Background Information on VNS Based on VENUS (US) Study

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VENUS Study

- DOE's Office of Fusion Energy in USA has initiated in May 1993 a new study called VENUS.
- The focus of the study is evaluation of VNS (Volumetric Neutron Source) as a dedicated facility for testing fusion nuclear components and material combinations. VNS will operate in parallel to ITER to achieve the US National Energy Strategy Goal of DEMO operation by the year 2025
- The first phase of VENUS is Concept Definition Study to
  - determine VNS requirements for fusion nuclear component and material testing
  - define an envelope of key features within which VNS must fit (size, power, duty cycle, availability, cost, etc.)
  - Identify promising design concepts for VNS that fit within the envelope
- Participating Organizations: UCLA, ORNL, LLNL and Others
- VENUS will serve as a mechanism for providing the USA technical input to International VNS activities such as IEA

Major **R&D** Tasks To Be Accomplished Prior to **DEMO**

1) **Plasma**
   - Confinement
   - Divertor
   - Disruption control
   - Current drive

2) **System Integration**

3) **Plasma Support Systems**
   - Magnets
   - Heating

4) **Fusion Nuclear Technology Components and Materials**
   [Blanket, First Wall, High Performance Divertors]
   - Materials combination selection
   - Performance verification and concept validation
   - Show that the fuel cycle can be closed
   - Failure modes and effects
   - Remote maintenance demonstration
   - Reliability growth
   - Component lifetime

ITER will address most of 1,2 and 3

Fusion Nuclear Technology (FNT) components and materials requires dedicated fusion-relevant facilities parallel to ITER.

DEMO Characteristics

A DEMO Plant is one that demonstrates dependability and reliability. The size, operation and performance of DEMO must be sufficient to demonstrate that there are no open questions about the economics of prototype/first commercial reactor.

Neutron Wall Loading	2-3 MW/m^2
Fluence	10-20 $MW.y/m^2$
Fuel Cycle	Self sufficient, demonstrate doubling time requirements
Plasma Mode of Operation	Steady state (or very long burn, short dwell)
Net Plant Availability	> 50% (Demonstrate reliability and maintainability)

Availability Requirements

- To achieve net plant availability of 50% means that :
  Availability per blanket module > 99%
- Such high availability requirements for blanket module imply that prior to DEMO, there would be aggressive development program for blanket that includes component reliability growth

Capabilities of Non-fusion Facilities for Simulation of Key Conditions for Fusion Nuclear Components Experiments

	Neutron Effects(1)	Bulk Heating(2)	Non-Nuclear(3)	Thermal/ Mechanical/ Electrical(4)	Integrated Synergystic
Non-Neutron Test Stands	no	no	partial	no	no
Fission Reactor	partial	partial	no	no	no
Accelerator-Based Neutron Source	partial	no	no	no	no

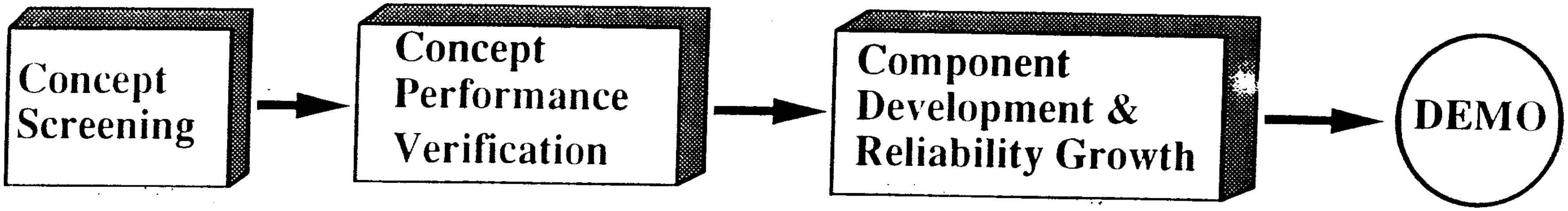
(1) radiation damage, tritium and helium production
(2) nuclear heating in a significant volume
(3) magnetic field, surface heat flux, particle flux, mechanical forces
(4) thermal-mechanical-electrical interactions (normal and off normal)

Contribution of Nonfusion Facilities to Resolving Critical Issues for Fusion Nuclear Technology

Critical Issue	Non-neutron Test Stands	Fission Reactors	Accelerator Based Neutron Sources	
			DT	d-Li
1. D-T fuel cycle self sufficiency	none	none	partial	none
2. Thermomechanical loadings and response of blanket components under normal and off-normal operation	small	small	none	none
3. Materials compatibility	some	some	none	none
4. Identification and characterizations of failure modes, effects and rates	none	none	none	none
5. Effect of imperfections in electric (MHD) insulators in self cooled liquid metal blanket under thermal/mechanical/ electrical/nuclear loading	small	small	none	none
6. Tritium inventory and recovery in the solid breeder under actual operating conditions	none	partial	none	none
7. Tritium permeation and inventory in the structure	some	partial	none	none
8. Radiation shielding: accuracy of prediction and quantification of radiation protection requirements	none	small	partial	small
9. In-vessel component thermomechanical response and lifetime	some	some	none	some
10. Lifetime of first wall and blanket components	none	partial	none	partial[a]

[a] - Partial: substantial contribution when followed by fusion test; not meaningful in the absence of fusion tests

Testing in Fusion Devices For Fusion Nuclear Development Can Be Classified Into a Number of Stages

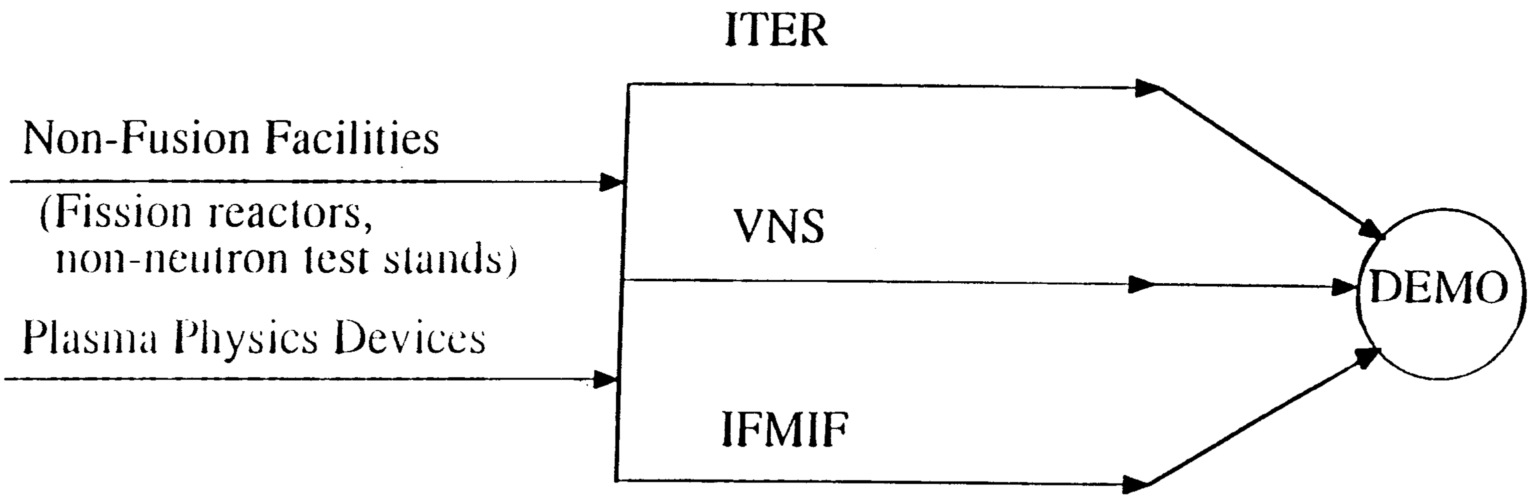


Concept Screening → **Concept Performance Verification** → **Component Development & Reliability Growth** → **DEMO**

	Concept Screening	Concept Performance Verification	Component Development & Reliability Growth
Required Fluence $MW.Y/m^2$	0.3	> 1.0	> 4 - 6
Size of Test Article	Submodules	Modules	Modules/Sectors

- Reliability Growth Testing is Most Demanding
  - Requires testing of components in real operating environment (n, γ, B, T, V)
  - Requires an aggressive design/test/fix iterative program
  - Requires many test modules and high fluence

Prudent and Optimum Path to DEMO Requires Three Parallel Facilities



<u>ITER</u>

Fusion core (plasma), system integration, plasma support technology

<u>VNS</u> [<u>V</u>olumetric <u>N</u>eutron <u>S</u>ource]

Dedicated fusion facility to test, develop, and qualify fusion nuclear technology components and material combinations [> 10 m3 test volume]

<u>IFMIF</u> ["Point" Neutron Source]

Small volume (<0.01 m3), high availability facility to address radiation effect life time issues

VNS Mission and Objectives

VNS Mission

To complement ITER as a dedicated fusion facility to test, develop and qualify those advanced fusion nuclear technology components and materials combinations that are required for DEMO operation by the year 2025.

FNT components and materials have the highest impact on the economic, environmental and safety attractiveness of fusion energy and they require extensive testing in an integrated fusion environment.

VNS Objectives

Parallel and Sequential Tests of FNT Components and Materials in Submodules, Modules and Sector in Fusion Environment
[neutrons, gamma-rays, surface heat flux, volumetric nuclear heating, magnetic field, tritium, etc.]

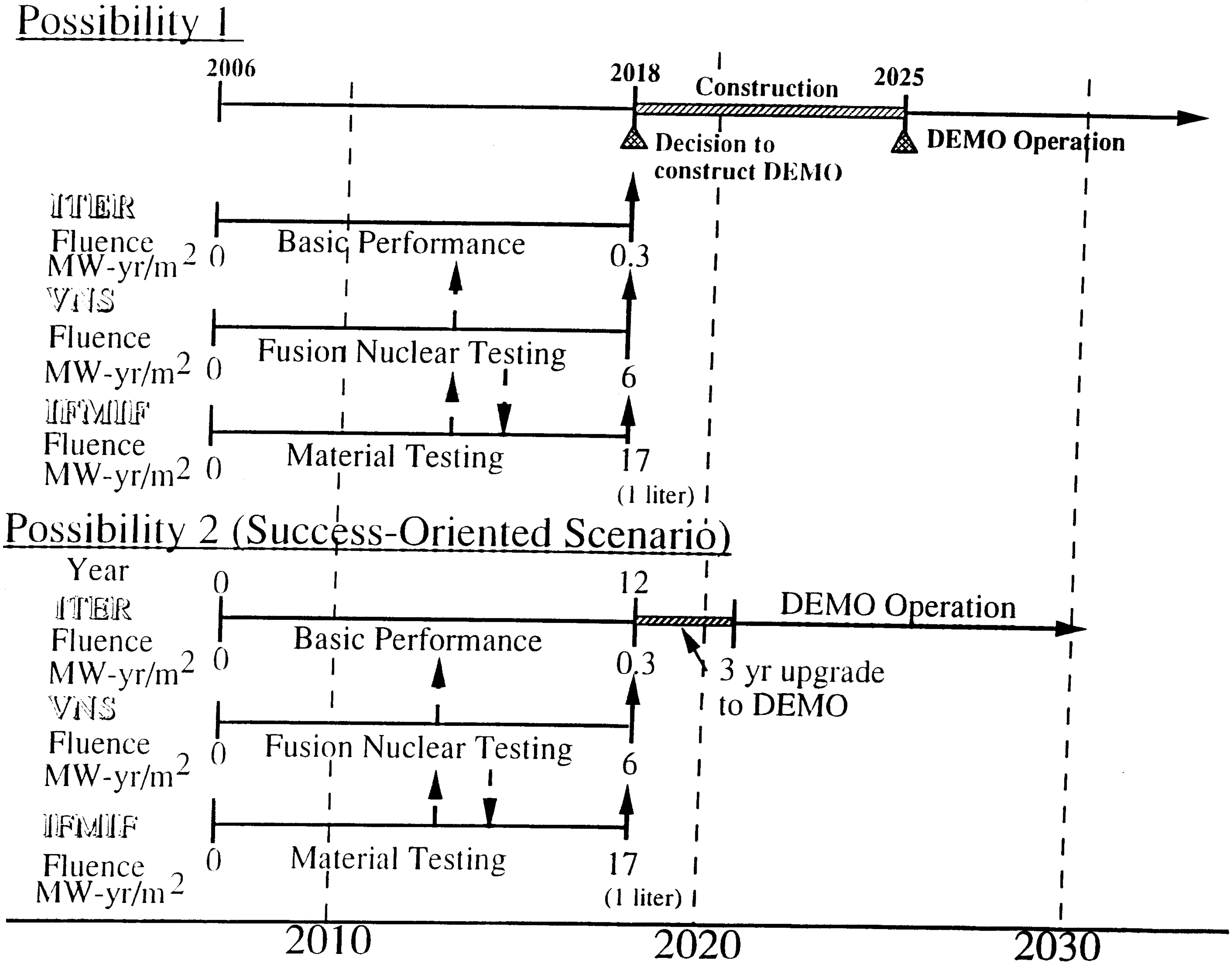
- Calibrate non-fusion tests against performance in the fusion environment
  Check/Validate Codes and Data

- Screen FNT Concepts and Material Combinations

- Performance Verification
  Select Reference Concepts
  Optimize Designs, Verify Performance
  Performance Specific Safety-Related Tests
  Response to off-normal events, operational margin

- Reliability Growth
  - Identify Failure Modes and Effects
  - Iterative design/test/fix programs aimed at improving reliability and safety
  - Failure Rate Data; Obtain Data Base sufficient to predict mean time between failure (MTBF) and component lifetime with sufficient confidence
  - Obtain data base to predict mean time to replace (MTTR) with remote maintenance
  - Obtain sufficient data to predict overall availability of FNT components in DEMO

VNS Increases Confidence in Successful Timely DEMO



Possibility 1

2006

2018

Construction

2025

Decision to construct DEMO

DEMO Operation

ITER Fluence MW-yr/m^2 0 Basic Performance 0.3

VNS Fluence MW-yr/m^2 0 Fusion Nuclear Testing 6

IFMIF Fluence MW-yr/m^2 0 Material Testing 17 (1 liter)

Possibility 2 (Success-Oriented Scenario)

Year 0 12

ITER Fluence MW-yr/m^2 0 Basic Performance 0.3

DEMO Operation

3 yr upgrade to DEMO

VNS Fluence MW-yr/m^2 0 Fusion Nuclear Testing 6

IFMIF Fluence MW-yr/m^2 0 Material Testing 17 (1 liter)

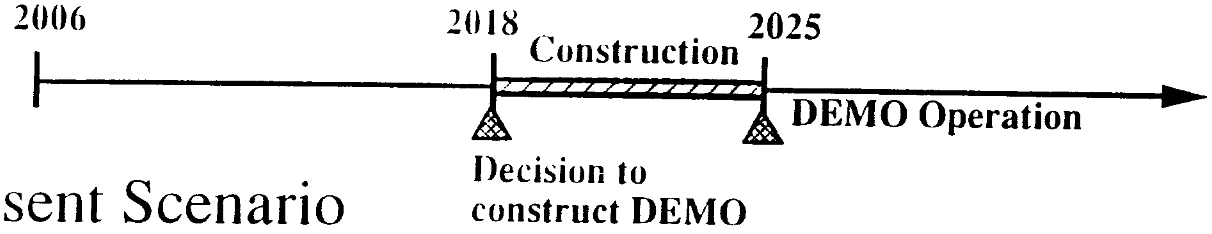
Physics and Nuclear Technology Requirements for Testing Are Very Dissimilar

	Fusion Power	Integrated Burn Time	Tritium Consumption
A. Physics and Plasma Support	3500 MW	15 days	8.0 kg
B. Fusion Nuclear Technology	20 MW	5 yr	5.6 kg

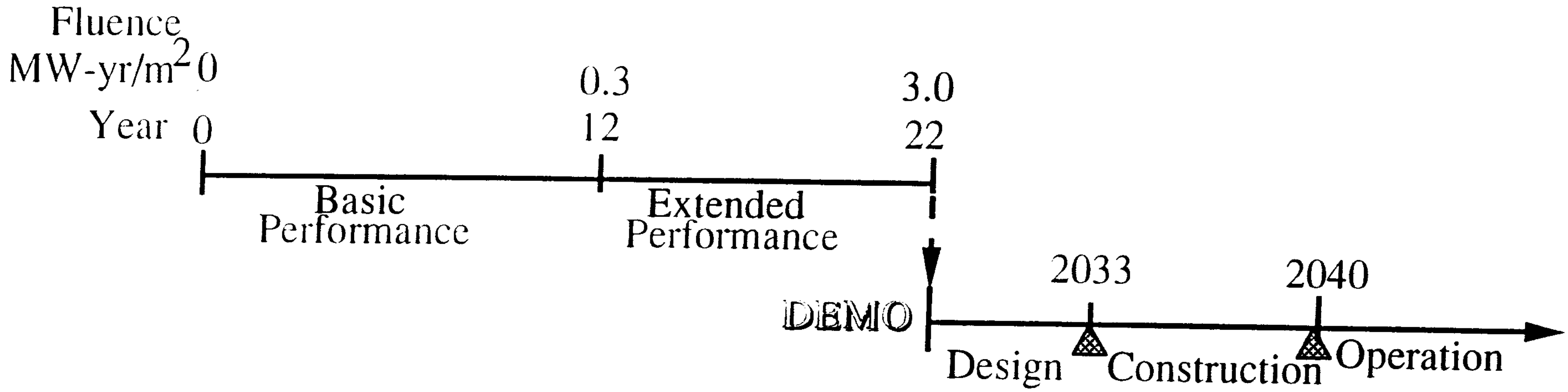
Combined * A and B	3500 MW	5 yr	976 kg

* Combining large power and high fluence leads to large tritium consumption requirements

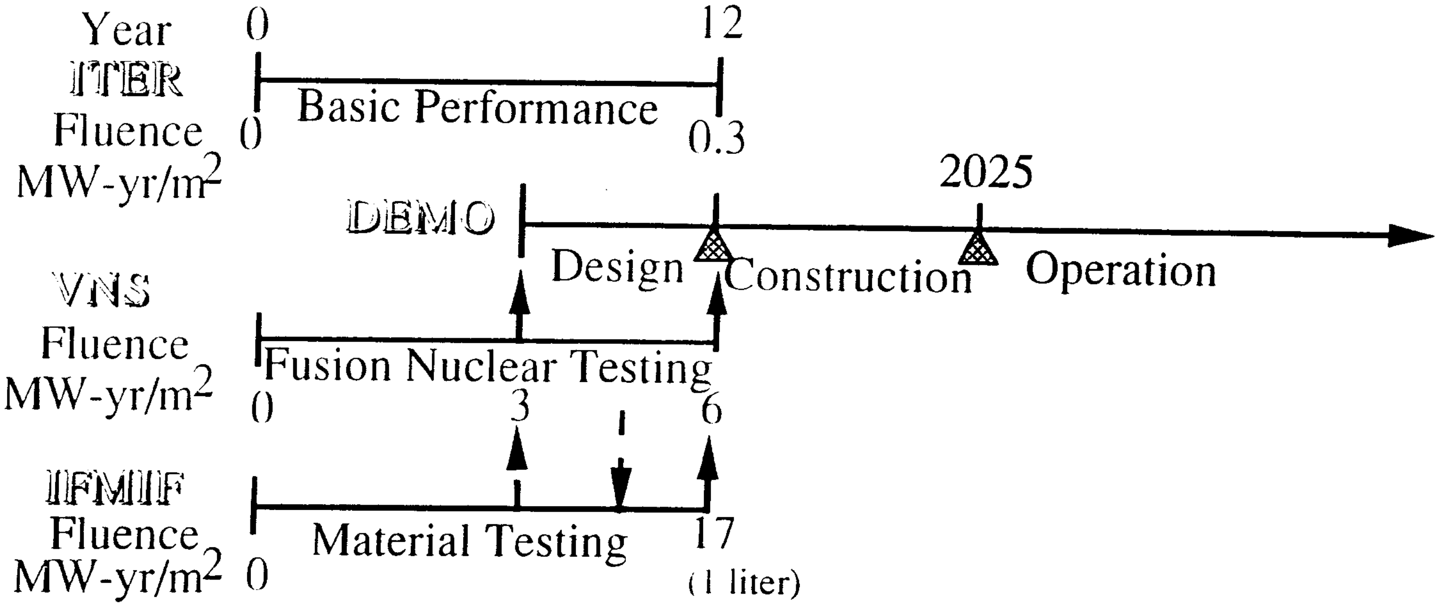
VNS Is Necessary to Meet DEMO Time Schedule



ITER Present Scenario



ITER, VNS, IFMIF Scenario (Reduced Technology Burden on ITER)



MAJOR DEVICE PARAMETERS OF FUSION FACILITIES

	ITER	**VNS**	**IFMIF***
Availability	10 %	30%	>70%
Wall Load, (MW/m^2)	2	1−2	$2^{(a)}$
Fluence @12yr, ($MW{\cdot}yr/m^2$)	0.3	6	17
Test Area [Volume)]	TBD	$>30m^2$ $[15m^3]$	$<0.02m^2$ $[0.001m^3]^{(b)}$
Cost Goal (relative units)	1	0.3	0.1

*Source: IAE Workshops (1989, 1992)

(a): 2 at 1 liter; 5 at 0.1 liter; 10^{15} n/cm^2−s; $E_n > 0.1$MeV
(b): at 2MW/m^2

VNS and IFMIF Complement Each Other

IFMIF will concentrate on lifetime neutron radiation effects in small limited volume (and limited time)

VNS will screen materials by testing material combinations in subcomponents scale with neutrons and other environmental conditions such as coolant conditions, welds, mechanical joints, effects of temperature, stress and damage gradients on large structures, clad/breeder interaction, fatigue, thermal cycling, etc.

- VNS will help IFMIF conserve space and time by screening materials based on performance of material combinations in sub-components-scale tests in integrated environment

- IFMIF will help VNS eliminate design choices with structural materials that have severely limited lifetime under neutron radiation effects.

Benefits of VNS

- Provide the fusion facility <u>needed</u> for testing, and developing nuclear components and material combinations for DEMO to adequate testing parameters (e.g. fluence). Test options for attractive economic, safety and environmental features.

- Strengthens Fusion Energy Development Plan and makes it more attractive.
  - Self consistent technical logic.
  - DEMO operation by the year 2025 is defendable.
  - Reduces risk.
  - Eliminates need for another device between ITER and DEMO.
  - VNS operation in parallel to ITER Basic Performance Phase, may enable ITER to operate as a DEMO during Second Phase (under high success-oriented scenario).
    - Fusion energy becomes nearer term option.
    - Reduce cost.
    - Keep industry and governments' interest high.

Benefits of VNS (cont'd)

- Reduce technological risk and cost to ITER
  - Reduce fluence need.
  - Eliminate need for breeding blanket during Phase 1.

- Provides additional experience in design, construction and licensing of a fusion device.

- VNS, parallel to ITER, enhances interest of the parties, particularly government's and industry's.

TABLE 1. Preliminary Testing Requirements on Key Parameters of VNS

Wall Load

- Minimum: > 1 MW/m^2
- Substantial benefits: 2–3 MW/m^2
- Much higher wall loads can be beneficial and will alter strategy (accelerated testing, more ambitious technology performance goals for fusion, etc.)

Surface Heat Load

- Critical for tests of first wall, solid breeder blankets, liquid-metal blankets
- Critical: > 20 W/cm^2
- Important: > 40 W/cm^2
- Methods to enhance surface heat flux in fusion test facilities are important

Plasma Burn Cycle

- Pulsing sharply reduces the value of many tests
- Minimum burn time: > 1000 s
- Maximum dwell time: < 100 s
- Prefer steady state

Minimum Continuous Time

- Many periods with 100% availability
- Duration of each period
  Critical: Several days
  Important: Several weeks

Availability

- Minimum: 20%
- Substantial benefits: 50%

Fluence

- Fluence requirements will depend on whether a neutron source or other means is available for high fluence material testing
- In general, component tests in the early stages of development are carried out to fluences lower than those for specimen
- In all cases, higher fluences are desirable but costly; modest fluence are still extremely valuable
- For component tests:
  Critical: 1–2 MW-yr/m^2
  Very important: 2–4 MW-yr/m^2
  Important: 4–6 MW-yr/m^2
  Desirable: 6–10 MW-yr/m

Minimum Size of Test Assembly

- Interactive tests: ~ 0.2m×0.2m×0.1m
- Integrated tests: ~ 1m×1m×0.5m

(Some liquid-metal blanket designs tend to require larger size, sector scale)

Test Surface Area

- Critical: > 5 m^2
- very important: > 10 m^2
- Important: 15–20 m^2
- Desirable: 20–30 m^2

Magnetic Field

- Critical: > 3 T
- Important: > 5 T

Test Program Phases

Basic device checkout

- achieve reliable plasma performance
- observe basic machine operation
- PIC performance characterzization

Screening test campaigns

- rapid removal and replacement capability
- increasing fluence and machine availability
- assess and reduce number of design options
- benchmark non-fusion results

Performance verification campaigns

- integrated module behavior
- modest fluence exposure (neutron effects)

Reliability growth

- identify failure modes and effects
- test/fix/improve
- statistical reliability data
- develop confidence in DEMO components

Test article types

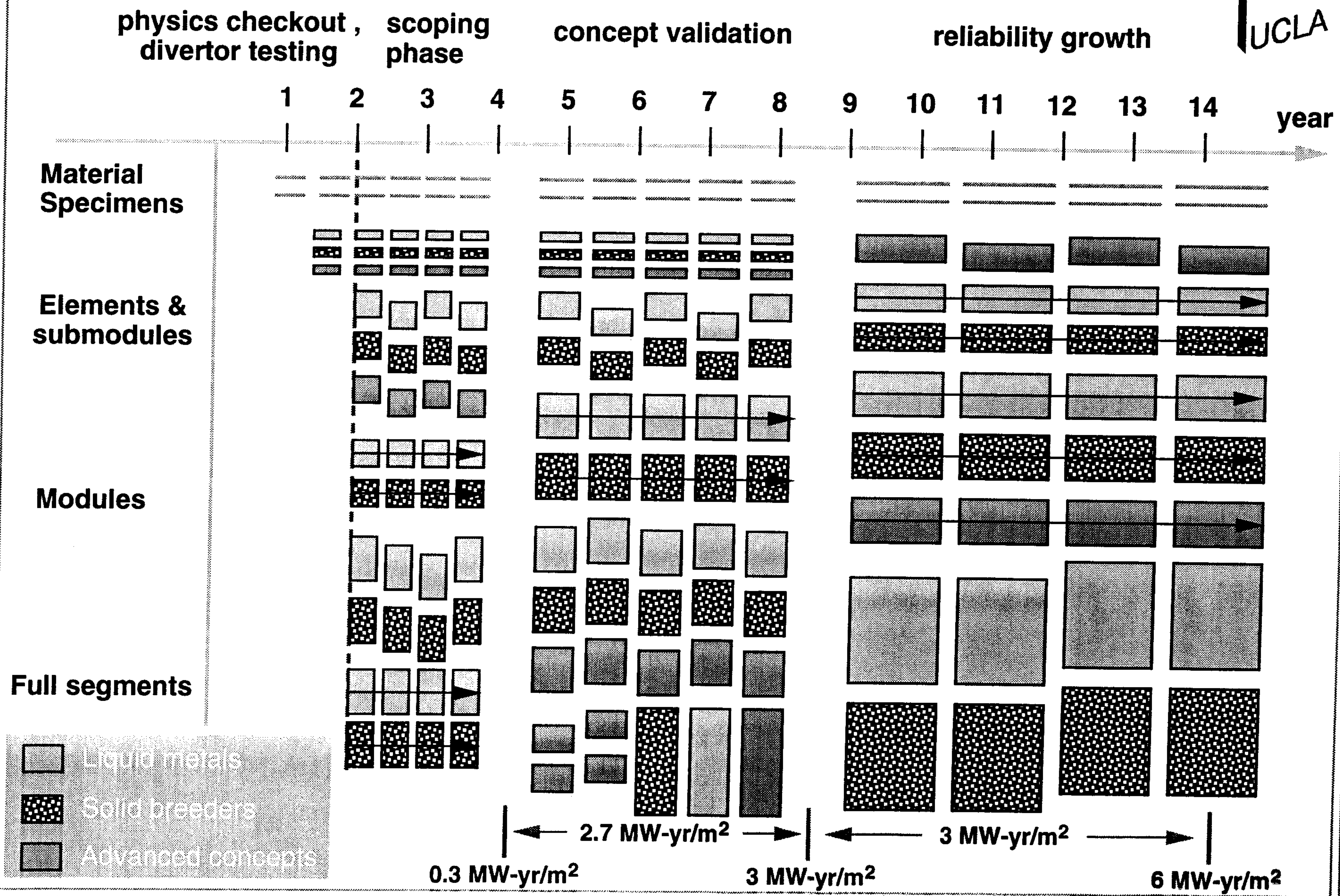
Material Specimens (1 cm × 1 cm)
- large number of coupons placed in a materials test module

Elements and Submodules (10 cm × 10 cm)
- grouped into modules with limited independent control and limited on-line instrumentation

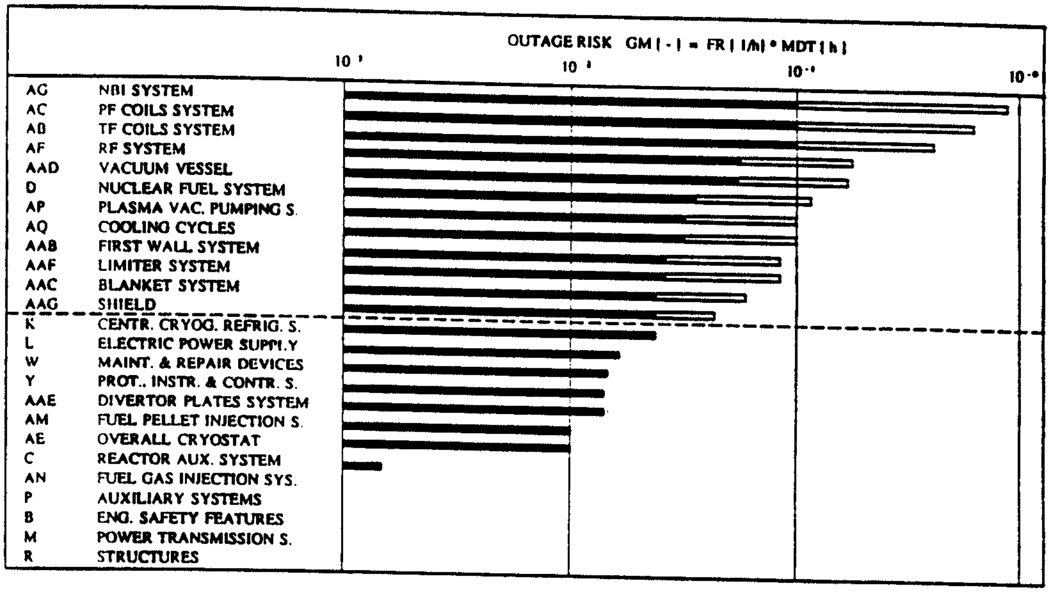
Modules (1 m × 0.5 m)
- separate services
- full prototype simulation

Segments (1 m × 5 m)
- incorporates complete reactor integration

Blanket Test Sequence for VNS Nuclear Test Facility



Achieving A High Plant Availability Requires A Very High Blanket Availability



- The outage risk is defined as, failure rate x mean down time, which gives the availability being equal to $\frac{1}{1+\text{outage risk}}$
  Plant outage risk = 0.717; Plant availability = 58%
  Blanket outage risk = 0.024 ; Blanket availability = 97.6%
- Failure rates for various components were from industrial engineering, processing engineering and nuclear power plant, etc.
- Components above line require improvement in failure rate data to achieve target values, components below line require verification of failure rate data.

Reference: R. Buende, "Reliability and Availability Issues in NET," Fusion Engineering and Design 11 (1989) 139-150

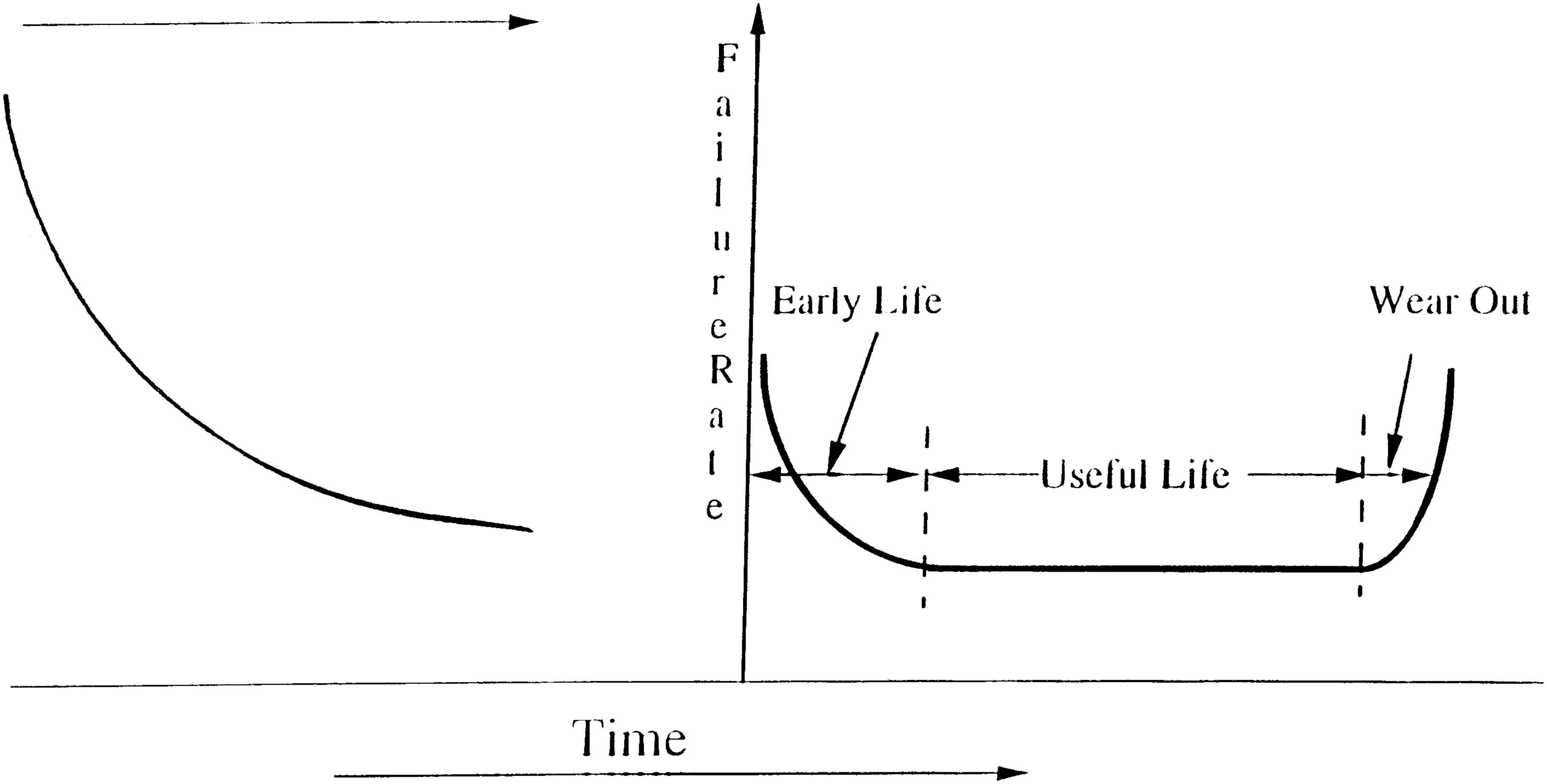
Requirements on Blanket Availability as a Function of Plant Availability

Plant Availability	Blanket Availability
75 %	> 99 %
58 %	97.6 %
55 %	90 %
51 %	80 %

Schematic Failure Rate vs Time
During Development and After Development

New Technology
Testing, R&D Phase*

Fully Developed Technology



*The curve shown is for an aggressive development program.

FAILURE IS DIFFERENT FROM DESIGN LIFETIME

Definition

Failure is defined as the ending of the ability of a design element to meet its function before its allotted lifetime is achieved, i.e. before the operating time for which the element is designed is reached.

Causes of Failures

- Errors in design, manufacturing, assembly and operation
- Lack of knowledge and experience
- Insufficient prior testing
- Random occurrence despite available knowledge and experience

UCLA

Achieving a Plant Availability of 60% Requires a MTBF of Blanket System >3 FPY

- Plant Availability of 60% Requires Blanket Availability > 97%*

Requirements on MTBF as a Function of MTTR (Blanket Availability = 97%)

MTTR Time to Replace	MTBF (FPY) Time Between Failure
2 weeks	1.2
1 month	2.7
3 months	8.1
6 months	16

* Number estimated based on the data presented in the paper, "Reliability and Availability Issues in NET" by R. Buende in Fusion Engineering and Design 11 (1989)

WHY EXPECTED FAILURE RATE IN ITER FW/B DURING EARLY YEARS OF OPERATION COULD BE MUCH HIGHER THAN BASE CASE ESTIMATES

Base Estimate Failure Rate (FR) Assumptions

- Mature well developed technology (fission reactors, steam generators, etc.)
- Bottom of bathtub of FR vs. operating time curve

Expected FR Estimate for ITER Early Years

Failure rate could be much higher because:

1) New Technology
    - No prior experience in actual system
    - Initial failure rate is higher by factors of 10 to 100 than bottom of bathtub
    - Prior testing is severely limited in simulating fusion environment

2) Fusion FW/B is More Complex than Steam Generators and Fission Core
    - Larger number of sub components and interactions (tubes, welds, breeder, multiplier, coolant, structure, tritium recovery, etc.)
    - More damaging higher energy neutrons
    - Other environmental conditions: magnetic field, tritium, vacuum, etc.
    - Reactor components must penetrate each other
    - Ability to have redundancy inside FW/B system is extremely limited

REMARKS ON FAILURE RATE AND RELIABILITY GROWTH

- Capability to replace first wall and blanket (individual modules as well as the entire FW/B system) in a reasonable time MUST be a design goal for fusion devices.
- Design concepts for FW/B (and other components) must aim at improving reliability. One of the most effective directions is to minimize features that are known to have high failure rate (e.g., minimize or eliminate welds, brazes, tube length).
- A serious reliability and availability analysis must be an integral part of the design process.
- R&D program must be based on quantitative goals for reliability (type of tests, prototypicality of test, number of tests, test duration).
- Reliability growth testing in fusion devices will be the most demanding (particularly on number of tests and time duration of tests). Reliability testing should include:
  - Identification of failure modes and effects.
  - Aggressive iterative design/test/fix programs aimed at improving reliability.
  - Obtain failure rate data sufficient to predict MTBF.

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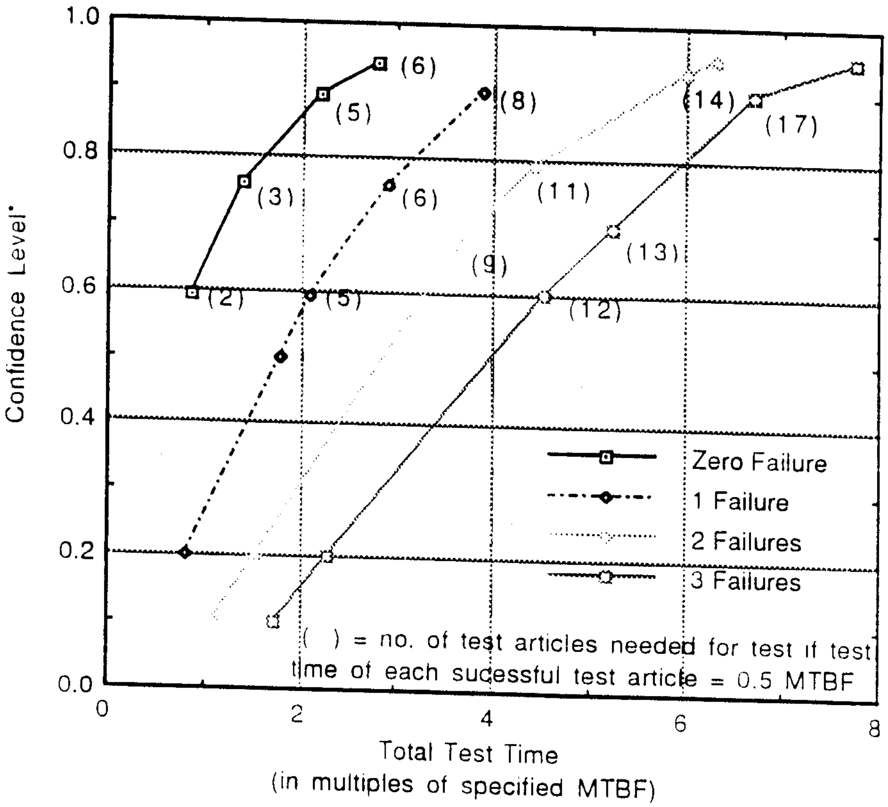
Test Time and Number of Test Articles vs Confidence Level

- For MTBF tests, the minimum test time per component = 0.5 MTBF (assuming that the component useful operating time is equal to the MTBF)
- This requirement implies that 6 test components are needed for achieving a 90% confidence level, if the number of failure is zero.
- With 1 failure during the test, the number of test articles would be 8 for achieving a 90% confidence and 7 for 80% confidence.



* Confidence level 0.8 means that the confidence of the lower limit on the MTBF being equal to the specified MTBF is 80%.

DESIGN CONCEPTS

FOR VNS

Design Concepts For VNS

- VNS must be a Magnetic Fusion Device
  Plasma is the only credible means at present to generate 14 MeV neutrons at a rate $>10^{19}$n/s

- A Tokamak: Appears to offer the best potential for VNS

  - Driven, Low Q, Plasma based on present data base
  - Experience from Large Physics Devices (e.g. JET, TFTR, JT-60 U, D-IIID)
  - Additional Technology data base required is part of what is being developed under ITER R&D

- Trade off studies have been carried out in the US for a Tokamak VNS. Attractive Design Envelope to meet VNS mission/objectives at a reasonable cost exists.

Cost depends on:
  - Desired Wall Load
  - Normal Conducting Versus Superconducting Magnets
  - Current Drive Capability

Suggested Ground Rules for Evolving VNS Design Concept

- Cost < 0.5 ITER
  (lower cost is encouraged)

- Low Fusion Power (< 400 MW)

- Surface Area at First Wall for testing
  $> 10\ m^2$

- Higher Wall Load
  $> 1 MW/m^2$ (prefer 2 if possible)

- Design for Maintainability and Higher Availability
  Duty Cycle x Availability > 0.3

- No Breeding Blanket
  Avoid use of unproven technologies

- Maximum Site Power Requirements < 700MW

[From Summary of IEA Workshop; Moscow July 12-18, 1993]

TABLE 3. VNS Options and Key Parameters Based on Tokamak

CONCEPT	ITER EDA[f]	S/C Shield[g]	N/C Shield[g]	H-I_{bs}[h] (Efremov)	N/C No Shield[g]	TK-T[i] (TSP-PPD)	N/C Single-Turn[g]	MTF[j] (Culham)
Neutron wall load (MW/m^2)	2.0	1.1	1.0	0.7 - 1.0	1.0 - 2.0	0.8 - 1.2	1.0 - 2.0	1.4
Major radius, R_0 (m)	7.75	4.64	2.6	2.5	1.52 - 1.74	1.5	0.91 - 0.97	0.53
Minor radius, a (m)	2.8	1.05	0.84	0.63	0.6 - 0.64	0.5	0.6	0.33
Plasma current, I_p (MA)	25	6.4	6.8	4.1 - 4.5	6.3 - 7.3	3.0 - 3.5	6.0 - 6.8	6.9
Magnetic field, B_{t0} (T)	6.0	7.7	6.7	6.8 - 7.5	6.8 - 8.0	3.5 - 4.2	3.6 - 4.7	2.4
Drive Power, P_{drive} (MW)	0	155	60	50	35 - 67	30 - 40	24 - 33	20
Fusion power, P_{fusion} (MW)	3170	400	150	90 - 130	65 - 158	35 - 45	42 - 90	20
Site power, peak/s.s. (MW)	800/400	400	700	500 - 700	690 - 700	TBD	230 - 330	100
Direct access test area (m^2)	TBD	110	52	30	21 - 23	TBD	17	6
Tritium consumption[k] (kg/yr)	TBD	5.0	1.7	1.3 - 1.9	0.8 - 2.0	TBD	0.4 - 1.0	0.2

[f] ITER-EDA information as of May 1993.

[g] "Initial Design Boundaries and Parameters of Small Tokamak VNS Envelope," presented by M. Peng, Oak Ridge National Laboratory, USA.

[h] "VNS on the basis of the High Bootstrap Fraction Tokamak," presented by A. B. Mineev, D. V. Efremov Scientific Research Institute of Electrophysical Apparatus, St. Petersburg, Russia.

[i] "The Compact Volumetric Neutron Source on the Tokamak Basis (TRINITI – "Kurchatov Institute" Version)," presented by S. V. Mirnov, Troitsk-Kurchatov Institute, Russia.

[j] "Tight Aspect Ratio Tokamak Neutron Source," presented by T. C. Hender, Culham Laboratory, Abingdon, UK.

[k] Assuming tritium a breeding ratio of unity for test blanket modules covering the entire test area for an achieved availability of 30%.

Representative Parameters for VNS with Superconducting (S/C), Multi-Turn Normal Conducting (M-T N/C), and Single-Turn Normal Conducting (S-T N/C)Toroidal Field Magnets.

	S/C	M-T N/C	S-T N/C
Major radius, R_0 (m)	4.64	1.7–2.2	0.8
Minor radius, a (m)	1.05	0.5–0.8	0.6
Plasma current, I_p (MA)	6.4	3.8–6.4	8.2
Externally applied toroidal field, B_{t0} (T)	7.7	7.5–6.0	2.4
Volume average density, $\langle n_e \rangle$ (10^{20} m^{-3})	1.5	1.1–1.3	1
Density-average temperature, $\langle T \rangle_n$ (keV)	9.5	14–10	11
Drive power, P_{drive} (MW)	140	38–70	27
Fusion power, P_{fusion} (MW)	360	58–120	32
Electric power consumption, peak/s.s. (MW)	370	530–700	200
Outboard accessible wall area (m^2)	56	16–22	11
Number of ports for plasma drive	3	3–2	2
Number of ports for nuclear test modules	9	9–6	6
First wall area, including inboard (m^2)	290	47–100	26

High Wall Load and High Availability in VNS are Necessary to Achieve Goal Fluence in Reasonable Time

Test	Fluence MW-y/m^2	Wall Load MW/m^2	Machine Time FPY
Scoping Test	0.3	1	0.3
		2	0.15
Performance Verification	1.0	1	1
		2	0.5
Reliability Growth	5.0	1	5
		2	2.5

Neutron Wall Load MW/m^2	Machine Time FPY	Calendar Time (years) Duty Cycle x Availability		
		10%	20 %	30%
1	6.3	63	31	21
2	3.15	31	16	11

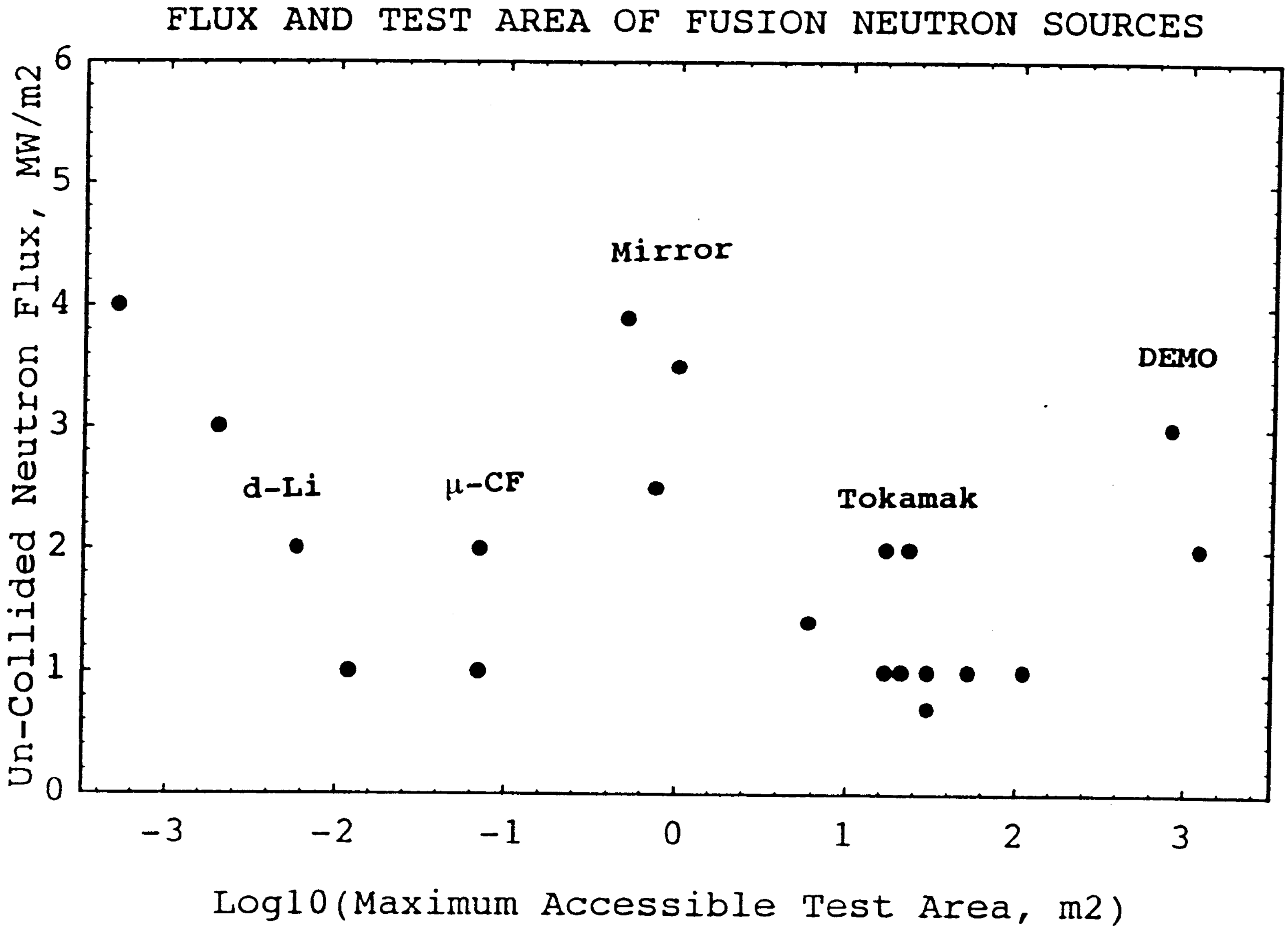


Figure 2. Maximum accessible test area and the un-collided neutron loading averaged over the test area for the VNS concepts presented at the workshop ("•" representing values from Tables 2 and 3). The values for a DEMO, and the high-flux neutron sources based on d-Li target and μCF are included for contrast.

List of Issues for VNS Design

- Must design for high availability
  25-35%
- Normal versus superconducting TF coil?
  - Inboard shield requirements
  - Ceramic insulators in N/C coils?
  - Demountable N/C TF coils?
  - Radiation limits
- Divertor heat load
- Current drive

Summary

- VNS (Volumetric Neutron Source) is a fusion facility, which operates parallel to ITER, for testing, developing and qualifying fusion nuclear components and materials for DEMO

- VNS, together with ITER and IFMIF, provide an optimum cost effective path for timely development of DEMO

- Requirements on VNS to effectively perform testing of nuclear components and materials have been identified. Examples are:
  - Neutron Wall Load: 1-2 MW/m^2
  - Neutron Fluence: 4-6 $MW \cdot y/m^2$
  - Plasma Burn Mode: Steady State (or long pulse)
  - Availability: 25-35%
  - Test Area at first wall: 10-30 m^2

- Programmatic constraints suggest that VNS capital cost be kept below one third to one half of ITER

- Fusion Power in VNS should be kept below 400 MW to minimize tritium consumption and avoid the need for breeding blanket

- VNS should rely on present day physics and technology

- VNS will help reduce the Technological Burden on ITER; e.g. eliminating the need for high fluence (operating ITER 3500 MW to high fluence is costly)

- An attractive design envelope for a Tokamak VNS that satisfies the technical and programmatic requirements exists

- Serious International effort is needed to further evaluate the testing requirements and to identify attractive design options for VNS