTBF for time-terminated reliability tests (Poisson distribution). Results are given for different numbers of failures.

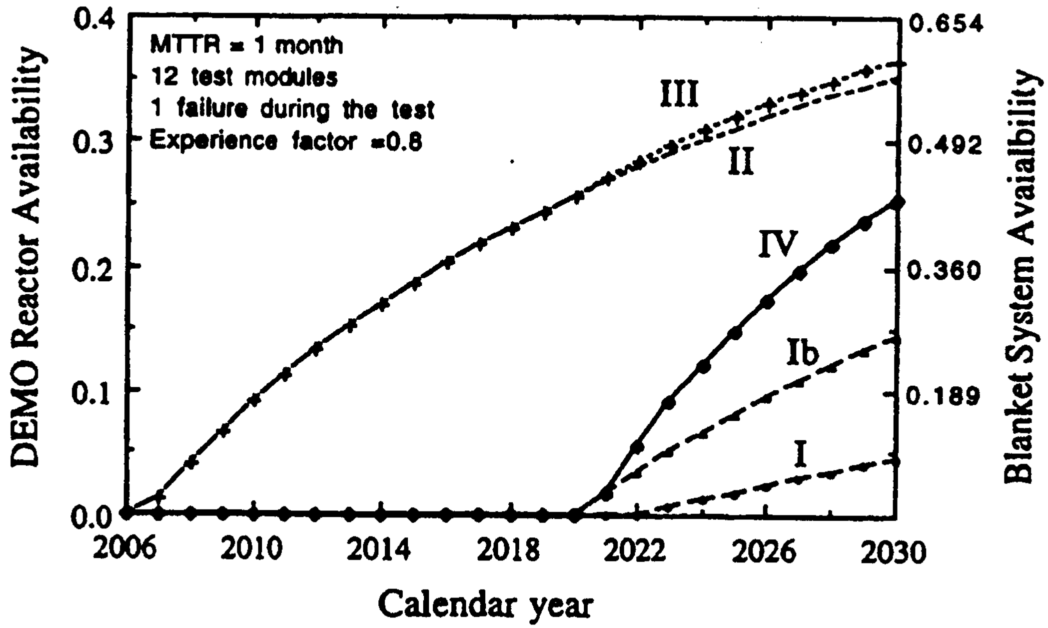


Fig. 9. The DEMO reactor availabilities obtainable with 80% confidence for different testing scenarios, MTTR = 1 month (scenario I is ITER only; scenario II is ITER BPP + VNS; scenario III is ITER + VNS; scenario IV is ITER + delayed VNS; and scenario Ib is ITER only, high fluence).

TABLE XXVII

Summary of DEMO Reactor Availability (%) Obtainable with 80% Confidence Compared with Calendar Year in the Various Scenarios*

Scenario	MTTR = 1 week[a]			MTTR = 1 month		
	2013	2018	2025	2013	2018	2025
I: ITER alone	0	0	7.1	0	0	1.8
II. ITER (BPP) + VNS	42.3	47.4	53.8	15.2	23.1	31.0
III: ITER(BPP + EPP) + VNS	42.3	47.4	54.5	15.2	23.1	31.9
IV: ITER + delayed VNS	0	0	37.5	0	0	14.8
Ib: ITER alone (high fluence)	0	0	25.2	0	0	8

*There are 12 test modules, one failure during the test, and an experience factor = 0.8.
[a]MTTR = mean time to repair.