Needs and Requirements for VNS:

A Volumetric Neutron Source Fusion Facility to test, develop and qualify Fusion Nuclear Technology Components and Material Combinations

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Needs and Requirements for VNS
(Volumetric Neutron Source Fusion Facility)

Outline

- VNS Mission and Objectives
- Relationship to ITER and IFMIF
- Framework for FNT Development
- Requirements of Nuclear and Material Testing on VNS Parameters and Design Features
- Reliability Growth Requirements
- Preliminary Test Program in VNS
- VNS Design Consideration
- Conclusions/Summary

Enclosure 1

CHARTER

INTERNATIONAL FUSION MATERIALS TEST FACILITIES STUDY

Bearing in mind the long-standing interest in this area, recognizing the strong recommendation from the Executive Committee for the IEA Implementing Agreement on Fusion Materials (Executive Committee) and noting the communication from the Chair of the ITER Council, the Fusion Power Co-ordinating Committee (FPCC) requests the Executive Committee to take action as follows:

OBJECTIVE: Develop a consensus and appropriate technical and managerial bases for decisions, if any, on two test facilities, i.e. 1) proceeding on the Conceptual Design Activities for an accelerator-based International Fusion Materials Irradiation Facility (IFMIF) that will meet the high flux, high energy ("14 MeV") neutron irradiation needs of the fusion materials programs of the partners, and 2) proceeding with studies that could lead to Conceptual Design Activities for a plasma-based source that could meet the high volume, high energy, neutron irradiation needs of the fusion materials programs of the participants.

APPROACH:

TASK 1: Involve the Russian Federation (RF), through the Associate Contracting Party route, as a full technical partner with interested IEA member partners in these efforts. Initial contact with the RF will be made by the Chair (or Vice-Chair) of the FPCC, after which the Executive Committee shall develop and, with the approval of the Governing Board, formalize the RF collaboration.

High Flux Source:

TASK 2: Develop as a technical approach to a possible international agreement, the design choice, a judgment of feasibility and a possible route of implementation to a single, acceptable design for IFMIF.

High Volume Source:

TASK 3: Review the possibilities and assess the programmatic requirements for a possible, high volume neutron source for future consideration by the interested international participants.

Schedule: The efforts of the Executive Committee should be organized to complete these tasks by October 1993, in anticipation of action on any next steps by the FPCC in January 1994.

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

R&D Tasks To Be Accomplished Prior to DEMO

[DEMO is the goal of present fusion R&D]

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

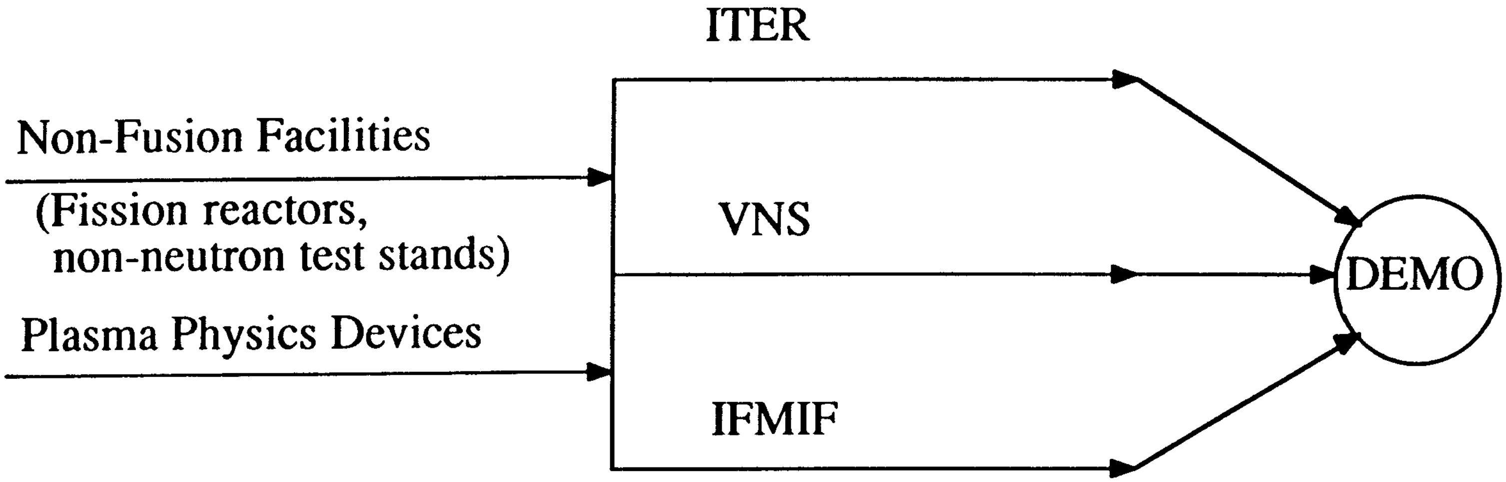
2) System Integration

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.

Prudent and Optimum Path to DEMO Requires Three Parallel Facilities



ITER

Non-Fusion Facilities

(Fission reactors,
non-neutron test stands)

VNS

DEMO

Plasma Physics Devices

IFMIF

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

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

IFMIF ["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

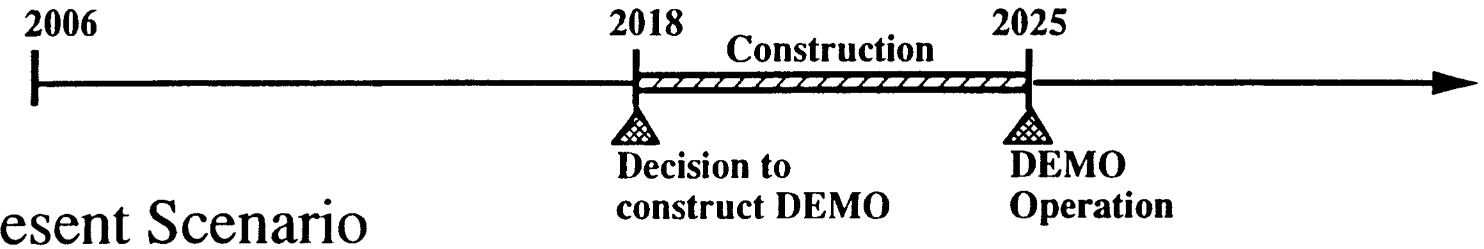
- Screen FNT Concepts and Material Combinations

- 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 Is Necessary to Meet DEMO Time Schedule



2006

2018

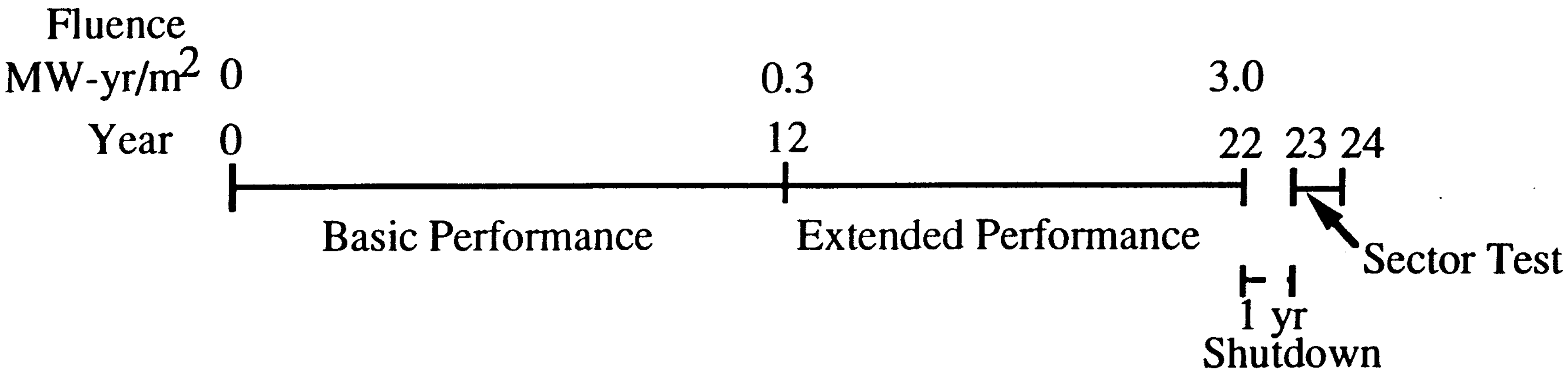
Construction

2025

Decision to construct DEMO

DEMO Operation

ITER Present Scenario



Fluence MW-yr/m^2 0 0.3 3.0

Year 0 12 22 23 24

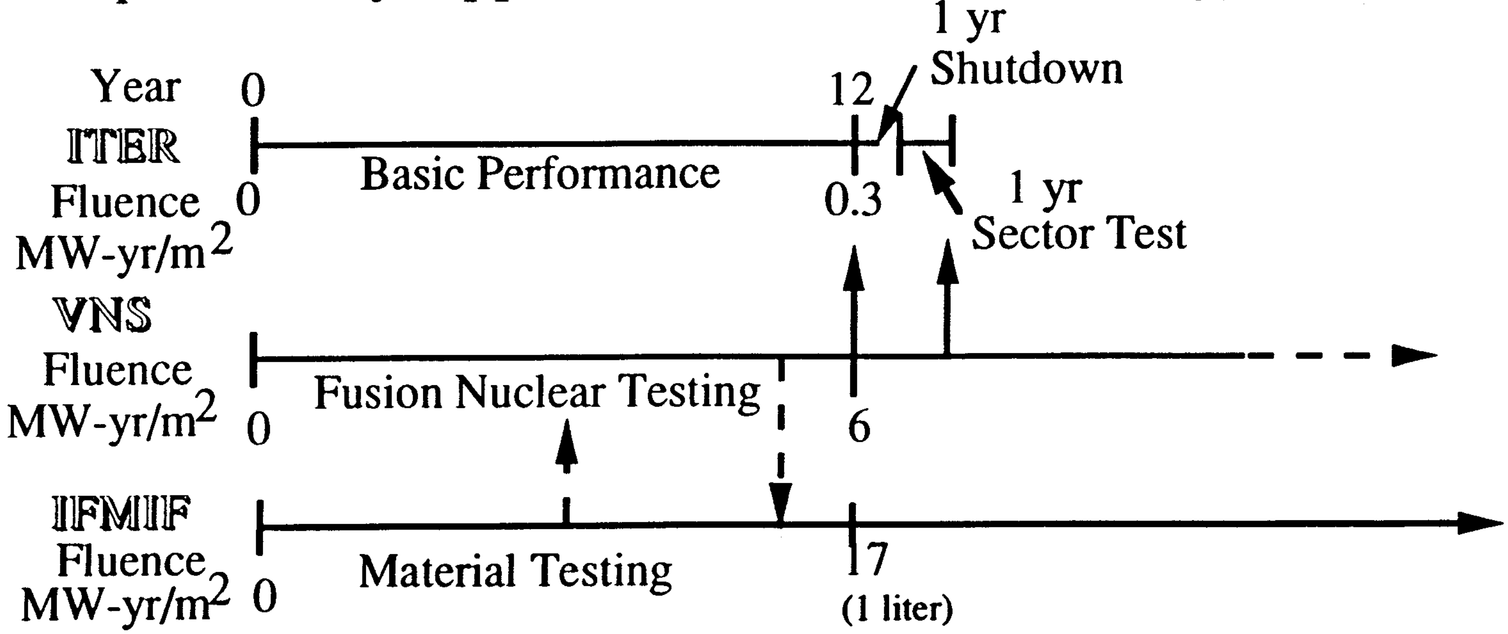
Basic Performance

Extended Performance

Sector Test

1 yr Shutdown

Complementary Approach (Reduced Technology Burden on ITER)



Year 0 12

1 yr Shutdown

ITER

Basic Performance

Fluence MW-yr/m^2 0 0.3

1 yr Sector Test

VNS

Fluence MW-yr/m^2 0 6

Fusion Nuclear Testing

IFMIF

Fluence MW-yr/m^2 0 17

(1 liter)

Material Testing

Physics and Nuclear Technology Requirements for Testing Are Very Dissimilar

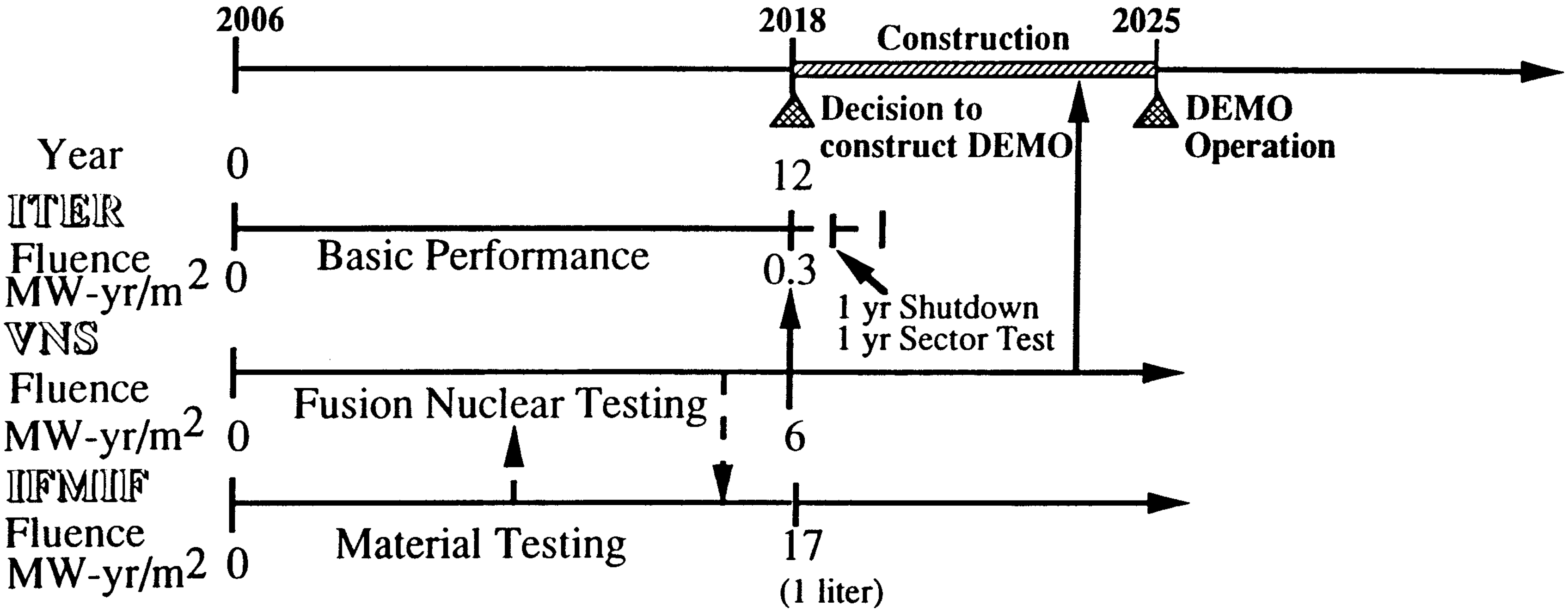
	Fusion Power	Integrated Burn Time	Tritium Consumption
A. Physics and Plasma Support	3500 MW	15 days	8.0 kg
B. Fusion Nuclear Technology	20 MW	5 yr	5.6 kg

Combined * A and B	3500 MW	5 yr	976 kg

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

VNS Increases Confidence in Successful Timely DEMO

Possibility 1



2006

2018

Construction

2025

Decision to construct DEMO

DEMO Operation

Year 0 12

ITER

Fluence MW-yr/m^2 0

Basic Performance

0.3

1 yr Shutdown
1 yr Sector Test

VNS

Fluence MW-yr/m^2 0

Fusion Nuclear Testing

6

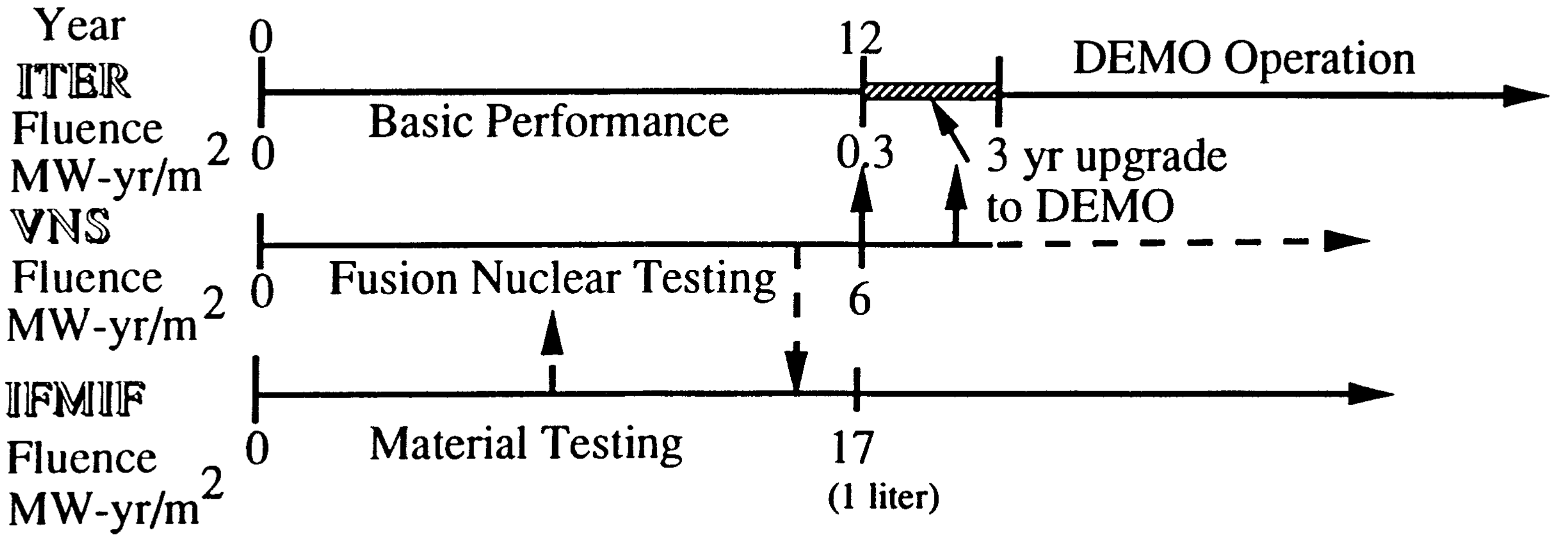
IFMIF

Fluence MW-yr/m^2 0

Material Testing

17
(1 liter)

Possibility 2 (Very High Success 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)

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·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>0.1MeV
(b): at 2MW/m^2

Role of Major Fusion Facilities

ITER	VNS	IFMIF
Limited Fluence	Medium Fluence, Large Volume	High Fluence, Small Volume
• Plasma Fusion Core • Tokamak System Integration •Plasma Support Technology • Testing of Nuclear Components - Limited Fluence - Sector-Type Tests	• Dedicated Tests for fusion nuclear component and material combinations - Calibrate non-fusion tests on component behavior - Validate codes - Screen material combinations - Concept screening - Concept validation [Testing in submodules, modules with all environmental conditions] • Aggressive reliability growth program to meet availability goals for nuclear components in DEMO	• Accelerated Tests of 14 MeV neutron damage effects on material properties (Primarily structural materials) • Calibrate non-fusion tests on neutron radiation effects on structural materials • Material property improvement

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.

ITER Fluence Scenario (Preliminary)

Year	Plasma	Neutron Wall Load		Required Burn Time/yr	Accumulated Fluence	
		Average	on Port	(duty cycle × A)	Average	on Port
Basic Performance						
1	H D	0	0	0	0	
2	H D, D ^{3}He	0	0	0	0	
3	D T	2.0	2.8	0.005	0.01	0.014
4	D T	2.0	2.8	0.005	0.02	0.028
5	D T	2.0	2.8	0.01	0.04	0.056
6	D T	2.0	2.8	0.01	0.06	0.084
7	D T	2.0	2.8	0.02	0.1	0.14
8	D T	2.0	2.8	0.02	0.14	0.20
9	D T	2.0	2.8	0.025	0.19	0.27
10	D T	2.0	2.8	0.025	0.24	0.34
11	D T	2.0	2.8	0.03	0.30	0.42
12	D T	2.0	2.8	0.03	0.36	0.50
Extended Performance						
13	D T	2.0	2.8	0.1	0.56	0.78
14	D T	2.0	2.8	0.1	0.76	1.06
15	D T	2.0	2.8	0.1	0.96	1.34
16	D T	2.0	2.8	0.125	1.21	1.7
17	D T	2.0	2.8	0.125	1.46	2.0
18	D T	2.0	2.8	0.15	1.76	2.5
19	D T	2.0	2.8	0.15	2.06	2.9
20	D T	2.0	2.8	0.15	2.36	3.3
21	D T	2.0	2.8	0.15	2.66	3.7
22	D T	2.0	2.8	0.15	3.0	4.2
Shutdown, Maintenance Demonstration						
23–24		0	0	0	3.0	4.2

VENUS Fluence Scenario [Example]

Year	Plasma	Neutron Wall Load (MW/m^2) Average	Neutron Wall Load (MW/m^2) on Port	Required Burn Time/yr (duty cycle × availability)	Accumulated Fluence ($MW\text{-}yr/m^2$) Average	Accumulated Fluence ($MW\text{-}yr/m^2$) on Port
Physics Checkout, Divertor Testing						
1	HD	0	0	0	0	
2	DT	1.0	1.4	0.05	0.05	0.07
Screening Phase						
3	DT	2.0	2.8	0.1	0.15	0.2
4	DT	2.0	2.8	0.15	0.3	0.5
Performance Verification						
5	DT	2.0	2.8	0.2	0.7	1.0
6	DT	2.0	2.8	0.2	1.1	1.5
7	DT	2.0	2.8	0.3	1.7	2.4
8	DT	2.0	2.8	0.3	2.3	3.2
9	DT	2.0	2.8	0.3	2.9	4.1
Reliability Growth						
10	DT	2.0	2.8	0.3	3.5	4.9
11	DT	2.0	2.8	0.3	4.1	5.7
12	DT	2.0	2.8	0.3	4.7	6.6
13	DT	2.0	2.8	0.3	5.3	7.4
14	DT	2.0	2.8	0.3	6.0	8.4

Benefits of VNS

Primary

Makes it possible to develop with reasonable confidence FNT Components and Material Combinations that meet the DEMO Performance Technical Requirements (particularly reliability/availability) with a self-consistent time schedule

Other Benefits

- Reduced Technological Risk and Cost to ITER
  - Reduce Fluence need
  - Eliminate Need for Breeding Blanket

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

- Forcing Function to developments concerned with remote maintenance and component reliability

Nuclear Testing Requirements

• Engineering Scaling Requirements

	Minimum	Highly Desirable
Neutron Wall Load (MW/m^2)	1	2
Plasma Burn Time	> 1000 s	Steady State (or long burn, hours)
Dwell Time	a	< 20 s
Continuous Test Duration (steady state or back-to-back cycle 100% availability)	> 1 week	2 weeks
Average Availability	10 - 15 %	25 - 35 %
Total Neutron Fluence (MW-a/m^2)	1.5	4 - 6
Test Port Size (m^2 x m)		
Module	0.5 x 0.3	1 x 0.5
Outboard Sector	2 x 0.5	4 x 0.8
Total Test Area (m^2)		
Module Only	5	10 - 20
Including Outboard Sectors	7	20 -30

• Programmatic Constraints

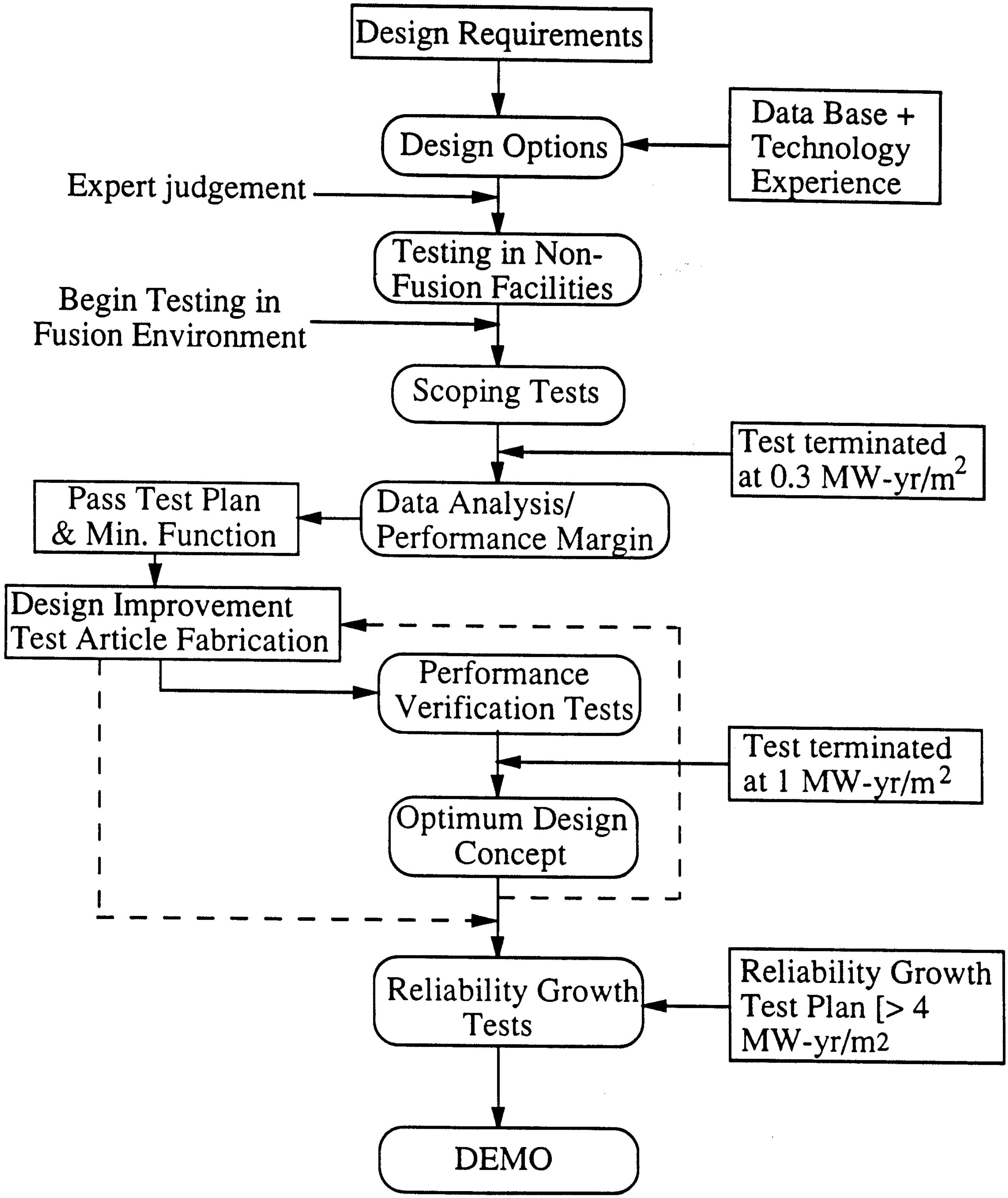
Test Time	12 yr
Fluence	6 MW-yr/m^2
Neutron Wall Load	2 MW/m^2
Duty Cycle x Availability	30 %

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

Fusion Nuclear Technology Development Approach


Design Requirements

Design Options

Data Base +
Technology
Experience

Expert judgement

Testing in Non-
Fusion Facilities

Begin Testing in
Fusion Environment

Scoping Tests

Test terminated
at 0.3 MW-yr/m^2

Data Analysis/
Performance Margin

Pass Test Plan
& Min. Function

Design Improvement
Test Article Fabrication

Performance
Verification Tests

Test terminated
at 1 MW-yr/m^2

Optimum Design
Concept

Reliability Growth
Tests

Reliability Growth
Test Plan [> 4
MW-yr/m2

DEMO

Some Considerations in Developing

Test Program For Blanket

RELIABILITY GROWTH

Blanket Module Availability vs Blanket System Availability

- The overall availability of a blanket system (BS), A_{BS}, is written as:

$$A_{BS} = \frac{MTBF_{BS}}{MTBF_{BS} + MTTR_{BS}} = \frac{1}{1 + \lambda_{BS}\, MTTR_{BS}}$$

where

$MTBF_{BS}$ = Mean time between failures of the blanket system
$MTTR_{BS}$ = Mean time to replace the blanket system
λ_{BS} = Failure rate of blanket system

and $$\lambda_{BS} = \frac{1}{MTBF_{BS}}$$

- In general, a blanket system consists of a series of modules. This implies that the failure rate of the blanket system is equal to:

$$\lambda_{BS} = n\ \lambda_n$$

and $$A_{BS} = \frac{1}{1 + \lambda_{BS}\, MTTR_{BS}} = \frac{1}{1 + n\lambda_n\, nMTTR_n}$$

where

n = # of modules (A module is the smallest physical element that can be replaced when a failure occurs.)
λ_n = Failure rate per module
$MTTR_n$ = Mean time to replace a module (approximated as that of a sector, i.e. $MTTR_n = MTTR_N$)

- Note that to replace a module, it is probablly needed to pull out a sector, then pull out the module from the sector

i.e. $$MTTR_n \geq MTTR_N$$

- A Blanket Module Availability (A_n)

$$A_n = \frac{1}{1 + \lambda_n MTTR_n}$$

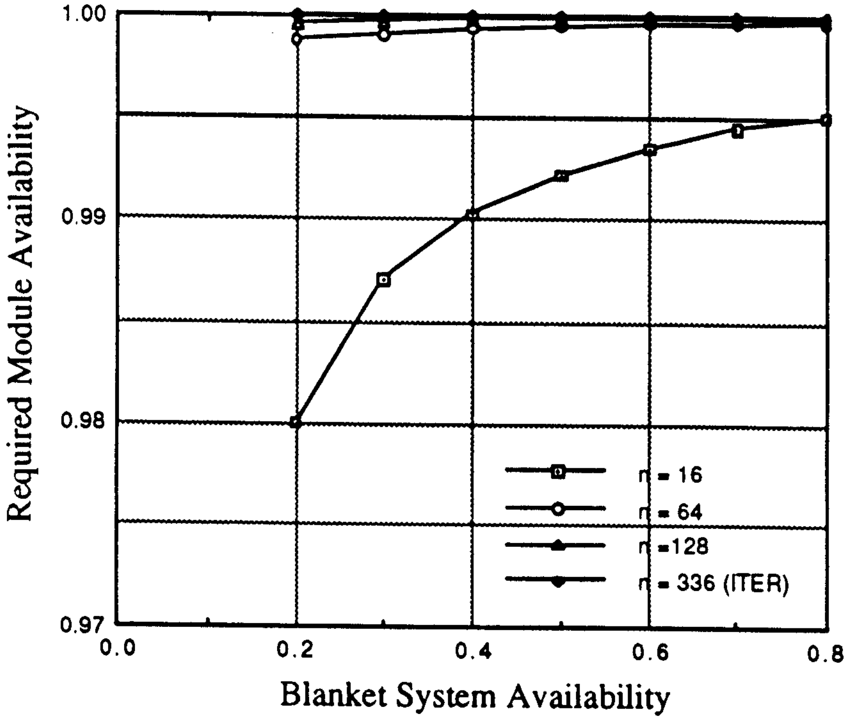
Achieving a High Blanket Availability Requires A Very High Module Availability

- A Blanket System Availability (A_{BS})

$$A_{BS} = \frac{A_n}{A_n(1-n^2)+n^2} \approx \frac{A_n}{n^2(1-A_n)} \qquad (n^2 >> 1)$$

or

$$A_n \approx \frac{1}{1 + \frac{1}{n^2 A_{BS}}}$$



MTTRn	Required MTBF (Years)			
	ABS = 0.5		ABS = 0.8	
	n = 16	n = 336	n = 16	n = 336
1 day	0.35	155	0.56	247
1 week	2.5	1084	3.9	1728

Reliability Testing: General Background

- Sequential Tests

- When this test is performed, no decision is made in advance as to the number of hours to be used for test. The accumulated results of the test at any point serve as a criterion for making one of three possible decisions:
  Accept the component
  Reject the component
  Continue testing

- MIL-STD-781 : A military standard for equipment reliability testing issued by DOD in 1967.

- The test plans may be used for both reliability demonstration tests (qualification) and reliability production acceptance tests (sampling).

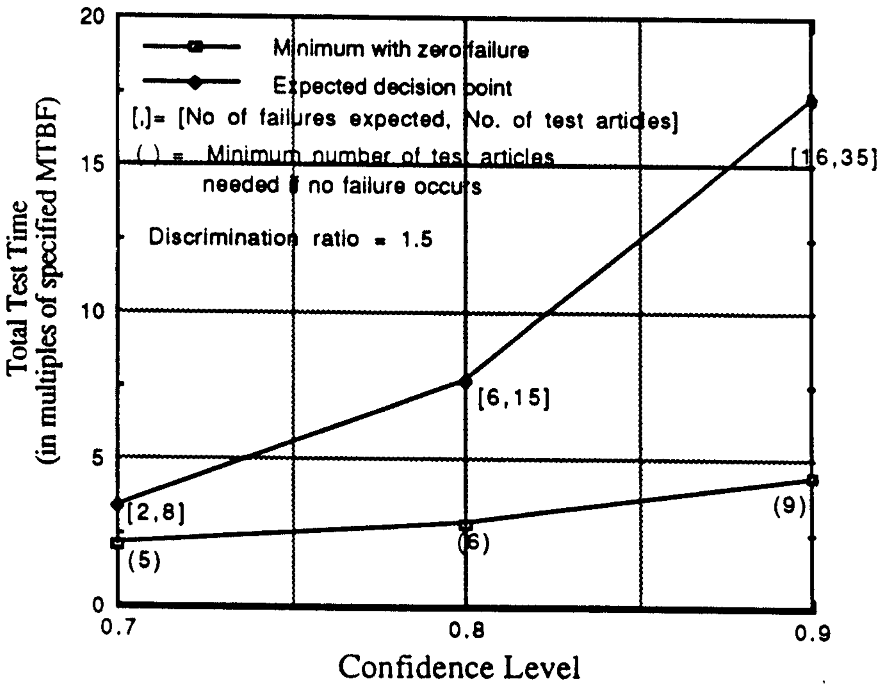
- Based on this plan, INTOR concluded that the achievement of 80% confidence in a given component mean time between failures (MTBF) in the constant failure rate regime of operation would typically require a cumulative test period of 3.5 times the MTBF. (i. e. 3.5 ≈ (7.6+ 2.4 + 1.14) / 3.)

TABLE XII.4-5. SUMMARY OF MIL-STD-781 SEQUENTIAL TEST PLANS

MIL-STD-781B Test Plan	Decision Risks α and β (%)	Discrimination Ratio = θ_0/θ_1	Time to Decision (in Units of MTBF)		
			Minimum (for MTBF > θ_1)	Expected (for MTBF = θ_0)	Maximum (Truncated)
I	10	1.5	4.40	17.3	33.00
II	20 ✓	1.5	2.79	7.6 ✓	14.60
III	10	2.0	2.20	5.1	10.30
IV	20 ✓	2.0	1.40	2.4 ✓	4.87
IVa	20 ✓	3.0	0.89	1.14 ✓	1.50
V	10	3.0	1.25	2.0	3.45
VI	10	5.0	0.35	0.64	1.25
VII	30	1.5	2.10	3.4	4.53
VIII	30	2.0	0.86	1.3.	2.25
IX	35,40	1.25	2.00	5.0	8.25

Test Time and Number of Test Articles vs Confidence Level (MIL-STD-781 Sequential Test Plan)

- Confidence level of 80%: $\alpha, \beta = 20\%$
- Minimum test time per component = 0.5 MTBF (assuming that the component useful operating time is equal to the MTBF)
- This requirement implies that a minimum number of 9 test components is needed for achieving a 90% confidence level, if the number of failure is zero.
- With most likely failure rates, the number of test articles is 35 for 90% confidence and 18 for 80% confidence.



Achieving A High Plant Availability Requires A Very High Blanket Availability

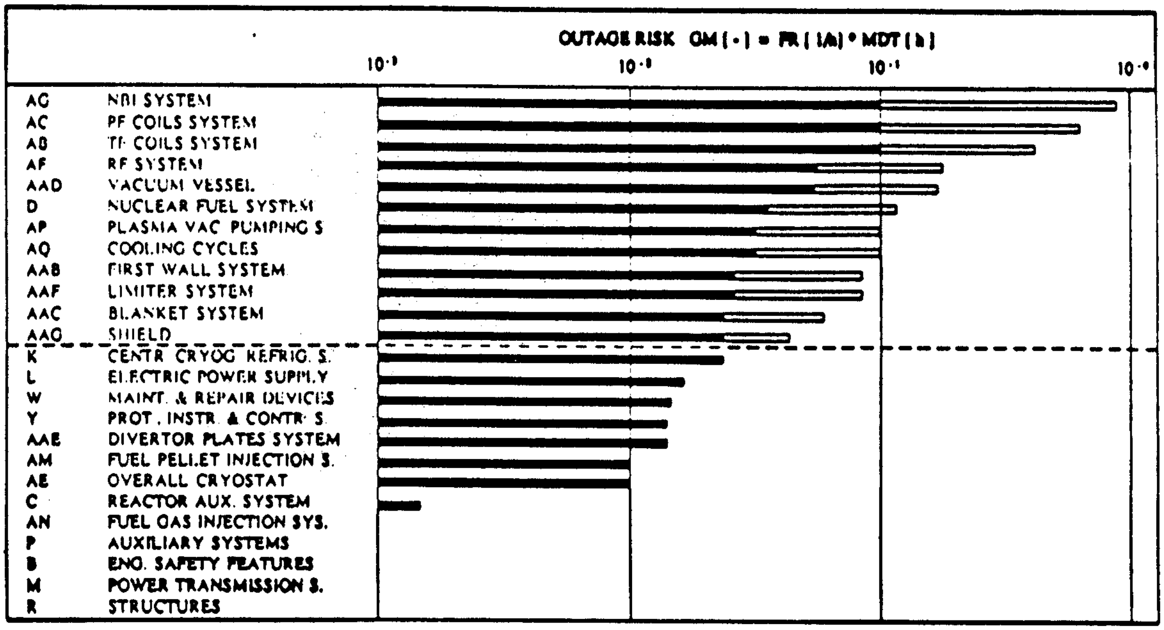


Fig. 4. Outage risk contributions of components.

- 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 %
37%	50 %

Reliability Growth :Background

- A discipline used to investigate the cause of each failure, and redesign to try to make sure it will not reoccur (a process known as test, analyze and fix).

- Past experience on reliability growth testing (non-fusion, a large variety of equipment such as pump) has shown that the rate of increase in the MTBF (M) of component can be expressed as(Duane Model):

$$M = A\, t^{\alpha}$$

where

α = development growth parameter (the larger the α the more effective is the development program).

M= cumulative MTBF (hrs)

t = testing time in hours

- Such a model would help to:
  - assess the effectiveness of the development process;

    The value of α is interpreted as:

$\alpha > 0.4$	Reliability has top priority; very effective development program
$\alpha = 0.3 - 0.4$	Reliability has high priority
$\alpha = 0.2 - 0.3$	Routine attention paid to reliability, important failure modes investigated and analyzed
$\alpha < 0.2$	Reliability has low priority

  - estimate how much more development effort is needed to ensure a reliability target is reached, or
  - estimate the final reliability of a product for a given amount of development effort.

Reliability Growth : Illustration

Consider the data set shown in Table 6.1 which shows the cumulative times of failure of pump for a washing machine:

Table 6.1

Failure number	*Cumulative time of failure (h)*	*Cumulative MTBF M_c*	ln(T)	ln(M_c)
1	103	103	4.6	4.6
2	315	157	5.7	5.1
3	801	267	6.7	5.6
4	1183	296	7.1	5.7
5	1345	269	7.2	5.6
6	2957	493	8.0	6.2
7	3909	558	8.3	6.3
8	5702	713	8.6	6.6
9	7261	807	8.9	6.7
10	8245	824	9.0	6.7

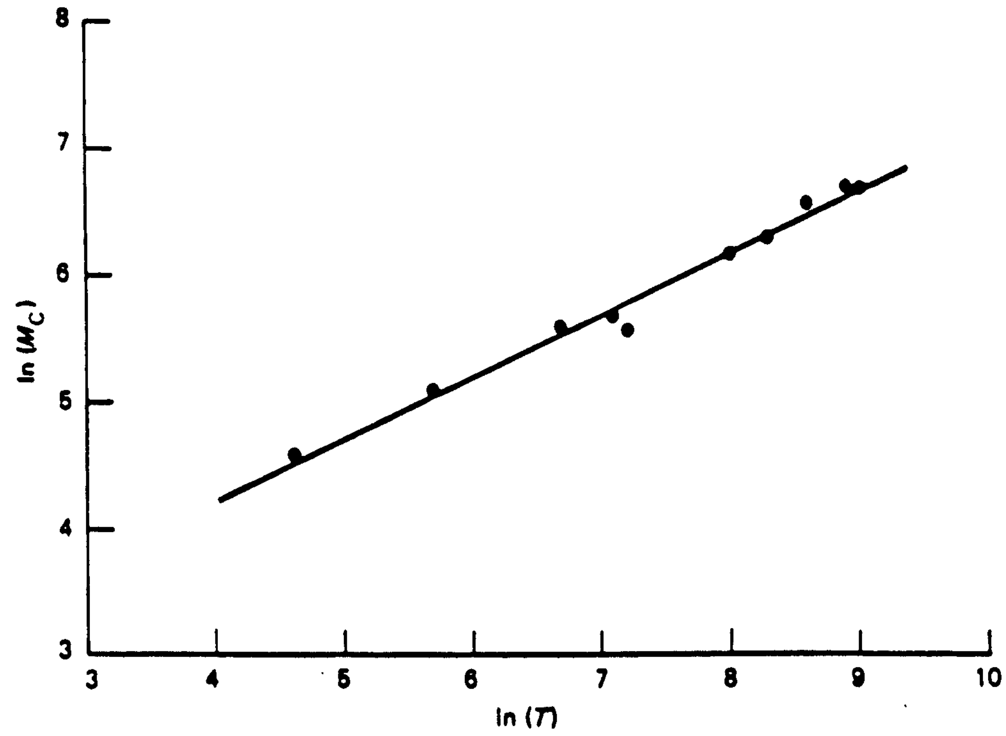


Figure 6.1

An Aggressive Development Program Leads to Less Test Time Required and Faster MTBF Growth

- The MTBF at the end of the development process will be somewhat higher than M_c because the early design has been modified to reduce the probability of certain failure modes that manifested themselves early on.

- The instantaneous failure rate (λ_i) at time t is expressed as:

$$\lambda_i = \frac{dn}{dt}$$

where n = number of failures at time t, and

$$n = \frac{t}{M_c} = \frac{t^{1-\alpha}}{A}$$

Therefor $$\lambda_i = \frac{d(t^{1-\alpha}/A)}{dt} = \frac{1-\alpha}{A}\, t^{-\alpha}$$

and $$M_i = \frac{1}{\lambda_i} = \frac{1}{1-\alpha}\, A\, t^{\alpha}$$

Requirements on Testing Time for Achieving a Blanket MTBF of 5 Years as a Function of Development Factors and A*

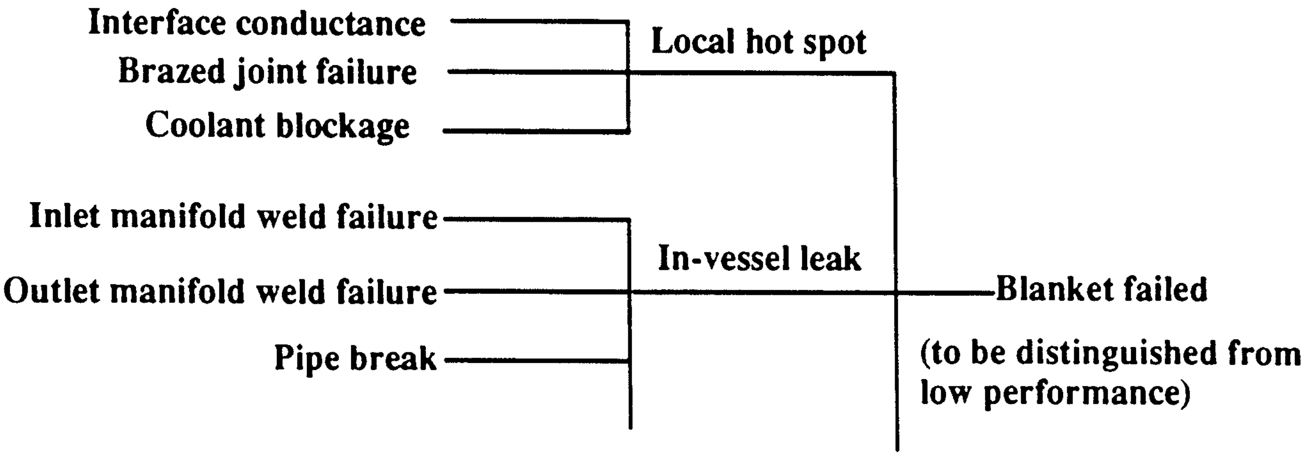
Target MTBF (M_i) for DEMO Blanket	Further Testing Time,Hours (Years) A = 100	
	$\alpha = 0.5$	$\alpha = 0.3$
$4.38\text{x}10^4$ hours (5 yrs)	$4.8\text{x}10^4$ (5.5)	$1.9\text{x}10^8$ ($2.2\text{x}10^4$)

* MTBF of Blanket at 1 hour of testing

A Process to Address Blanket Reliability by Defining Tests Through Fault Tree Analysis

The process involves:

- Breaking the blanket down to the level of constituents- pipes (straight pipe, bends and welds), manifolds, cladding,etc.
- Identifying all possible failure modes of the blanket on the lowest level of breakdown
- Setting -up the event trees representing the sequence of effects following on the primary failures up to the final consequence
- Setting-up the fault tree representing the outage logic
- Assessing the occurrence rates of the various failure modes identified
- Identifying those constituents which contribute most to failure rate
- Defining reliability life tests for those constituents



Interface conductance
Brazed joint failure
Coolant blockage
Local hot spot

Inlet manifold weld failure
Outlet manifold weld failure
Pipe break
In-vessel leak

Blanket failed

(to be distinguished from low performance)

Example MIL-STD-781B Test Plan I

Accept line:

$$t = \frac{\ln(\frac{\theta_0}{\theta_1})}{(\frac{1}{\theta_1} - \frac{1}{\theta_0})}(r) - \frac{\ln(\frac{\beta}{1-\alpha})}{(\frac{1}{\theta_1} - \frac{1}{\theta_0})}$$

Reject line:

$$t = \frac{\ln(\frac{\theta_0}{\theta_1})}{(\frac{1}{\theta_1} - \frac{1}{\theta_0})}(r) - \frac{\ln(\frac{1-\beta}{\alpha})}{(\frac{1}{\theta_1} - \frac{1}{\theta_0})}$$

θ_0 = specified MTBF
θ_1 = minimum MTBF we are willing to accept
α = The probability of rejecting equipment(s) with true MTBF greater than th specified MTBF will be less than α.
β = The probability of accepting equipment(s) with true MTBF less than the minimum MTBF (θ_1) acceptable will be less than β.
r = number of failures

Decision risks	10%
Discrimination ratio	1.5: 1

Reliability Testing

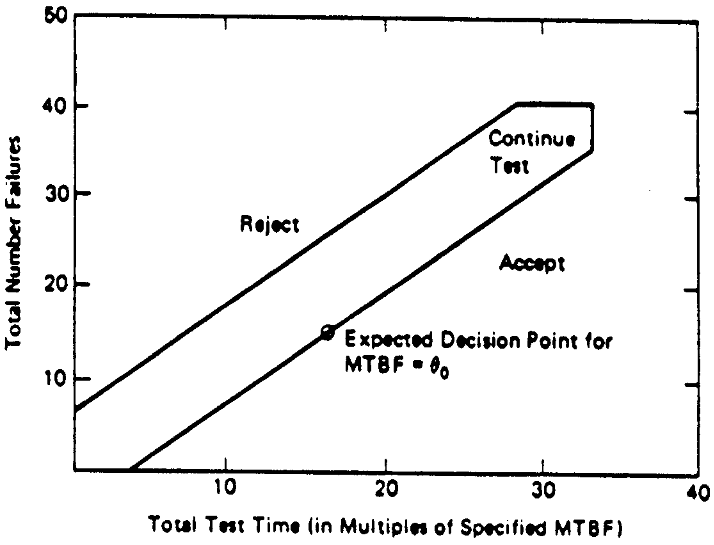


Figure 11-3 *Accept-reject criteria (test plan I).*

	Total Test Time*			Total Test Time*	
No of Failures	*Reject (Equal or Less)*	*Accept (Equal or more)*	*No of Failures*	*Reject (Equal or Less)*	*Accept (Equal or More)*
0	N/A	4.40	21	12.61	21.43
1	N/A	5.21	22	13.42	22.24
2	N/A	6.02	23	14.23	23.05
3	N/A	6.83	24	15.04	23.86
4	N/A	7.54	25	15.85	24.67
5	N/A	8.45	26	16.66	25.48
6	0.45	9.27	27	17.47	26.29
7	1.26	10.08	28	18.29	27.11
8	2.07	10.89	29	19.10	27.92
9	2.88	11.70	30	19.90	28.73
10	3.69	12.51	31	20.72	29.54
11	4.50	13.32	32	21.53	30.35
12	5.31	14.13	33	22.34	31.16
13	6.12	14.94	34	23.15	31.97
14	6.93	15.75	35	23.96	32.78
15	7.74	16.56	36	24.77	33.00
16	8.55	17.37	37	25.58	33.00
17	9.37	18.19	38	26.39	33.00
18	10.18	19.00	39	27.21	33.00
19	10.99	19.81	40	28.02	33.00
20	11.80	20.62	41	33.00	N/A

* Total test time is total unit hours of "equipment on" time and is expressed in multiples of the specified MTBF. Refer to Paragraph 11.5(h)-4 for minimum test time per equipment

Highlight of Test Program
on VNS

Scope of Testing in VENUS

Information Obtained from Basic Device

- Divertor Operation
- Heating and Current Drive Systems
- Protective Armor and Limiters
- Neutronics and Shielding
- Magnet Systems
- Tritium Processing

Testing in Specialized Test Ports

- Materials Test Module
  - Material Properties Specimen Matrix

- Blanket Test Modules
  - Screening Tests
  - Performance Verification
  - Reliability Growth

- Divertor Test Modules
  - Engineering Performance
  - Design Improvements and Advanced Divertor Testing

- Current Drive and Heating Launchers

Demonstration of Remote Maintenance Operations

Primarily through frequent changeout of various test articles

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

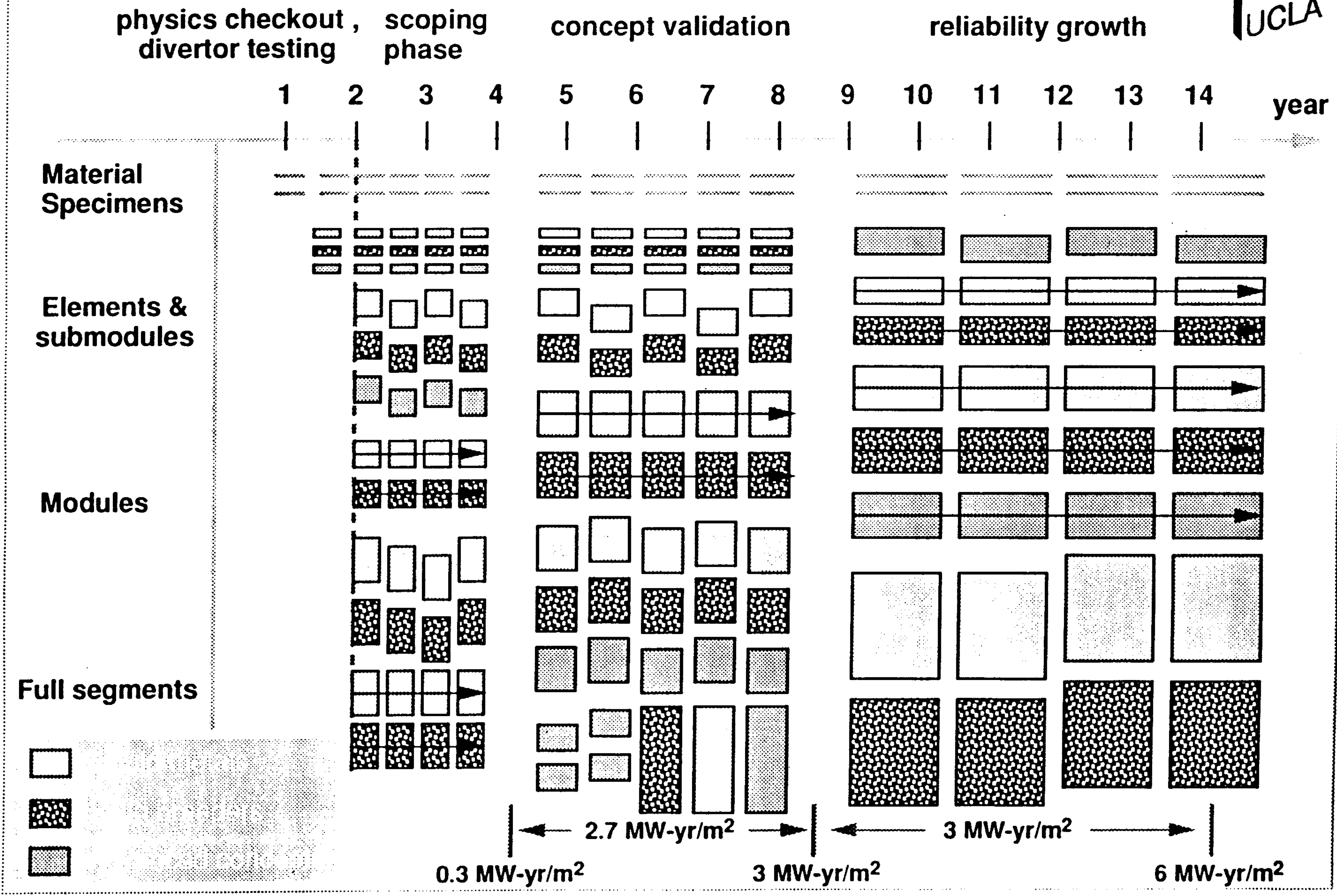
Material Specimens (1 cm × 1 cm)
- large number of coupons placed in a materials test module

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



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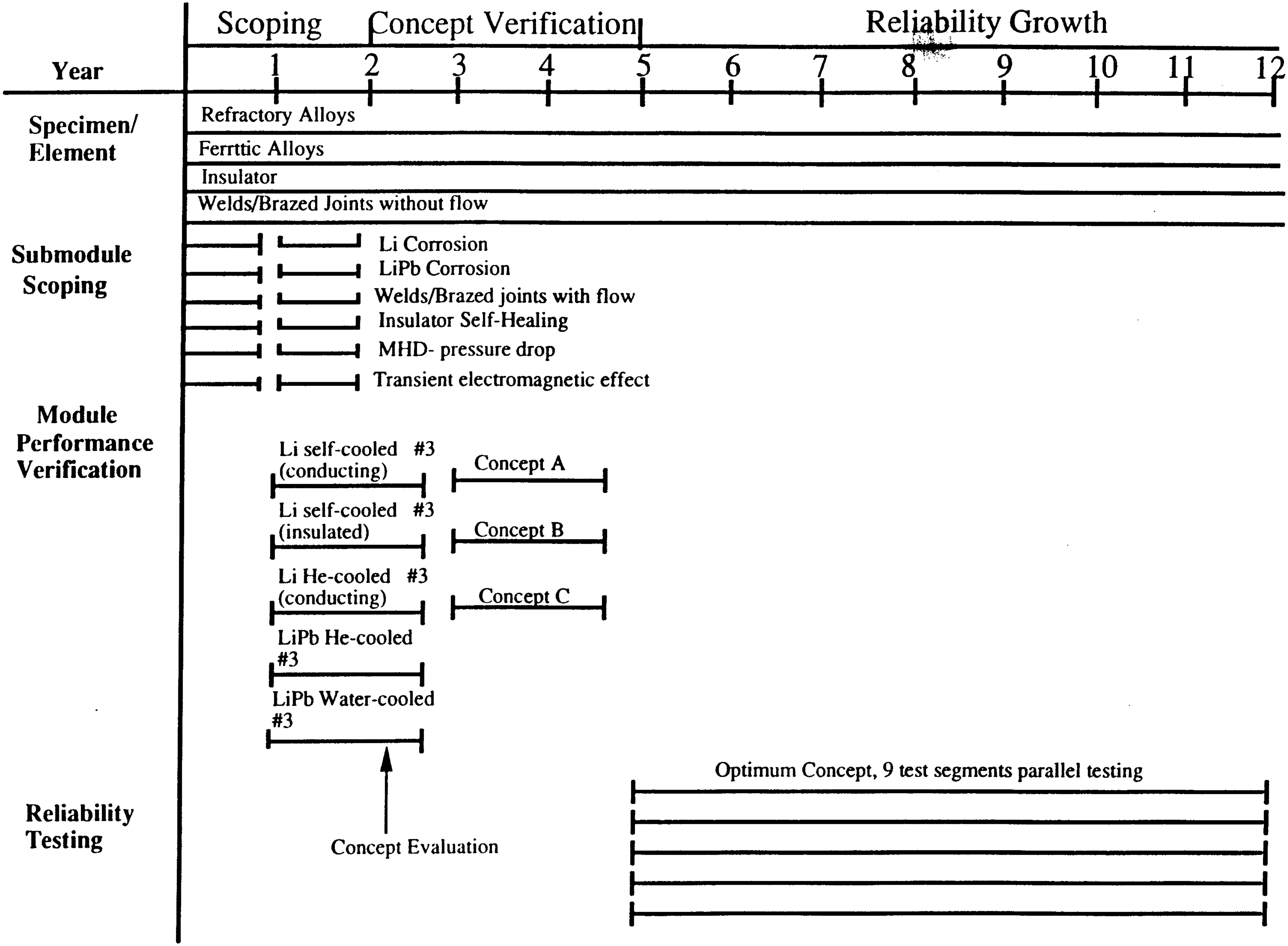
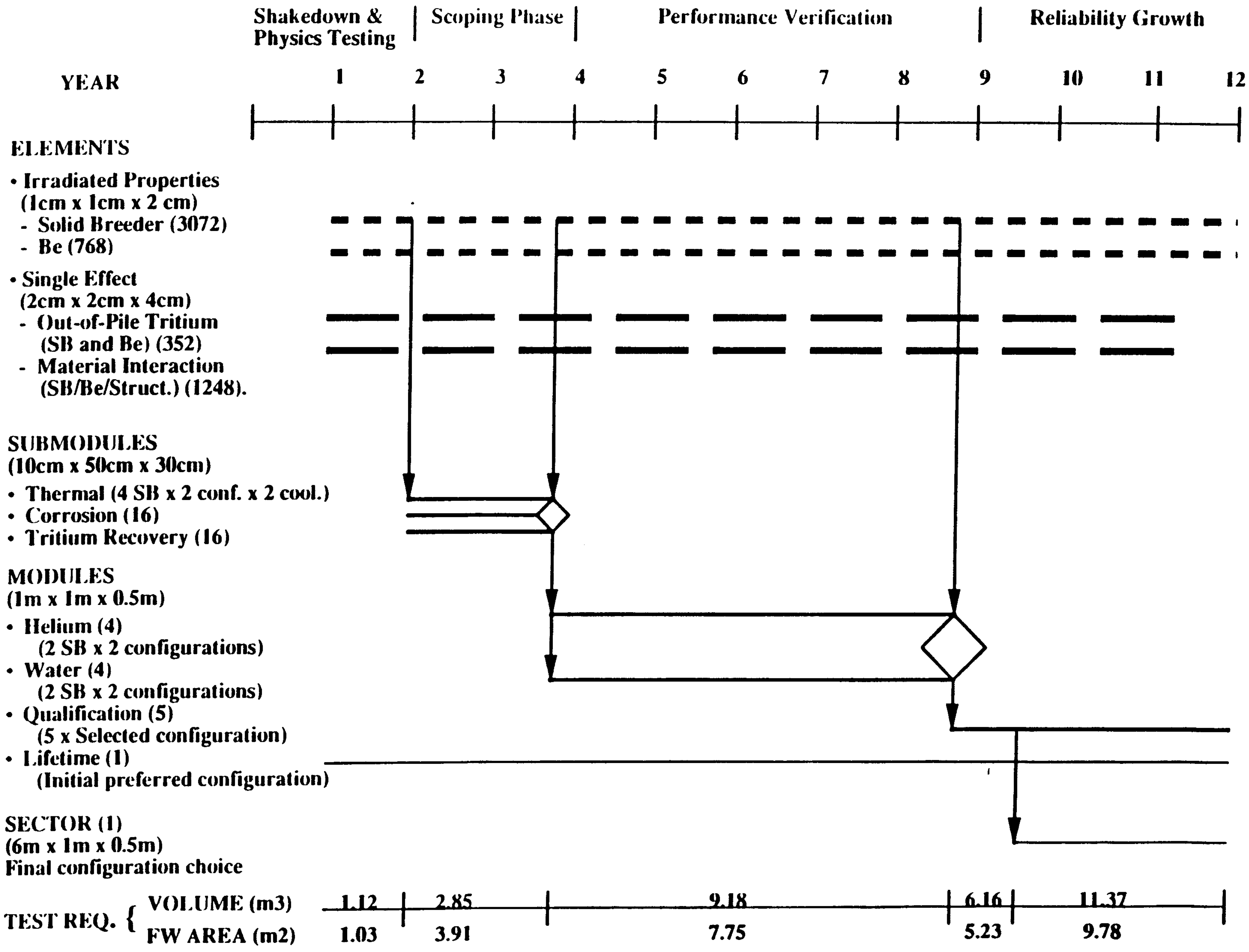
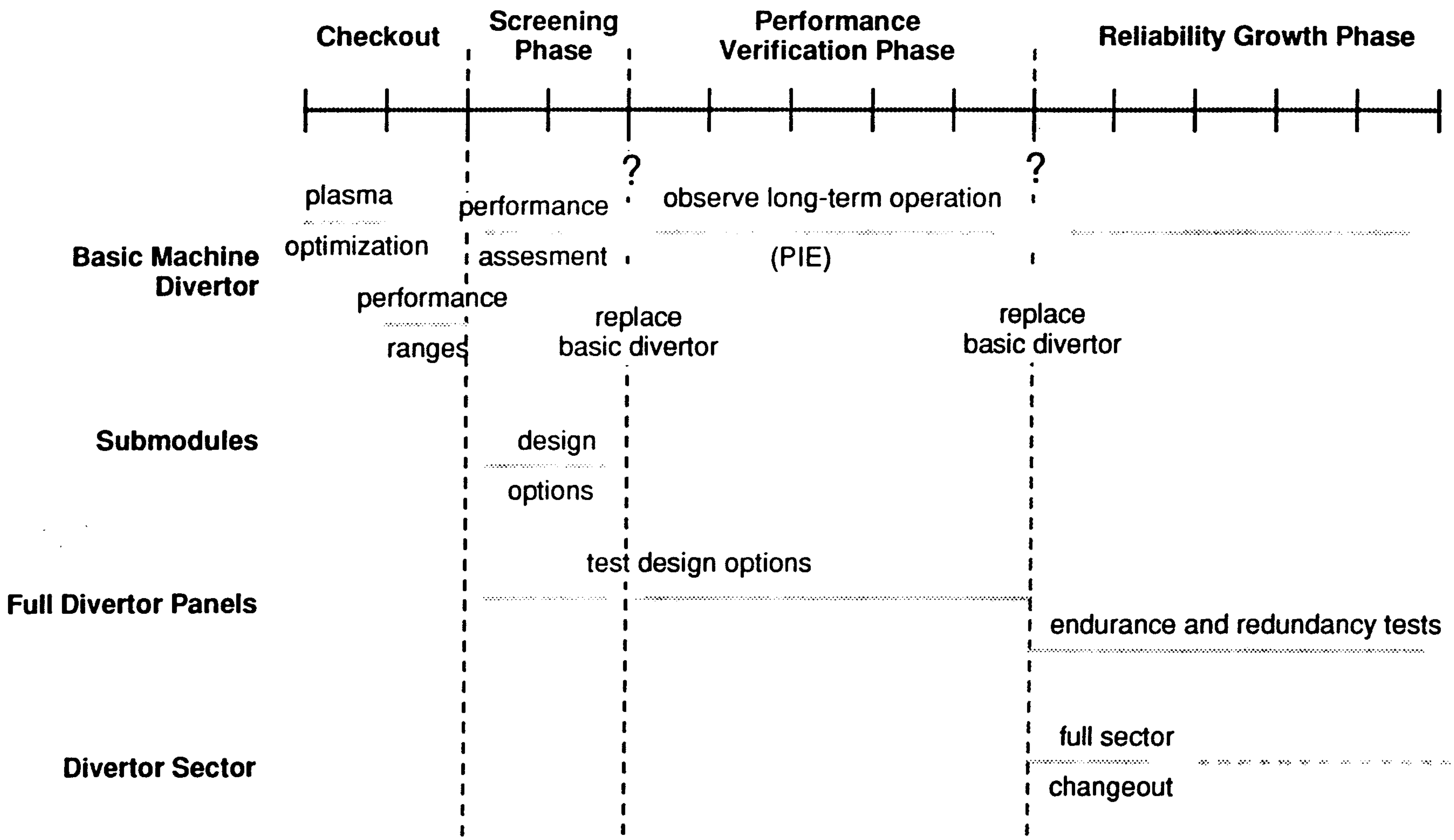
Example of Test Sequence for Liquid Metal Blankets



EXAMPLE TEST SEQUENCE FOR SOLID BREEDER BLANKETS



Example Test Sequence for Divertors



Checkout

Screening Phase

Performance Verification Phase

Reliability Growth Phase

Basic Machine Divertor

plasma optimization

performance ranges

performance assesment

?

observe long-term operation (PIE)

?

replace basic divertor

replace basic divertor

Submodules

design options

Full Divertor Panels

test design options

endurance and redundancy tests

Divertor Sector

full sector changeout

Solid Breeder Testing Strategy

- Parallel and Sequential Tests
- Basic Tests
  - Property measurements on specimens over lifetime of VNS
- Single-Effect Tests
  - Small-scale tests over lifetime of VNS
  - Help calibrate non-fusion tests
  - Code and model validation
- Submodule Tests
  - Concept screening
- Module Performance Verification Tests
  - Four modules selected from concept screening results
- Qualification Test
  - Five modules of selected configuration from performance verification results for reliability growth
- Sector Test
  - Final fully integrated performance verification test on selected configuration
- Lifetime Test
  - Make the most use of fluence by inserting one or two modules from the start to the end of operation

Solid Breeder Test Matrix

- Revisit Earlier Work with More Detailed Assumptions for Test Matrix Estimates

- Example for Basic Tests:

  - Number of specimens for solid breeder irradiated properties

    4 properties
    4 solid breeders
    2 material forms
    3 porosities
    4 temperature levels
    4 fluence levels
    2 for duplication

    TOTAL: 3072

  - Specimen size 1 cm x 1 cm x 2 cm

  - However, each specimen would need to be contain inside a shell to isolate it from its neighbors and to set the appropriate boundary conditions (e.g. neutronics or temperature) (N.B For larger test submodules and modules, space would also be required for coolant, purge lines and diagnostics, i.e to service the test submodule or module)

  - Thus, assume test volume required per specimen 2 cm x 2 cm x 3 cm

  - Set required test area at the first wall based only on highest fluence condition

EXAMPLE SOLID BREEDER TESTS IN VENUS

Tests	SB (SBxformxpor)	Be Form (formxpor)	Structure	T	Fluence	Dupl.	Total	Element Size (Test Size)	Volume m^3	FW Area m^2
Basic Tests										
Solid breeder irradiated properties (4 properties)	4 x 2 x 3			4	4	2	3072	1 x 1 x 2 cm (2 x 2 x 3 cm)	0.037	0.077
Be irradiated properties (4 properties)		2 x 3		4	4	2	768		0.009	0.019
Single Effect Tests										
Solid breeder tritium recovery	4 x 2 x 2			4	4	1	256	2 x 2 x 4 cm (3 x 3 x 5 cm)	0.012	0.014
SB/structure interaction	4 x 2 x 1		3	4	4	1	384		0.013	0.022
Be tritium inventory &rec.		2 x 3		4	4	1	96		0.004	0.005
SB/Be interaction	4 x 2 x 1	2 x 1	3	4	4	1	768		0.035	0.043
Be/structure mechanical inter.		2 x 1	3	4	4	1	96		0.004	0.005

EXAMPLE SOLID BREEDER TESTS IN VENUS

Tests	SB	Be	Structure	Config.	Total	Element Size (Test size)	Volume m^3	FW Area* m^2
Multiple Effect Tests (submodule)								
Thermal:								
water	4	1	1	2	8	10 x 50 x 30 cm	0.288	0.48
helium	4	1	1	2	8	(15 x 60 x 40 cm)	0.288	0.48
Corrosion:								
water	4	1	1	2	8		0.288	0.48
helium	4	1	1	2	8		0.288	0.48
Tritium Recovery and Permeation:								
water	4	1	1	2	8		0.288	0.48
helium	4	1	1	2	8		0.288	0.48
Integrated Tests:								
Module:								
Full module performance verification:								
water	2	1	1	2	4	1 x 1 x 0.5 m	4.03	3.36
helium	2	1	1	2	4	(1.2 x 1.2 x 0.7 m)	4.03	3.36
Qualification (5 x selected configuration)	1	1	1	1	5		5.04	4.2
Lifetime (1 x initial preferred conf.)	1	1	1	1	1		1.01	0.84
Sector								
Prototypical full sector test	1	1	1	1	1	6 x 1 x 0.5 m (6.5 x 1.2 x 0.7 m)	5.21	4.55

---

* Preliminary assumption is that all submodules and modules require plasma interface. FW test area estimates are thus quite conservative.

Liquid Metal Blanket Test Types

- Specimen/Element Testing
  - Irradiation effects on material properties and physical integrity
  - Test will continue during all of testing phase, but specimens will be pulled or replaced frequently.
  - Data provides input to module and sector test design and operation.
  - Data will be compared to laboratory and fission reactor data.
- Submodule Testing
  - Scoping Test
  - Tests will address critical issues and short term failure modes in related with various design concepts
- Module Testing
  - Performance Validation Tests
  - Integrated performance
    - MHD/Thermal Hydraulics
    - Mass Transfer
    - Thermo-mechanical Behavior
    - Failure Mode Scoping
    - Tritium Recovery/Containment
    - Transient Behavior
  - Results of module tests will be used to select concepts/design for segment tests and provide long term data for DEMO blanket
- Segment Testing
  - Prototypic Configuration/Maintenance
  - Prototypic Poloidal and FW Boundaries
  - Reliability Testing

Liquid Metal Test Matrix

Tests	Typical Test Article Sizes (Toroidal x Poloidal x Radial; cm)	Number of Test Articles
Basic tests (Specimen/Element)		
Structural material irradiated properties	2.54 x 1 x 2.54	5000
Insulator material irradiated properties	2.54 x 1 x 2.54	500
Welds/brazed joints behavior experiments	10 x 10 x 10	100 (material x shape x fluence)
Multiple-effect/multiple interaction tests (Submodule)		
Corrosion verification	25 x 25 x 25	2x2x3 (material x velocity x temperature x redundance)
Welds/Brazed joints with flow	25 x 25 x 25	5 x 2 x 3 x 5 (geometry x velocity x temperature x redundance)
Insulator self-healing	25 x 25 x 25	5 x 2 x 3 x 5 (geometry x velocity x temperature x redundance)
MHD pressure drop	25 x 25 x 25	5 x 3 x 5 (geometry x velocity x redundance)
Transient electromagnetic effect	Variable x 25 x 25	5 x 5 (toroidal dimension x redundance)
Performance Validation (Module)		
Integrated performance test - stage 1	100 x 100 x 50	5 x 3 (concept x redundance)
Integrated performance test - stage 2	100 x 100 x 50	3 x 3 (concept x redundance)
Reliability Growth	100 x 100 x 50	9
Total Test Area for LM (m^2)	15	

Divertor Testing Possibilities in VNS

Groundrule:

In VNS, stable and reproducible plasma conditions are important for the mission. (Basic divertor operation should not be affected by testing).

Fixed Parameters

- plasma-facing material in the divertor
- divertor overall geometric envelope

Test Parameters

- coolant composition and conditions
  (temperature, pressure, chemistry, tritium concentration & chemistry)
- heat sink material (copper alloys, refractory alloys, carbon, Be)
- channel configuration (fins, roughening, flow paths, ...)
- method of bonding plasma-facing material to coolant
  - monoblock
  - duplex braze
  - liquid braze

Divertor Test Summary

1. Basic Machine Divertor Test Schedule

Initial performance verification
- thermal hydraulic and mechanical behavior
- tritium balance

Operating range demonstration and transients
- off-normal demonstration of thermal hydraulic and mechanical

Long-term operation
- observe thermal-hydraulic and mechanical behavior
- observe tritium behavior and loop chemistry
- occasional removal and replacement of panels for PIE

2. Alternate and Advanced Design Tests

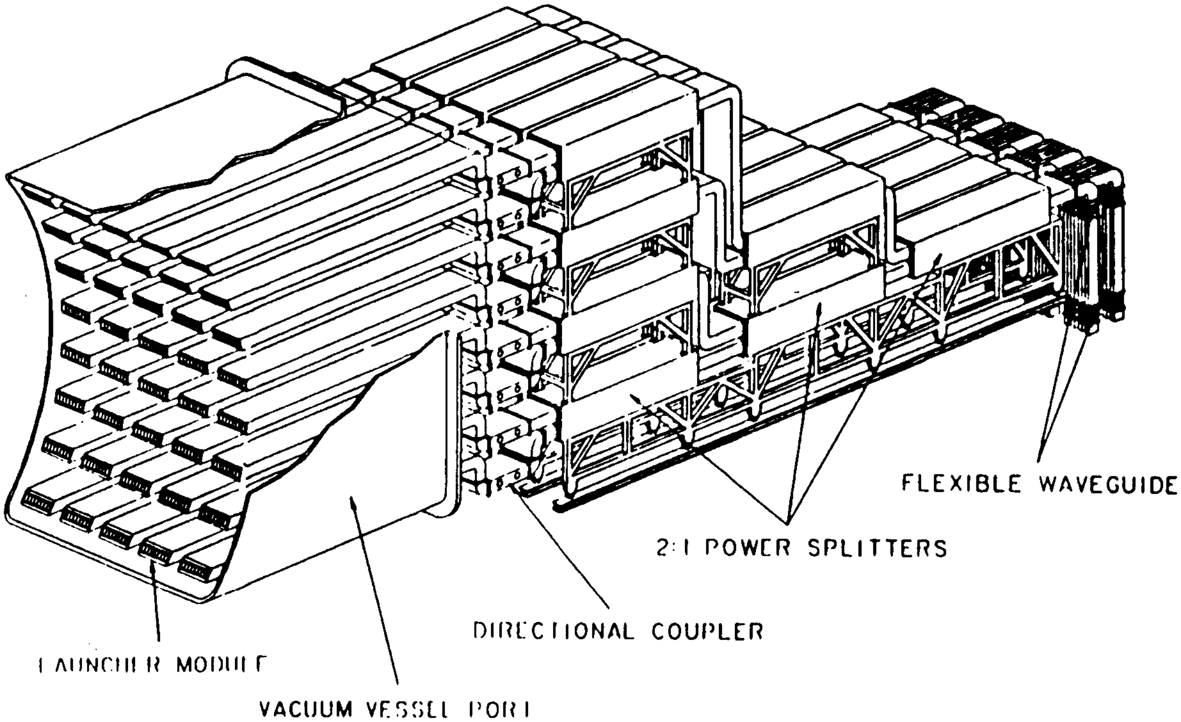
Test Port Submodules (25 cm × 25 cm)
- Materials Combinations × Configurations ~ 10
- Test Redundancy ~3 → 30 submodules

Full Divertor Panel (1 m × 1 m)
- Reduce design options to 2–3
- Reduce redundant tests to 1–3
- → ~5 total

Full Divertor Sector
- 1 or 2 (possibly)

Heating and Current Drive Systems Test Program

The primary nuclear component is the launcher array (~1.5 m × 2 m)



ITER LOWER HYBRID CURRENT DRIVE LAUNCHER

Key features:

- very close to plasma
- complex, actively-cooled structures (this is a **high-heat-flux** component)
- electrical insulators at the vacuum vessel with simple streaming paths
- Be cover and protective limiters needed
- open paths for particle and radiation transport

Changes in performance are likely due to nuclear effects:

- electromagnetic spectrum degradation
- reduced coupling to the plasma
- thermomechanical issues
- shielding effectiveness

Observations:

- waveguides and launchers are important nuclear components, requiring a substantial development and testing effort
- at present, nuclear aspects of heating and current drive seem to be ignored

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
  > 1MW/m^2 (prefer 2 if possible)

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

- No Breeding Blanket
  Avoidance use of unproven technologies

- Maximum Power Requirements < 700MW

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

Example of VNS Tokamak Design

[Examples only Based on Conservative Assumptions; Trade off Studies are Presented Later; More Effort is Necessary to Select an optimum design]

	Normal Conducting	Superconducting
Average Neutron Wall Load (MW/m^2)	1.0	1.0
Major Radius, M	2.83	5.52
Aspect Ratio	3.4	4.2
Axial Magnetic Field, T	7.1	7.2
Plasma Current, VA	6.2	7.9
Total Fusion Power, MW	160	500
Current Drive Power, MW	60	110
Inboard Shield thickness, m	0.2	0.9
Q	2.7	4.9
TF Resistive Power, MW	500	N/A
Power Operating Cost (M$/yr) (at 30% availability)	90	35
Direct Cost (B$)	1.9	2.5

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

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 $MW \bullet y/m^2$
  - 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

ITER Fluence Scenario (Preliminary)

		Neutron Wall Load		Required Burn Time/yr (duty cycle × A)	Accumulated Fluence	
Year	Plasma	Average	on Port		Average	on Port
Basic Performance						
1	H D	0	0	0	0	
2	H D, D ^{3}He	0	0	0	0	
3	D T	2.0	2.8	0.005	0.01	0.014
4	D T	2.0	2.8	0.005	0.02	0.028
5	D T	2.0	2.8	0.01	0.04	0.056
6	D T	2.0	2.8	0.01	0.06	0.084
7	D T	2.0	2.8	0.02	0.1	0.14
8	D T	2.0	2.8	0.02	0.14	0.20
9	D T	2.0	2.8	0.025	0.19	0.27
10	D T	2.0	2.8	0.025	0.24	0.34
11	D T	2.0	2.8	0.03	0.30	0.42
12	D T	2.0	2.8	0.03	0.36	0.50
Extended Performance						
13	D T	2.0	2.8	0.1	0.56	0.78
14	D T	2.0	2.8	0.1	0.76	1.06
15	D T	2.0	2.8	0.1	0.96	1.34
16	D T	2.0	2.8	0.125	1.21	1.7
17	D T	2.0	2.8	0.125	1.46	2.0
18	D T	2.0	2.8	0.15	1.76	2.5
19	D T	2.0	2.8	0.15	2.06	2.9
20	D T	2.0	2.8	0.15	2.36	3.3
21	D T	2.0	2.8	0.15	2.66	3.7
22	D T	2.0	2.8	0.15	3.0	4.2
Shutdown, Maintenance Demonstration						
23–24		0	0	0	3.0	4.2

List of Issues for VNS

- Need High Availability
- Radiation Effects on Normal Conducting Copper
- Radiation Limits on Insulator
- Feasibility of Ceramic Insulator
- Divertor Heat Load
- Current Drive