

REQUIREMENTS AND DESIGN ENVELOPE FOR A VOLUMETRIC NEUTRON SOURCE (VNS) FUSION FACILITY FOR FUSION NUCLEAR TECHNOLOGY DEVELOPMENT

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Abstract

REQUIREMENTS AND DESIGN ENVELOPE FOR A VOLUMETRIC NEUTRON SOURCE (VNS)
FUSION FACILITY FOR FUSION NUCLEAR TECHNOLOGY DEVELOPMENT.

The paper shows that timely development of fusion nuclear technology (FNT) components, e.g. blanket, for DEMO requires the construction and operation of a fusion facility parallel to ITER. This facility, called VNS, will be dedicated to testing, developing and qualifying FNT components and material combinations. Without VNS, i.e. with ITER alone, the confidence level in achieving DEMO operating goals has been quantified and is unacceptably low (< 1%). An attractive design envelope for VNS exists. Tokamak VNS designs with driven plasma ($Q \sim 1-3$), steady state plasma operation and normal copper toroidal field coils lead to small sized devices with moderate cost.

1. INTRODUCTION

Most major world fusion program plans call for a DEMO by about the year 2025. Therefore, a database satisfactory for the engineering design must be available by the year 2015. The success of DEMO in demonstrating the potential safety and environmental advantages of fusion as well as satisfactory economics and reliability depends largely on the successful development of fusion nuclear technology. A study, called VENUS [1, 2], in the U.S. with collaboration of Russian scientists and engineers, has evaluated the R&D needs for construction and operation of Fusion Nuclear Technology (FNT) components for DEMO. The evaluation emphasized the need for and role of facilities. The FNT issues and types of testing were evaluated. The role and limitations of non-fusion facilities were investigated. The results showed a

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definite necessity for substantial testing in the fusion environment. The FNT requirements for fusion testing were then quantified. Component failures and reliability testing were found to be particularly demanding.

The study then evaluated several scenarios for fusion facilities between now and DEMO. Quantitative measures of risk, cost, and time schedule were developed and utilized. A scenario with only ITER was found to lead to an unacceptably high risk and serious and costly delays in DEMO. The need for a facility, called VNS, dedicated to FNT testing and development was clearly evident. Design concepts for VNS that best serve FNT testing needs at modest cost were investigated. An attractive design envelope for Tokamak VNS was identified.

The conclusions of this work are believed to be very important to planning the world fusion R&D programs. Because of space limitations here, only a brief summary of the important topics is provided. Further details can be found in references 1 and 2.

2. FNT ISSUES AND ROLE OF NON-FUSION FACILITIES

The critical issues for FNT and the contribution of non-fusion facilities to resolving them were evaluated. The most striking conclusion is that there is no critical issue that can be resolved by testing in non-fusion facilities alone. No significant information can be obtained from non-fusion facilities for some critical FNT issues such as identification and characterization of failure modes, effects and rates.

Of particular significance, our results show that an accelerator based d-Li neutron source of the type proposed [3] for the International Fusion Material Irradiation Facility (IFMIF) contributes only to the lifetime issue. An IFMIF type facility provides very small test space ($< 300 \text{ cm}^3$) at an equivalent neutron wall load of 1 MW/m^2 , which is suitable only for specimen irradiation tests for material science. Such tests are useful only if parallel submodule engineering tests are carried out in a VNS fusion testing facility.

A key conclusion from this evaluation is that FNT development requires fusion testing facilities.

3. TESTING REQUIREMENTS IN FUSION FACILITIES

Table 1 shows the results of the study concerning FNT requirements on major parameters for testing in fusion facilities with the goal of developing the database to construct DEMO blanket and other FNT components. Steady state plasma operation is necessary as pulsing makes it very difficult to obtain adequate testing information. The fluence requirements were carefully evaluated for the three stages of FNT testing in fusion facilities: 1) concept screening, 2) performance verification, and 3) component engineering development and reliability growth (CEDAR) testing. Stages 1 and 2 require fluences of $0.3 \text{ MW}\cdot\text{y/m}^2$ and $1\text{-}3 \text{ MW}\cdot\text{y/m}^2$, respectively. CEDAR (Stage 3)

TABLE 1. FNT REQUIREMENTS ON MAJOR PARAMETERS FOR TESTING IN FUSION FACILITIES, WITH EMPHASIS ON TESTING NEEDS TO CONSTRUCT DEMO BLANKET

Parameter	Value
Neutron Wall Load, MW/m ²	1-2
Plasma Mode of Operation	Steady State
Minimum Continuous Operating Time (i.e. test campaign periods with 100% availability), Weeks	1-2
Neutron Fluence (MW•y/m ²) at Test Module	
Stage I: Scoping	0.3
Stage II: Concept Verification	1-3
Stage III: Component Engineering Development and Reliability Growth	4-6
Total Neutron Fluence for Test Device, MW•y/m ²	>6
Total Test Area, m ²	>10

is the most demanding and was evaluated in detail. Based on this, it is found that fluence of ~4-6 MW•y/m² and a test area at the first wall > 10 m² are required for engineering development and reliability growth.

4. DEMO GOALS, FAILURES AND RELIABILITY TESTING

Based on previous DEMO studies and industry/utility requirements the DEMO should have steady state plasma operation, 2-3 MW/m² wall load, self-sufficient fuel cycle, thermal conversion efficiency > 30% and reactor availability > 60% (i.e. plant availability > 50%). Availability allocation studies [4] show that a blanket system availability of 98% must be achieved in order to realize DEMO reactor availability of 60%. Our investigation shows that this goal 1) is most demanding on fusion testing requirements, particularly fluence

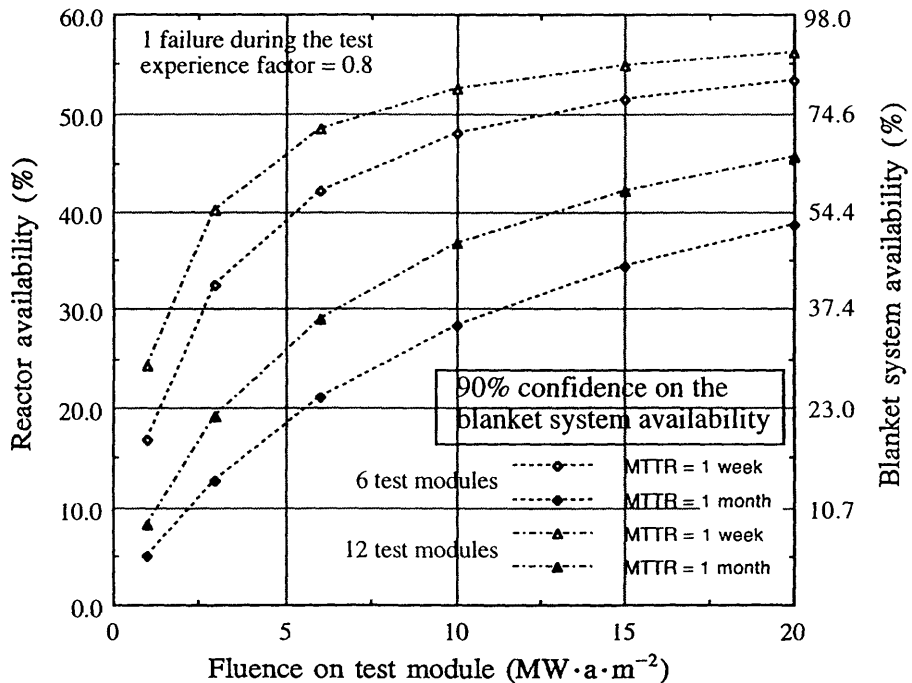


FIG. 1. Achievable DEMO reactor and blanket system availability as a function of fluence on test module. Results are given for two values of the number of test modules (6 and 12) and two values of the reactor downtime to replace a failed blanket module (MTTR = 1 week and MTTR = 1 month).

and number of test modules, and 2) will be the most difficult to achieve because of large uncertainties regarding failure modes and rates in a blanket in the fusion environment.

We calculated the mean lifetime between failure (MTBF) for the blanket required to achieve a given availability goal for DEMO. Unfortunately, there is presently no data on failure rates in blankets since none was ever tested in fusion reactors. We analyzed failure rate data from steam generators and fission reactors and derived an upper limit on the expected MTBF in fusion blankets of 0.01–0.2 years. In contrast, the MTBF values required to achieve DEMO availability of 60% range from 1–10 years for the entire blanket. The results are alarming and indicate that achieving DEMO availability of 60% will be extremely difficult. Failure modes and rates are critical areas for blanket development.

CEDAR testing in the fusion environment prior to DEMO is crucial in order to achieve reasonable availability. Figure 1 shows the achievable DEMO blanket and DEMO reactor availability's as a function of fluence on test modules. The results are given for 6 and 12 test modules and MTTR = 1 week

and 1 month. The results show that 1) it will be extremely difficult to achieve 60% DEMO reactor availability, 2) downtime to replace a failed blanket module must be < 1 week, and 3) blanket test modules must be tested for ~4-6 MW•y/m² fluence.

5. ROLE OF ITER AND NEED FOR VNS

Our evaluation shows that ITER [5] cannot satisfy the FNT fusion testing and development requirements (see Table 1) because of its: 1) pulsed operation (1000 s burn, 1200 s dwell) with low plasma duty cycle (45%), 2) low fluence (0.1 MW•y/m² in Basic Performance Phase, BPP; and 1 MW•y/m² in Extended Performance Phase, EPP), 3) short continuous operating time, and 4) time schedule.

Figure 2 shows an ITER alone scenario. The fluence at the end of 24 years of operation is not sufficient to provide reasonable confidence in DEMO blankets. However, even if this very large risk to DEMO FNT components is tolerated, an ITER alone strategy results in 17 years delay in the beginning of DEMO operation.

The total fusion power required for FNT testing is only ~20 MW but ~5 full power years of operation are needed. This leads to tritium supply requirements of < 6 kg. In contrast, ignition physics requires ~1500 MW of

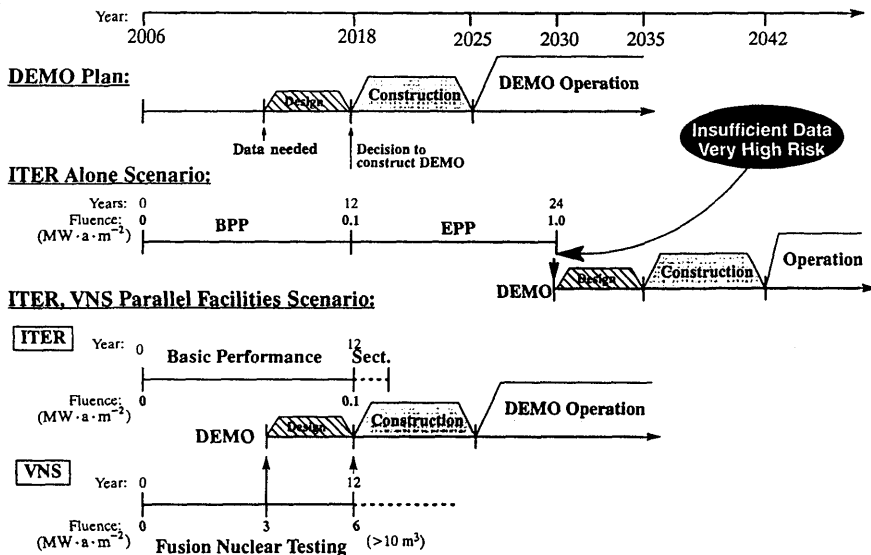


FIG. 2. Two scenarios for fusion facilities for DEMO: ITER alone, and VNS parallel to ITER.

TABLE 2. DESIGN OPTIONS FOR TOKAMAK VNS UTILIZING: (1) SUPERCONDUCTING TF COILS; (2) NORMAL CONDUCTING TF COILS WITH STANDARD ASPECT RATIO (A); AND (3) NORMAL CONDUCTING TF COILS WITH LOW ASPECT RATIO

Representative ITER parameters are also shown

	ITER	VNS		
		Super Conductor	Normal Conductor Standard A	Normal Conductor Low A
Wall Load, MW/m ²	1	1	1-2	1-2
Inboard Shield, m	1.2	0.72	0.23	0.03
Major Radius, m	7.75	4.6	1.5-1.6	0.79-0.81
Minor Radius, m	2.8	1.05	0.6	0.6
Plasma Current, MA	24	6.4	6-7.1	9.4-10.4
Toroidal Field, T	6	7.7	4.3-5.5	2-2.4
Drive Power, MW	0	140	30-46	19-29
Fusion Power, MW	1500	360	82-172	32-65
Power Consumption, MW	200	330	540-700	130-180
First Wall Area, m ²	1300	290	66-70	26

fusion power (ITER level) but only for ~10 to 15 full power days; which requires a tritium supply of < 4 kg. However, if the FNT testing mission is combined with ignition mission, operation of 1500 MW for 5 full power years requires incredibly large tritium supply of ~420 kg. The cost is several billion dollars and such tritium quantities are not actually available.

We conclude that two parallel facilities should be constructed and operated in parallel:

- (a) ITER for plasma operation, plasma support technology, and system integration (except blanket);
- (b) VNS, a driven plasma small size device to test, develop, and qualify fusion nuclear technology and materials for DEMO.

The ITER/VNS parallel facilities path is the only scenario that allows DEMO operation by the year 2025. With ITER alone, the confidence level is < 1% but with VNS, the confidence level is ~60%.

6. DESIGN OPTIONS

Design options for tokamak VNS were explored as shown in Table 2. Small size tokamaks ($R < 2$ m) with driven ($Q \sim 1-3$) steady state plasma and normal copper TF coils provide attractive options for VNS. The surface area of the first wall is a factor of 20 smaller than ITER. The cost of VNS is < 25% of ITER. The ITER/VNS scenario provides a net saving in the total R&D cost to DEMO.

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DISCUSSION

D.D. RYUTOV: For a neutron flux of 1.5 MW/m^2 and fusion power of 100 MW, the tritium consumption required to accumulate $6 \text{ MW}\cdot\text{a/m}^2$ would amount to approximately 30 kg. Do you think that this amount is really available?

M.A. ABDOU: Yes, over the entire operating period of ~ 12 years, in order to accumulate $6 \text{ MW} \cdot \text{a}/\text{m}^2$. Let me mention two other points: (1) the tritium supply issue is really one of the reasons you need a VNS (the idea is to keep the fusion power low and run for high fluence); and (2) the VNS would have roughly one third of the surface area of the first wall covered by a blanket test module producing tritium.