USA Progress Report On
ITER Test Program

Presented by

Mohamed A. Abdou

Alice Ying

Contributors:

M. Abdou
M. Tillack
A. Ying
S. Sharafat
M. Youssef
R. Mattas

US View on the ITER Test Program

" The development of a viable Test Program on ITER is vital to the mission success of ITER and to the US interests for the successful development of fusion energy."

(Dr. C. Baker, US Home Team Leader)

However

- Resources for the Test Program are very limited
- JCT credit (D2 and D3) is very small
- Coordination between Home Teams and JCT needs substantial improvement

USA Progress Report on ITER Test Program

Outline

- Framework for Fusion Nuclear Technology Development: US Perspective
- Requirements on Fusion Testing
  - Major Parameters
  - Engineering Features
- Benefits of ITER Basic Device Operation
- Test Port Design, Configuration, Maintenance [Integration Issues]
- Test Program Description
  - Solid Breeder
  - Materials
  - Divertor
  - Liquid Metals
  - Neutronics
  - rf antenna
- Ancillary Equipment
  - Description
  - integration requirements
- International Program Approach and Issues

Components and Technical Areas for Test Program

1. Blanket / First Wall

2. Plasma Interactive and High Heat Flux Components
    - Divertors, Limiters
    - PFC parts of Plasma Heating, Current Drive (rf antennas, launchers, etc.)

3. Materials

4. Shield

5. Neutronics

6. Tritium Processing System

7. Instrumentation and Control

8. Heat Transport and Power Conversion

Table 1. 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
Plasma mode of operation	Steady state or very long burn, short dwell
Net plant availability	> 50% (demonstrate reliability and maintainability)
Thermal conversion efficiency (gross electric/thermal power)	> 30%
Disruption resistance	One major disruption during lifetime

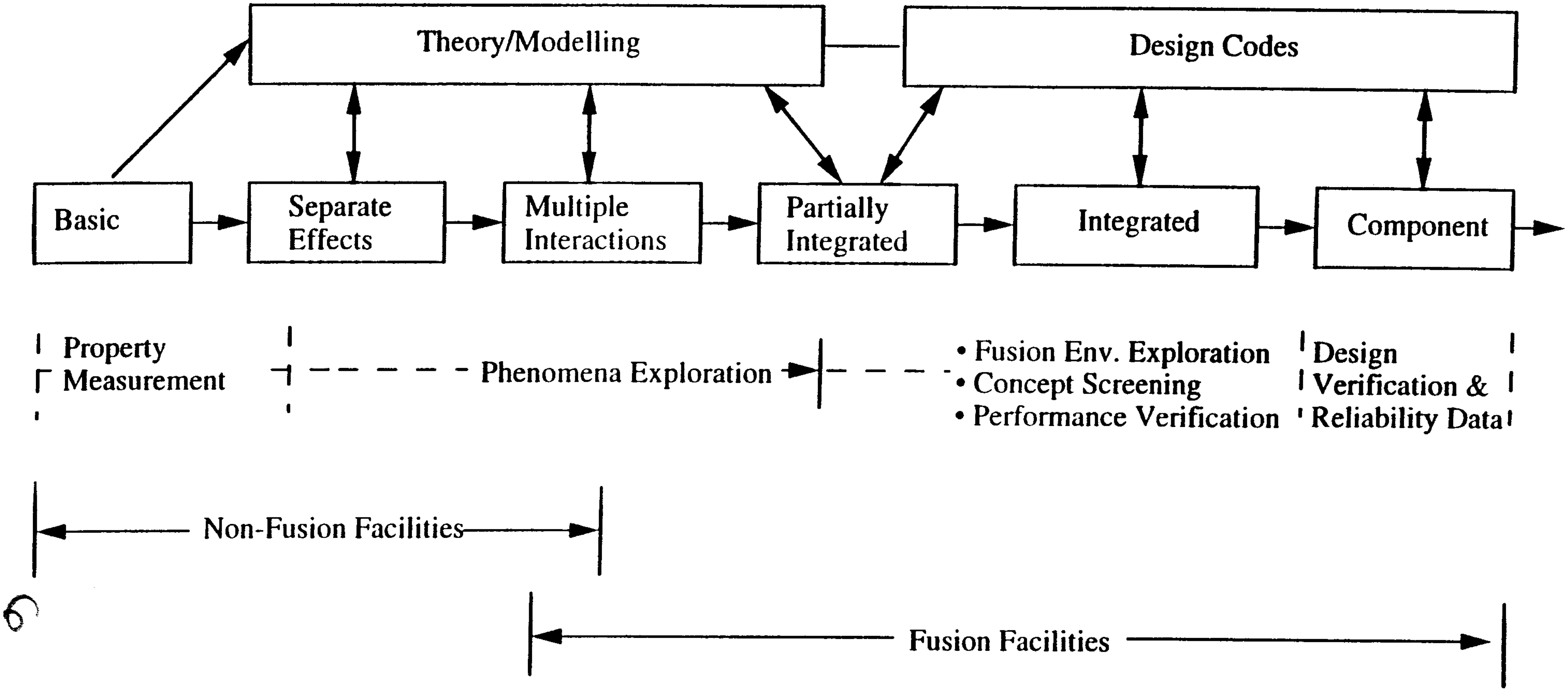
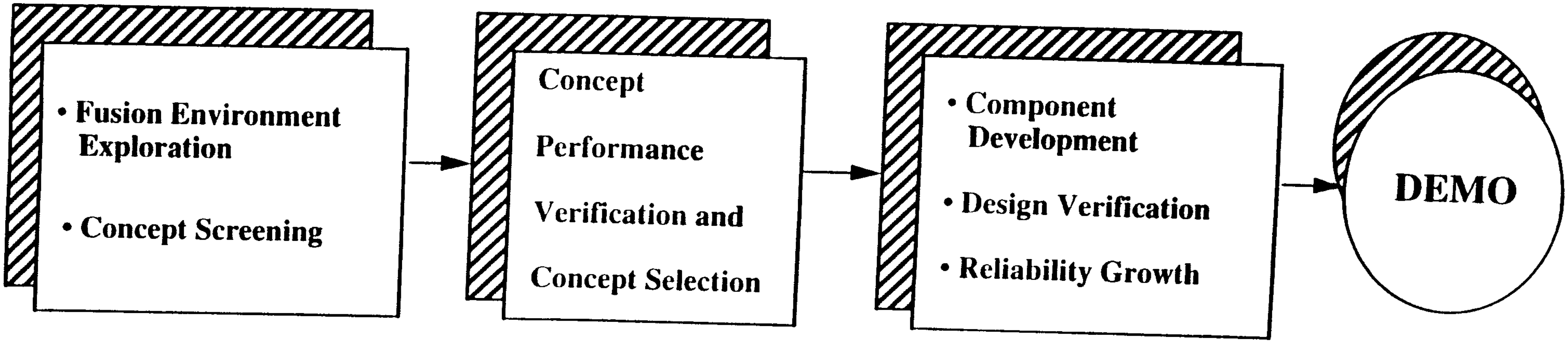


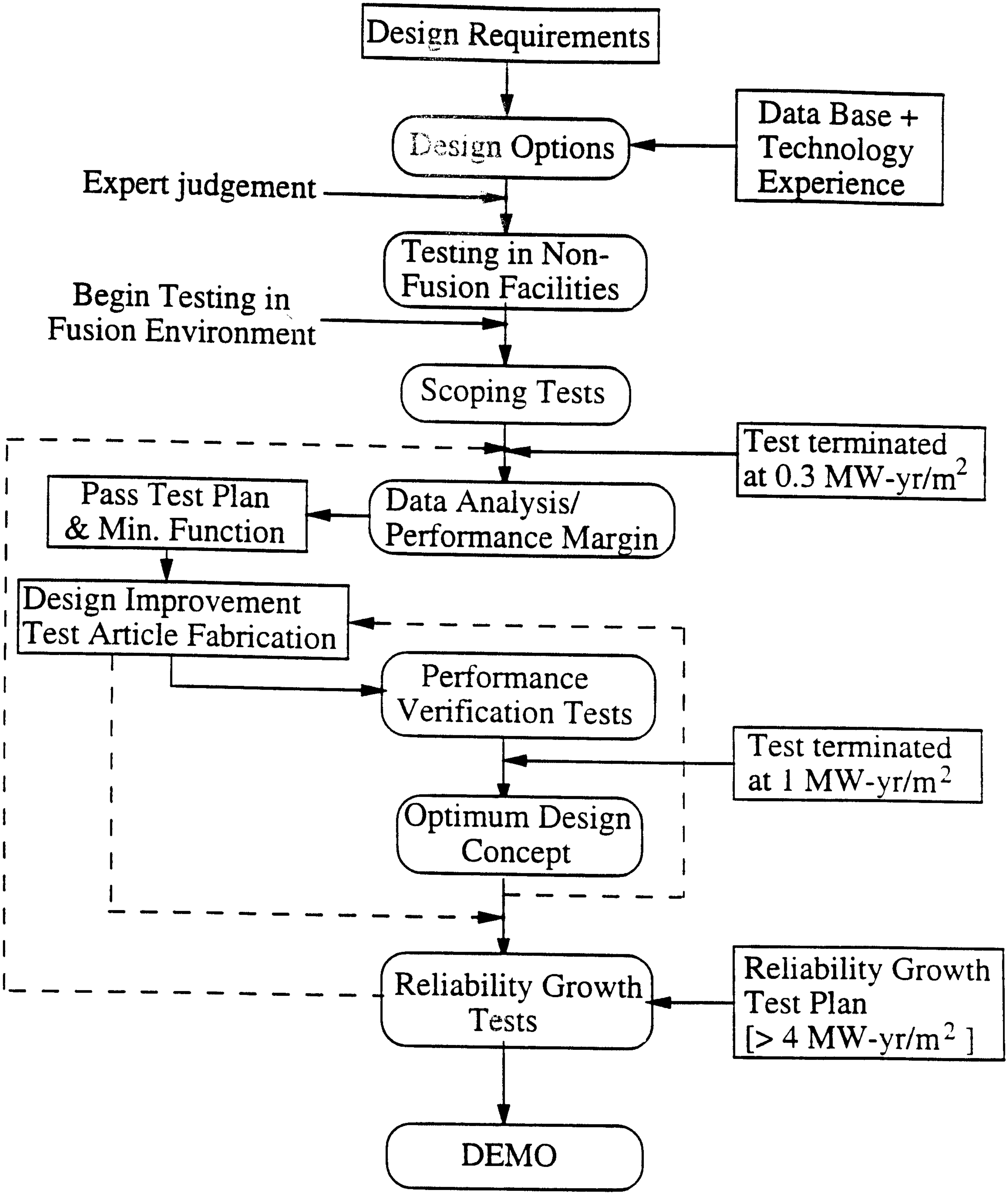
Figure 1. Types and role of experiments and facilities for fusion nuclear technology



	Stage I	Stage II	Stage III
Required Fluence MW-y/m^2	0.3	> 1	> 4 - 6
Size of Test Article	submodules	modules	modules/sectors

Figure 2. Stages of fusion nuclear testing in fusion facilities

Fusion Nuclear Technology Development Approach



Scope of Testing in ITER

Information Obtained from Basic Device

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

Testing in Specialized Test Ports

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

- Materials Test Module
  - Material Properties Specimen Matrix

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

- Alternate Current Drive and Heating Launchers

Fusion Nuclear Technology Testing Requirements on Fusion Testing Facility Parameters

Device Parameter	Minimum for a useful Test Facility	Needed Prior to DEMO
Average neutron wall load at the test module, MW/m^2	1	1-2
Average surface heat flux at the test module, MW/m^2	0.2	0.4
Annual neutron fluence (at the test module), $MW\text{-}yr/m^2$	> 0.1	0.4
Total neutron fluence (at the test module), $MW\text{-}yr/m^2$	≥ 1	4
Device total neutron fluence (average at the first wall), $MW\text{-}yr/m^2$	2	6
Plasma burn time	≥ 1000 s	1 - 3 hours (to steady state)
Dwell time	*	≤ 20 s
"Continuous" test duration	≥ 1 week	2 weeks
Number of "continuous" tests per year	3	7
Average availability	10 - 15%	30 %
Number of ports	5	7 (+ segment or sector)
Minimum port size	2 - 3 m^2	outboard segment
Total test area	10 m^2	20 - 30 m^2 (+ segment or sector)

* Minimum acceptable dwell time is highly dependent on the design concept, and is difficult to specify. Further analysis in this area is recommended.

Fusion Nuclear Technology Testing Requirements on Configuration and Engineering Features of Testing Facility

1. Need exposure of test module first wall to plasma.

2. Need easy access to place and remove test article (access to inside of vacuum vessel without welding and rewelding).

3. Sufficient space at the first wall:

   - adequate dimensions in the poloidal and toroidal directions for test articles (varies among design concepts to be tested).

   - space around test modules for boundary conditions.

   - space for manifolds, and access lines (purge streams, etc.), and instrumentation.

4. Space outside the reactor for ancillary equipment supporting the test program (heat rejection, tritium processing, etc.).

Present Issues for ITER Test Program Activity

1. Plasma Dwell Time:

Desirable:	< 50 S
Acceptable:	< 200 S
ITER:	~ 1200 S

Can plasma dwell time be reduced in ITER?

Burn time:

ITER: 1000 S

Acceptable but some tests can be more useful if burn time is increased (longer burn is particularly more crucial for long dwell time).

Present Issues for ITER Test Program (Cont'd)

2. Fluence:

Needed by the year 2015: >3-4 MW y/m2
ITER BPP: 0.1-0.3 MW y/m2
by the year 2015

- Can something be done to enhance BPP fluence?
- We should try hard to have test program start from day one of DT operation during BPP

3. COT and Test Campaign Definition for BPP

Needed:	> 1-week periods of back to back cycles (i.e. device availability 100%).
ITER BPP:	Only 1 month integrated burn time during BPP?

- What is the resolution here? What can we assume for ITER operation?

Present Issues for ITER Test Program (Cont'd)

4. Plasma Exposure

- Most test modules need to be exposed to the plasma. Is this acceptable from ITER Basic Design Viewpoint?

- Be coating redeposition on test module surfaces may be an issue. Need analysis.

5. Test Port: Shape, Size and Access

CDA:	1 x 2 m^2,	rectangle, horizontal, single-motion maintenance.
EDA:	0.7 x 6 m^2,	odd shape, complex withdrawal procedure.

- Implications on test module design and prototypicality.
- Implications on access, removal and replacement.

Present Issues for ITER Test Program (Cont'd)

6. Safety Restrictions
   e.g. Liquid Metal Compatibility with Water

7. Approach to International Test Program and Test Port Allocation

Other Issues for Test Program

A. Resources to develop and analyze details of test programs.

B. Distributing responsibilities and coordination among parties and JCT.

C. R & D for developing Test Module (Hardware).

Benefits of ITER to Fusion Components Development

- Benefits (to DEMO and beyond) come from two areas:

    1.) Information form operation of Basic Device components (e.g. TF coils, plasma heating system test program)

    2.) Information from test program experiments (specific test articles, e.g. blanket modules)

- Benefits from Basic Device:

    1.) Construction and Short Term Operation

    - Confirmation of analytical techniques, manufacturing processes, environments and operational characteristics.
    - Validation of performance in early life

    2.) Long Term Operation

    - Failure Mode Identification
    - Failure Rate Data
    - Failure Recovery Time

- How to Obtain Benefits from Operating Basic Device:

To obtain these benefits, a special purpose goal-oriented program must be established for:

1.) Documentation
Document information and lessons from construction, assembly, operation ,failures, etc.

2.) Instrumentation
Special purpose instrumentation to measure performance parameters (e.g. on ITER basic components, temperature, strains, etc.) during operation.

3.) Failure Mode Characterization
Detection systems and analysis program to identify failure modes, causes and effects.

4.) Reliability Data
Program to collect and analyze "reliability" data and to extrapolate to DEMO. Requirements can be quantified here to obtain useful data. [work in progress]

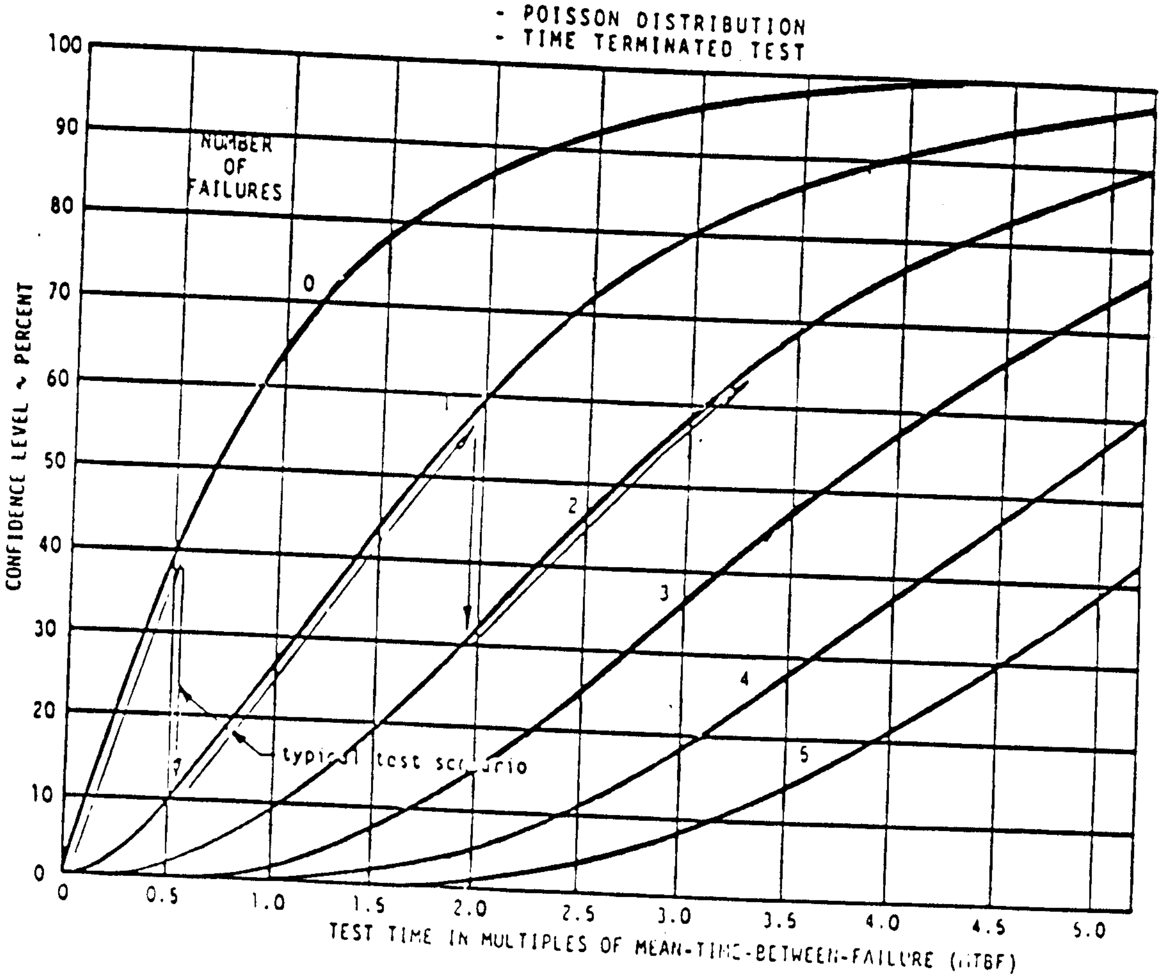


FIG. XII.4-1. A constant failure rate is the standard choice for reliability deonstration*

*REF: Anthony Coppola, "Bayesian Reliability Tests are Practical" RADC-TR-81-106, July 1981.

ITER BLANKET TEST–PORT CONFIGURATION, REPLACEMENT, AND MAINTENANCE APPROACH

M. Abdou
A. Ying, S. Sharafat,
M. Tillack

ITER Blanket Test Program Meeting
Garching, Germany
April 1994

CROSS SECTIONAL VIEW OF ITER TEST PORT CONFIGURATION

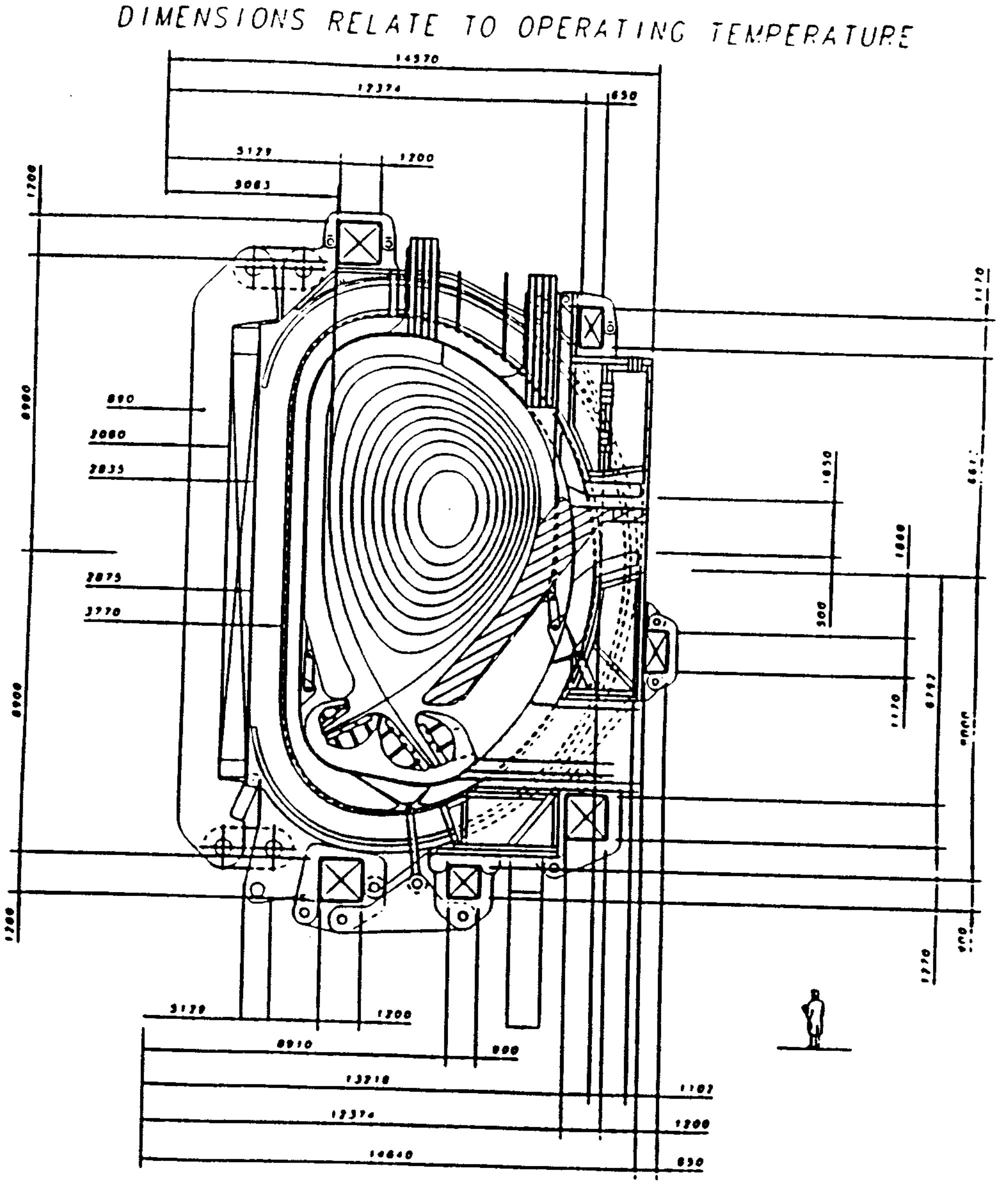


Fig. 6.1: ITER section showing the space allocation for blanket test modules.

Test Port Design, Configuration and Maintenance

- Using present ITER configuration
  [6 ports, each is half outboard segment 0.7 m x 6 m x 0.6 m]

  - we suggest three different configurations:

    1) 6-12 submodules arranged within the port
    2) 2-3 subsections, each section occupying the full poloidal length of the test port
    3) only one module occupying the test port

  - we developed engineering design details

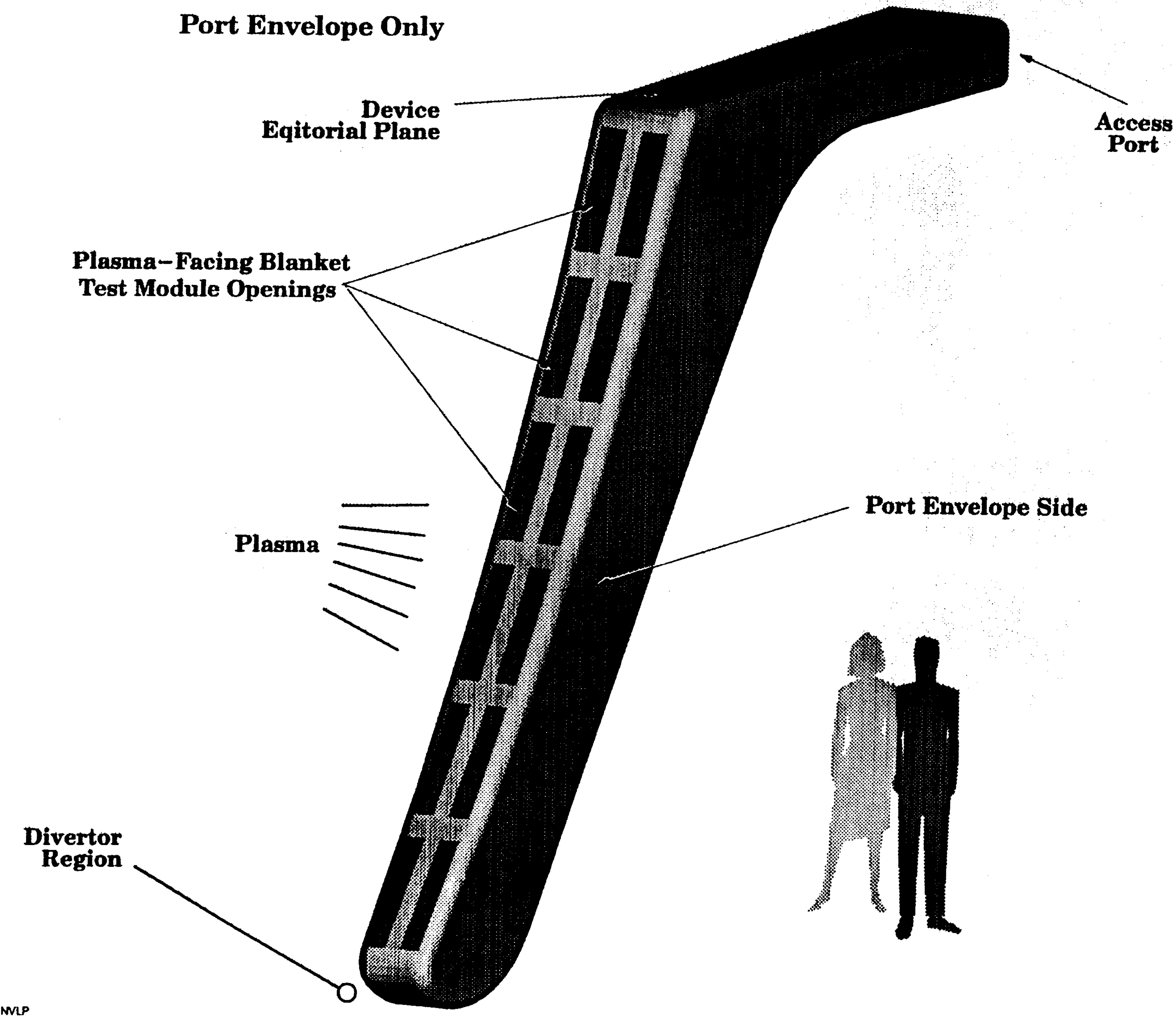
  - we identified several serious concerns and problem areas

- <u>Alternative test port for ITER</u>

  we began to identify other alternatives to the present test port configuration design

ITER BLANKET TEST–MODULE PORT

Port Envelope Only

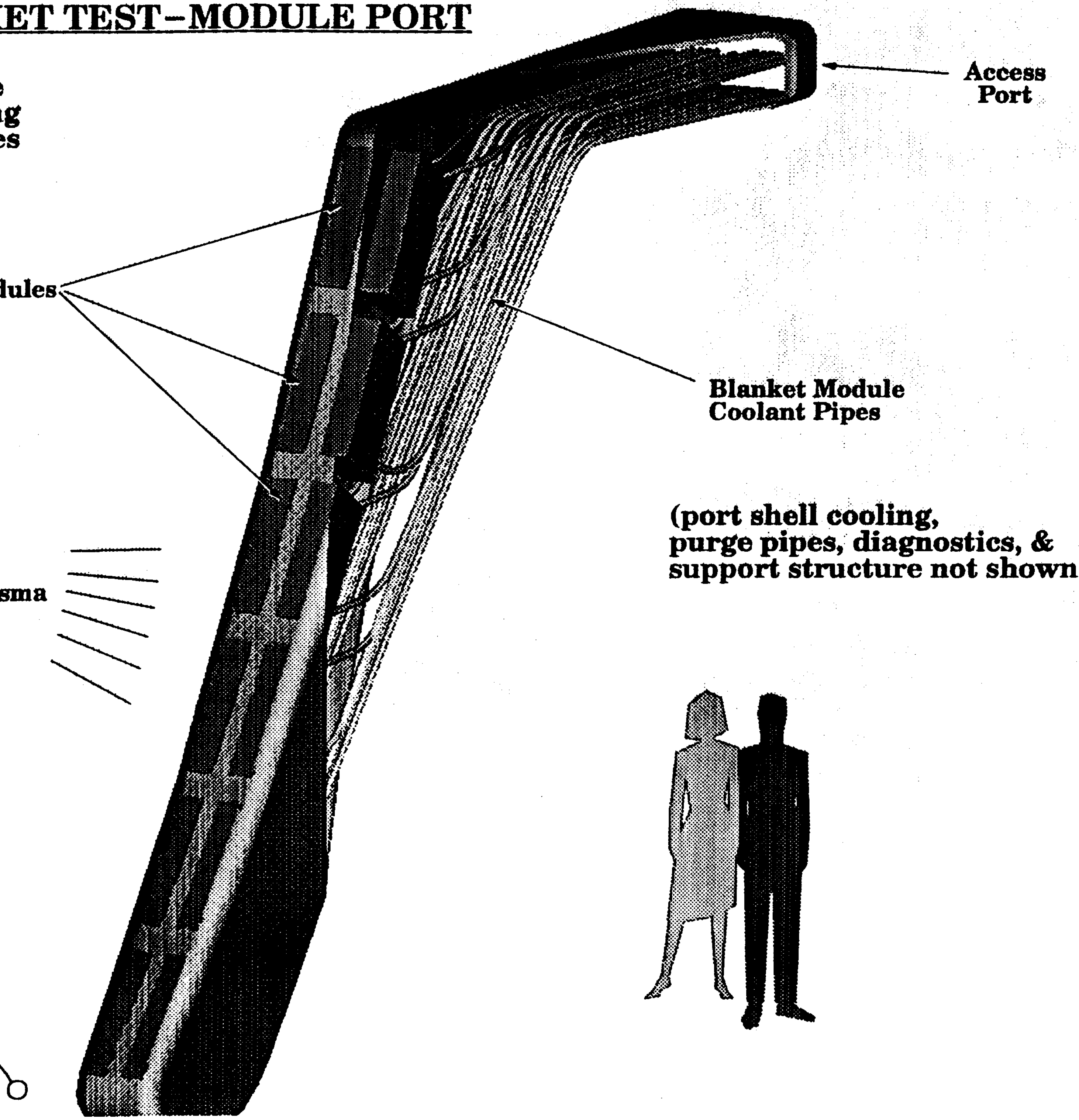


23

UCLA
93 9404 PORT ENVLP

ITER BLANKET TEST–MODULE PORT

Cut Envelope
Module Piping
All 12 Modules



Access Port

Blanket Test Modules

Blanket Module Coolant Pipes

Plasma

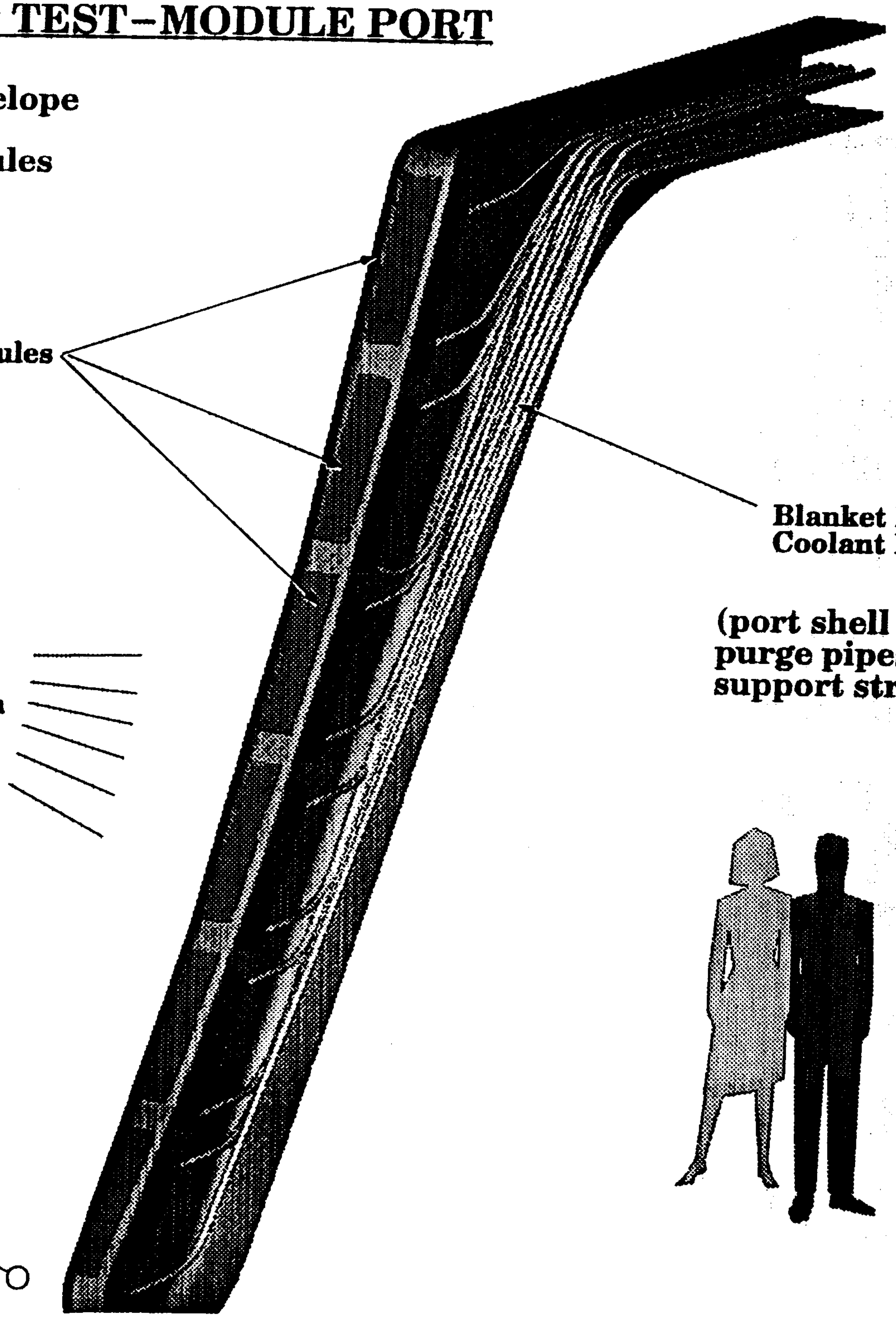
(port shell cooling, purge pipes, diagnostics, & support structure not shown)

Divertor Region

UCLA
SS:9403 TP PP RCUT

ITER BLANKET TEST-MODULE PORT

Half of Port Envelope
Module Piping
6 of 12 Test Modules



Access Port

Blanket Test Modules

Blanket Module Coolant Pipes

(port shell cooling, purge pipes, diagnostics, & support structure not shown)

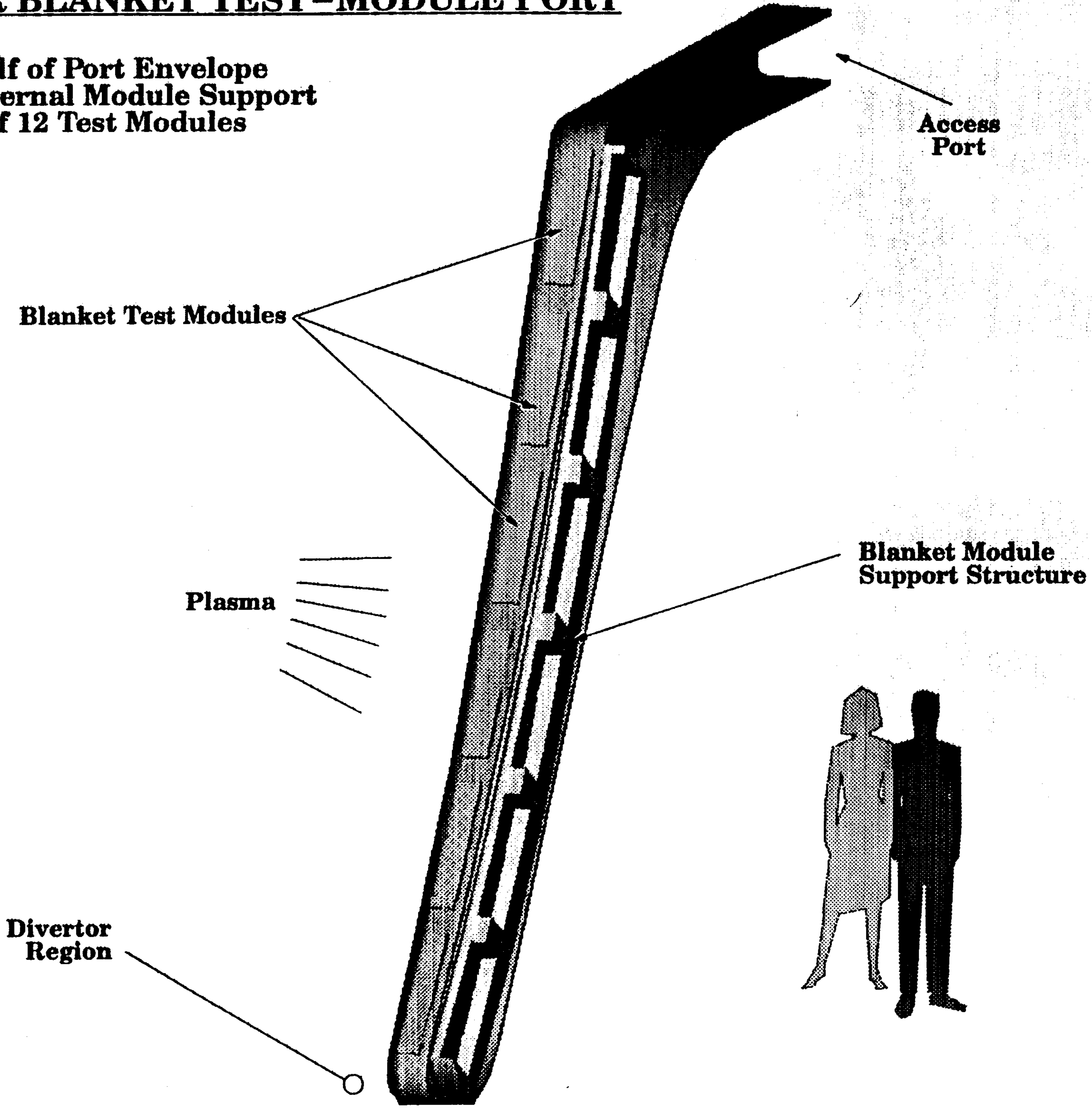
Plasma

Divertor Region

UCLA
SS 9403 TP PP HLF

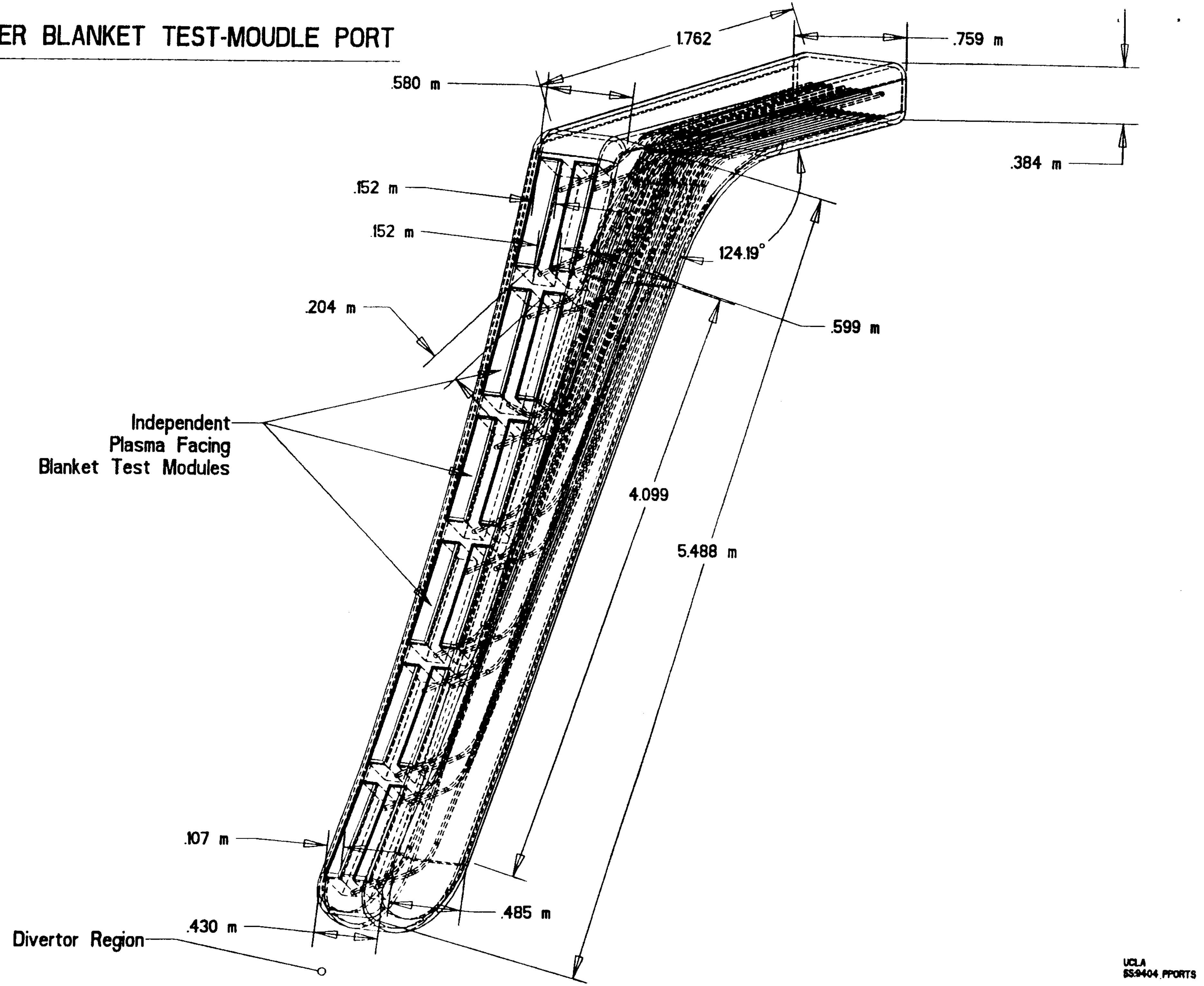
ITER BLANKET TEST–MODULE PORT

Half of Port Envelope
Internal Module Support
6 of 12 Test Modules



UCLA
SS 9403 TP OP SUP

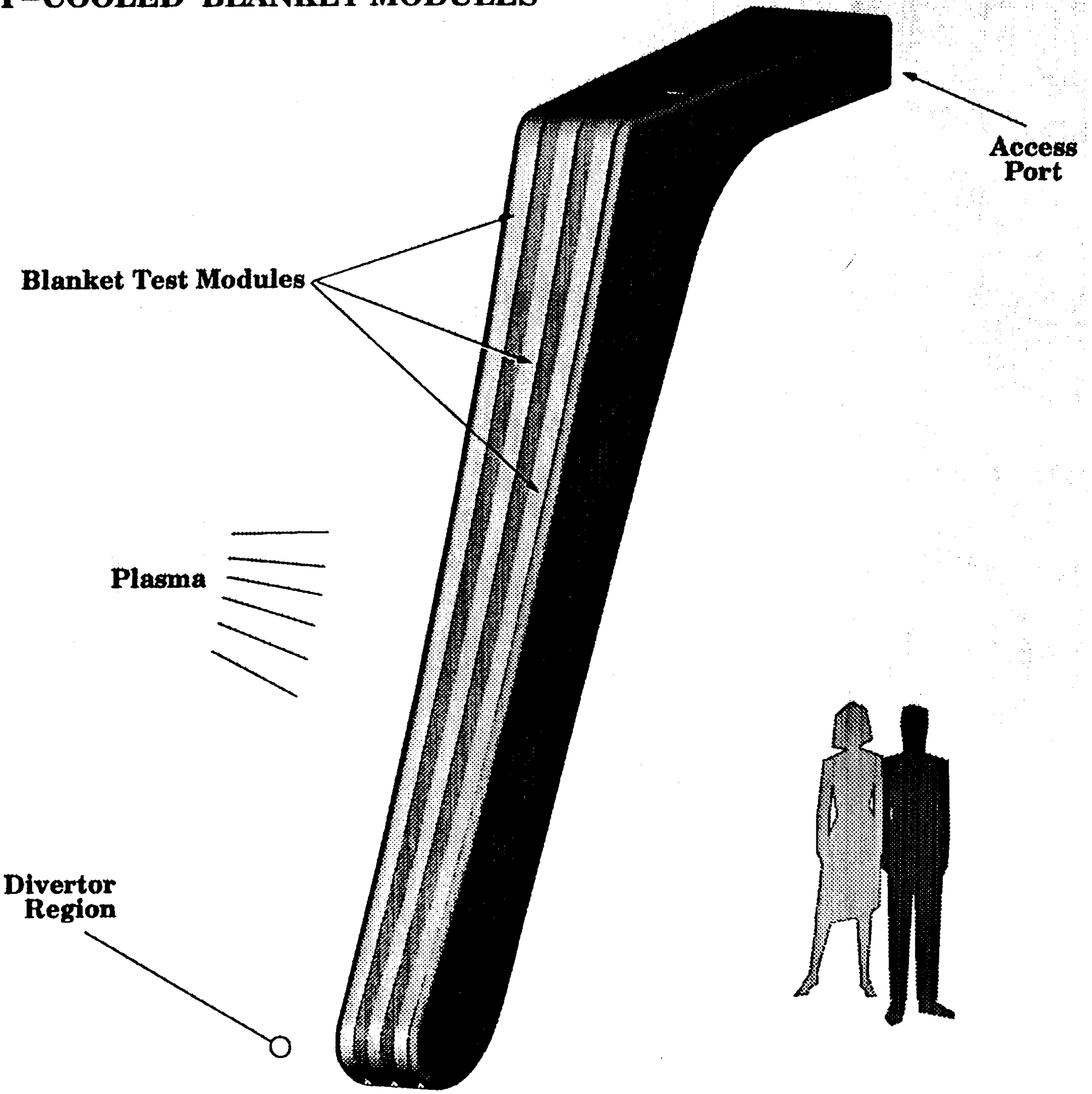
ITER BLANKET TEST-MOUDLE PORT



UCLA
SS9404.PPORTS

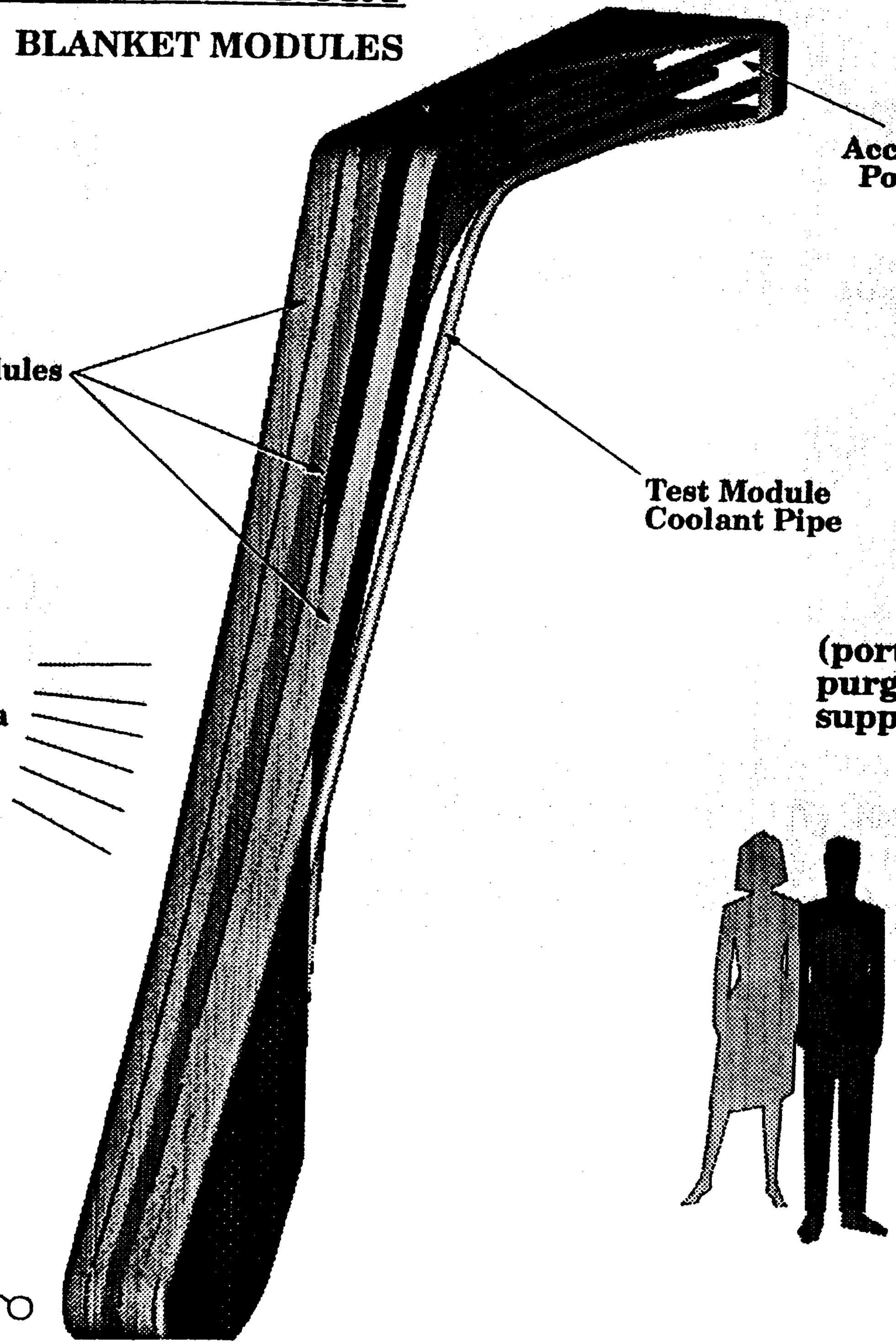
ITER BLANKET MODULE TEST PORT

POLOIDALLY-COOLED BLANKET MODULES



ITER BLANKET MODULE TEST PORT

POLOIDALLY-COOLED BLANKET MODULES



Access Port

Blanket Test Modules

Test Module Coolant Pipe

Plasma

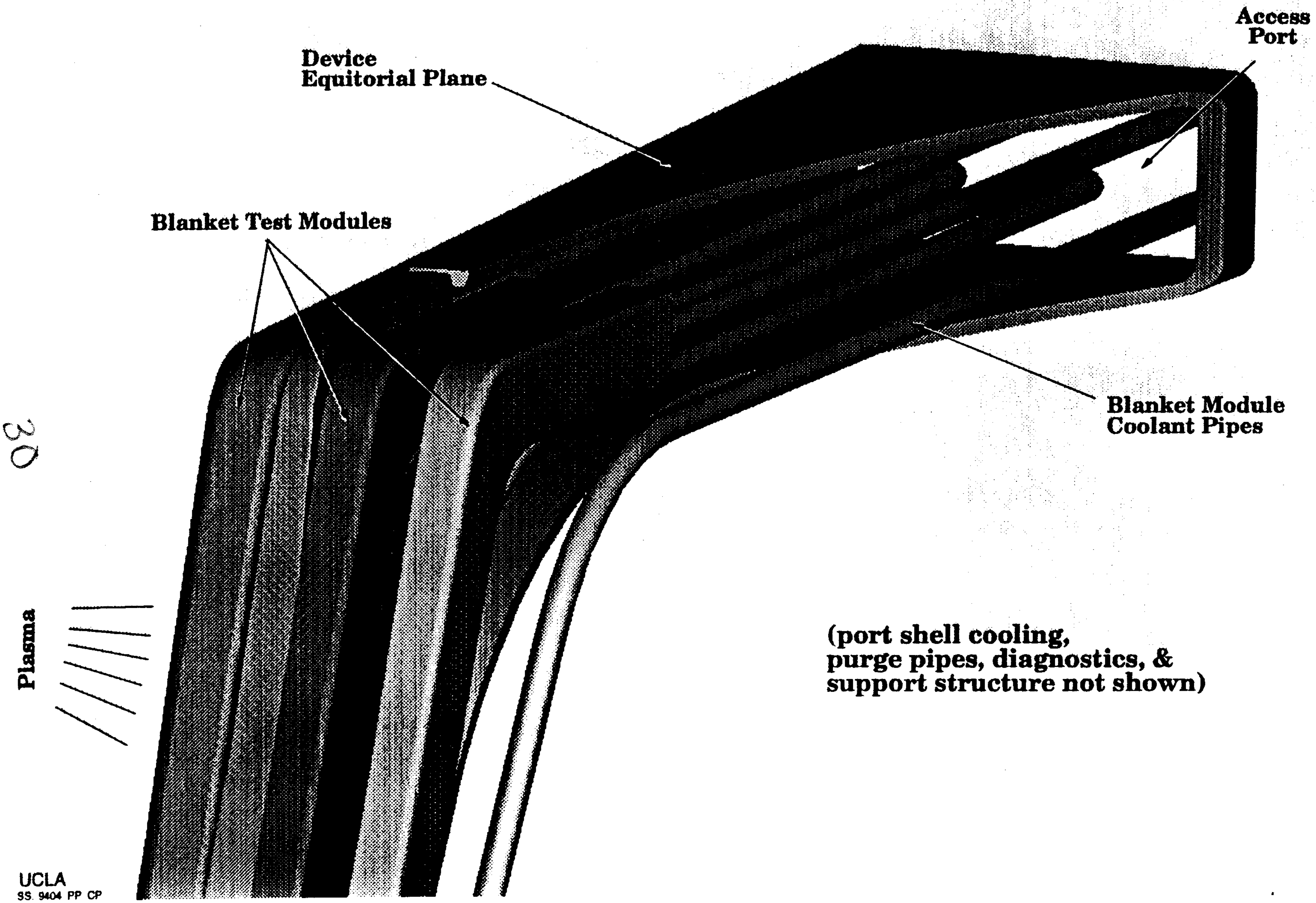
(port shell cooling, purge pipes, diagnostics, & support structure not shown)

Divertor Region

UCLA
SS.9403 PP OP

ITER BLANKET MODULE TEST PORT

POLOIDALLY–COOLED BLANKET MODULES
(closeup view)

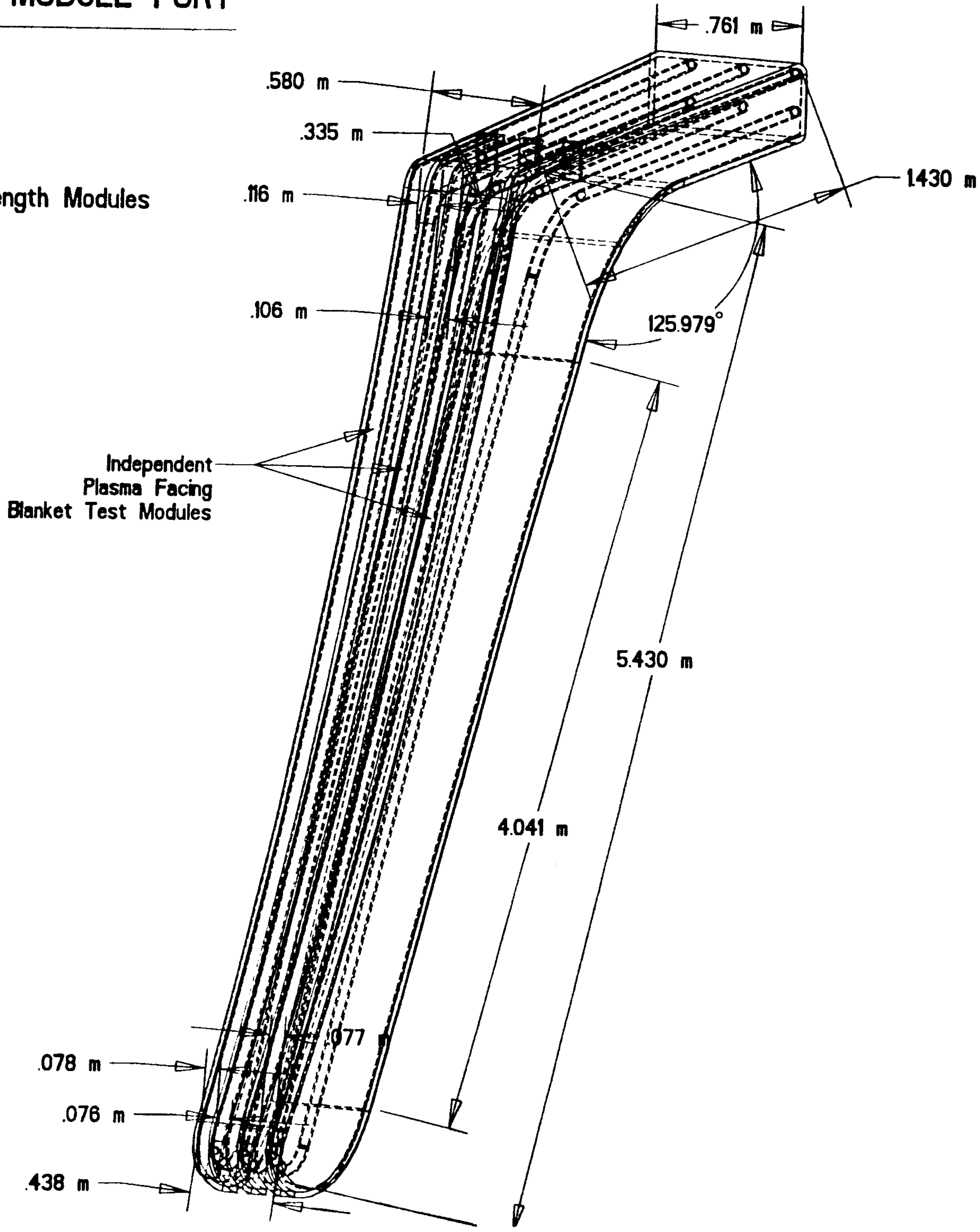


(port shell cooling,
purge pipes, diagnostics, &
support structure not shown)

UCLA
SS. 9404 PP CP

ITER BLANKET TEST-MODULE PORT

Toroidally-Cooled Full-Length Modules



UCLA
SS9404 PPORTS

Drawbacks of Present ITER Test Port

- Access and Maintenance

  - present test port configuration requires removal of entire test port for replacement of any single submodule

  - once the test port is removed, replacement of the submodules is difficult and time consuming:

    - removal of many submodules to gain access to "lower" submodules
    - may need to break port envelope structure

Note: Direct access to remove individual submodules independent of other submodules is crucial because

- replacement schedule (e.g., fluence interval) varies greatly among submodules
- individual submodules may fail

- Size and Shape
  - all supply lines (coolant, gas purge, etc.) for all test submodules must pass through a single opening of the test port

    Nearly impractical: overcrowding, have to handle all supply lines in order to extract one single submodule
  - width in toroidal direction not enough for some toroidally cooled test modules
  - need for "time-independent" boundary condition may limit severely the size and number of submodules
  - difficult to design "support" of submodules
- Need to cool the test port structure envelope
- Vacuum Seal

  Interface between test port and vacuum vessel needs to be studied.

  Does it account for "open port" for module exposure to plasma?

Suggested Alternative to ITER Test Port Configuration

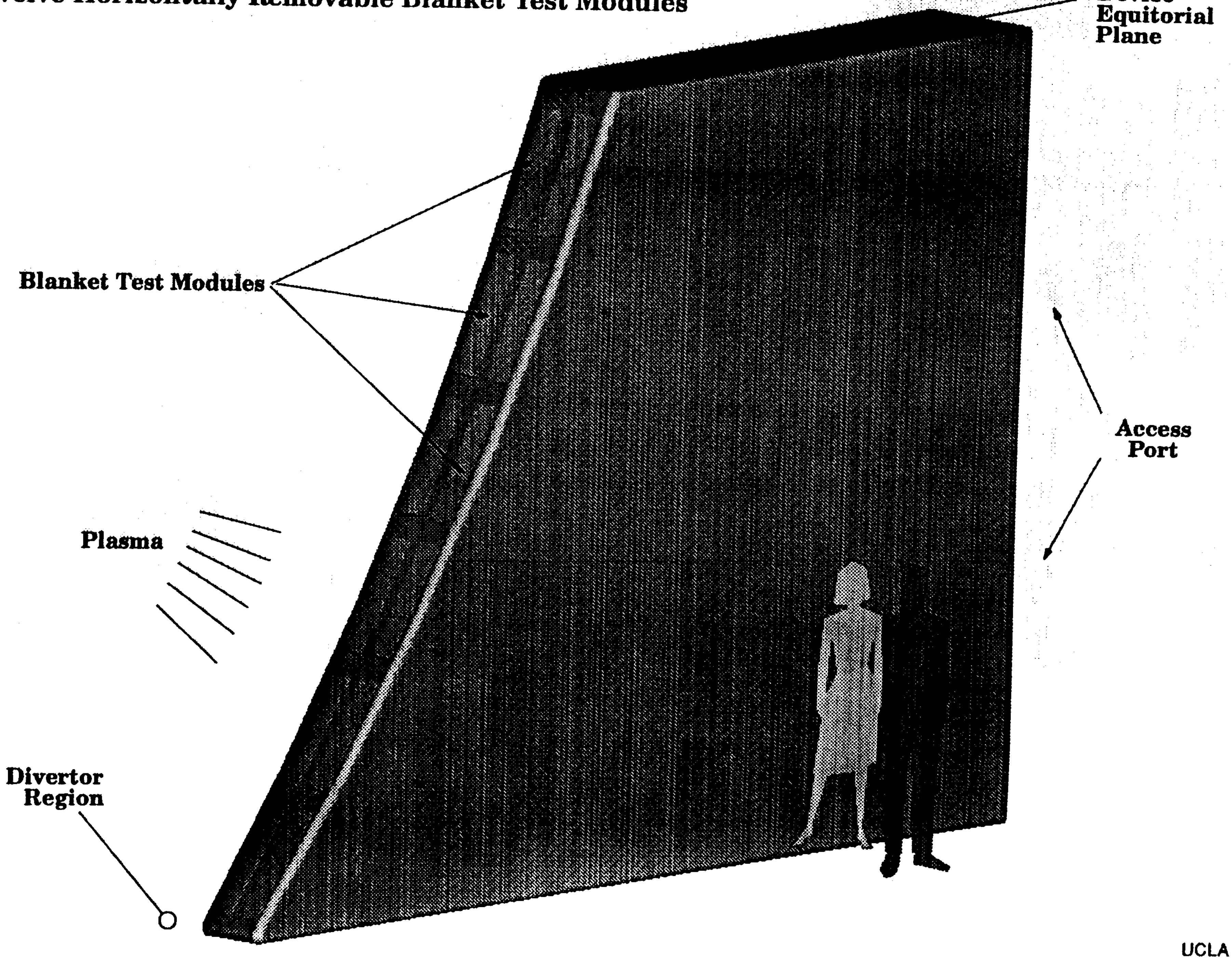
- Need configuration that allows
  - rapid insertion/removal
  - operations on one submodule should be independent of other submodules
  - avoid welding/rewelding of vacuum seals

- Suggested Option

Horizontal Submodule Removal Concept

A Preferred Alternative to the ITER Test Port Design

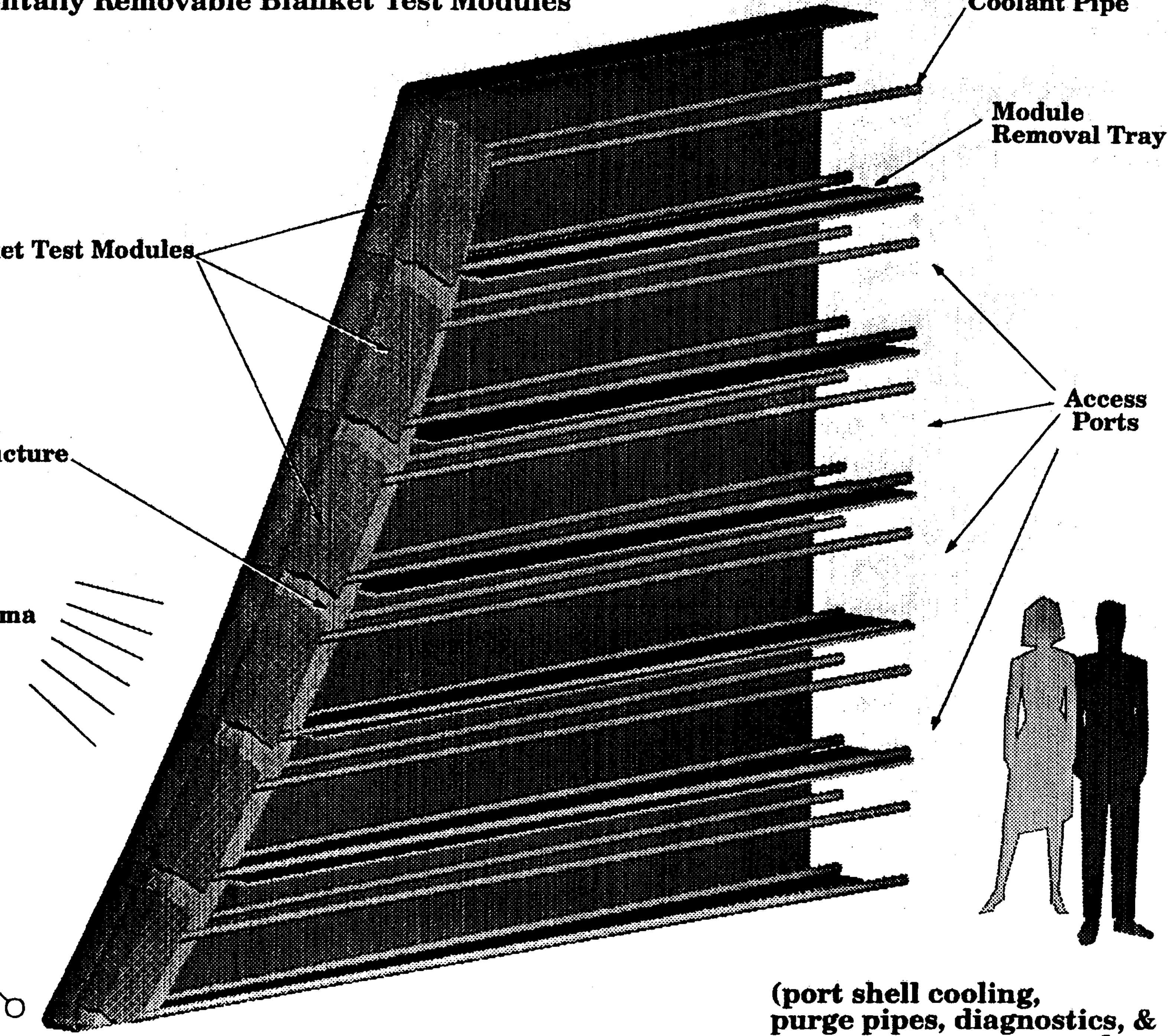
Twelve Horizontally Removable Blanket Test Modules



UCLA
SS: 9404_HP

A Preferred Alternative to the ITER Test Port Design

Twelve Horizontally Removable Blanket Test Modules



(port shell cooling,
purge pipes, diagnostics, &
support structure not shown).

UCLA
SS:9404_HP_OP

Possible Vacuum Seal Concept to Accommodate the Horizontal Test Port Configuration

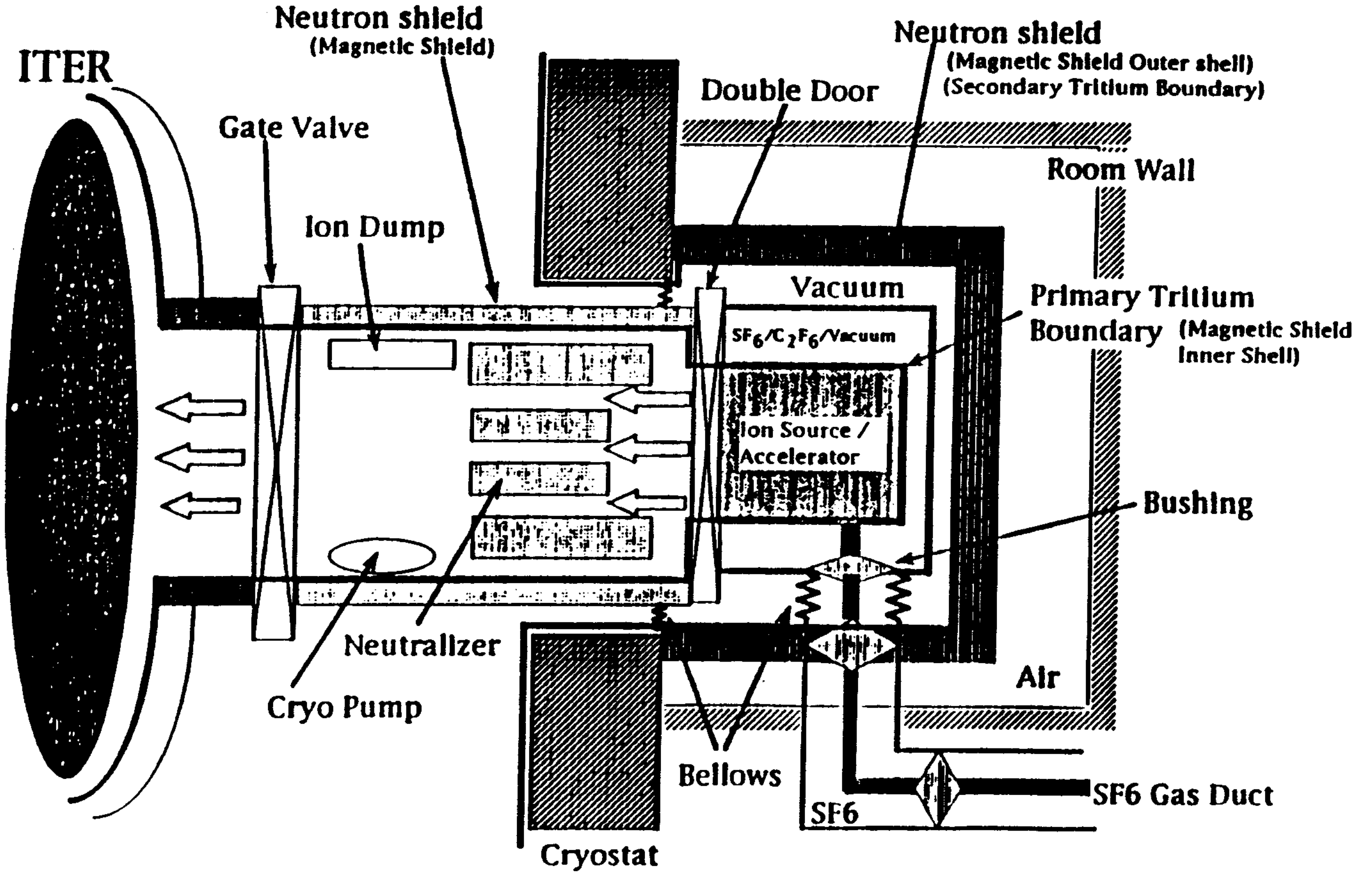
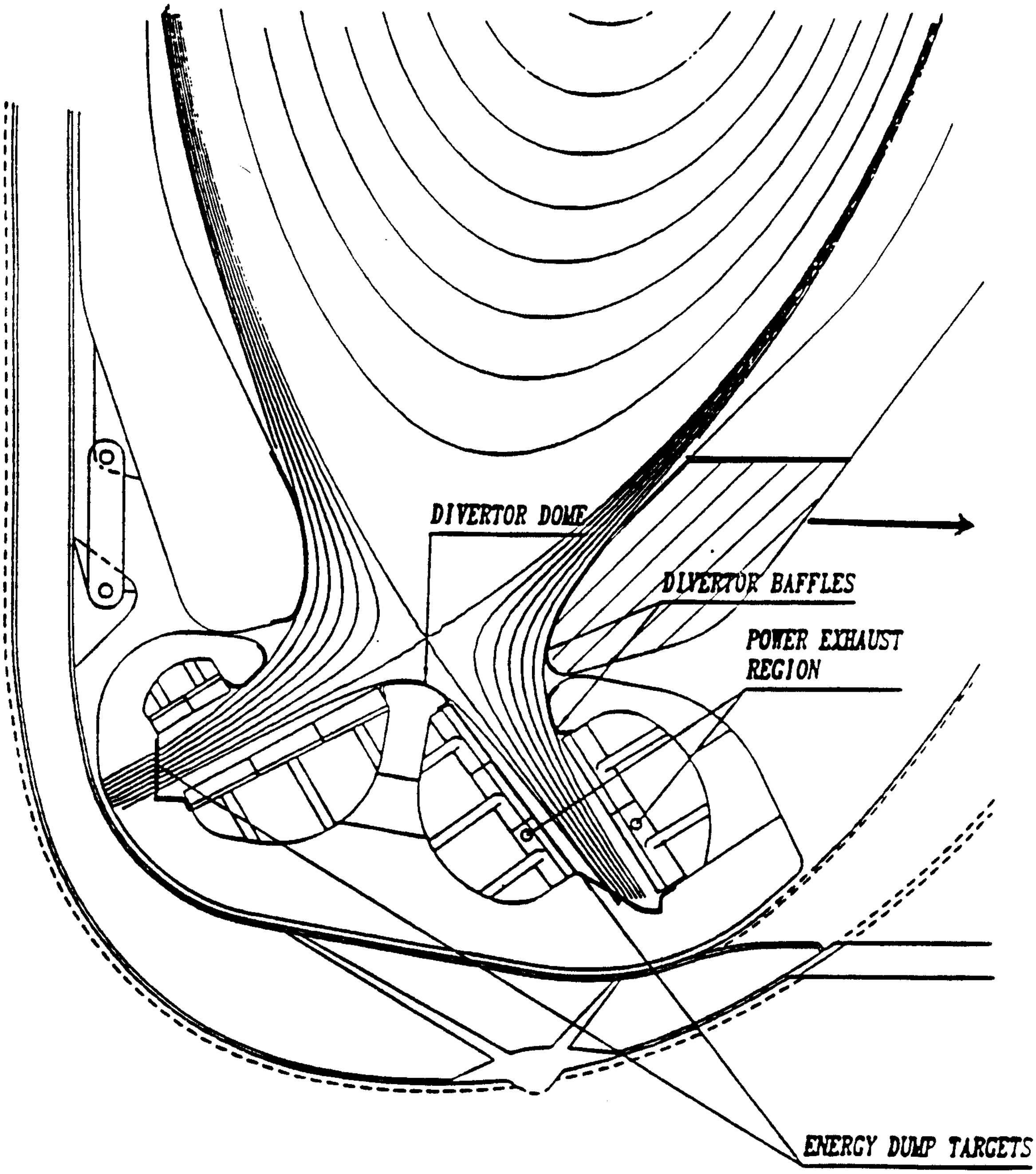


Fig.2 Schematic of a neutral beam injector for ITER

Suggested Additional Test Port Configuration for High Heat Flux Component Testing



ig. 3 *Cross-section through a divertor cassette showing the baffle, the dome, the power exhaust region and the energy dump targets*

Test Program
Description

Test Program Description [Type and Size of Test Articles, Test Article Design, Test Matrix, Test Schedule, etc.]

- Solid Breeder Blanket Test Program
- Liquid Metal Blanket Test Program
- Fuel Cycle Tests
- Neutronics Tests
- Materials Tests
- Divertor Tests
- Plasma Heating Engineering (e.g. rf antenna tests)
- Safety Tests
- Overall Schedule

Blanket Options for DEMO

Breeder	**Coolant**	**Structural Material**
A. Solid Breeders Li_2O, Li_4SiO_4, Li_2ZrO_3, etc.	He or H_2O	Fs, V alloy, SiC
B. Self Cooled Liquid Metals Li, LiPb	Li, LiPb	FS, V alloy with Electric Insulator (SiC with LiPb only)
C. Separately Cooled Liquid Metals Li LiPb	He He or H_2O	FS, V alloy FS, V alloy, SiC

- All options have feasibility and performance issues.
- Resolving many of these issues requires testing of material combinations in subcomponents in the fusion environment (n, γ, B, T, V, etc.).
- R & D needs: basic properties, material interactions, synergistic effects; technology for alloy production, fabrication, etc.

Solid Breeder Blanket Test Matrix

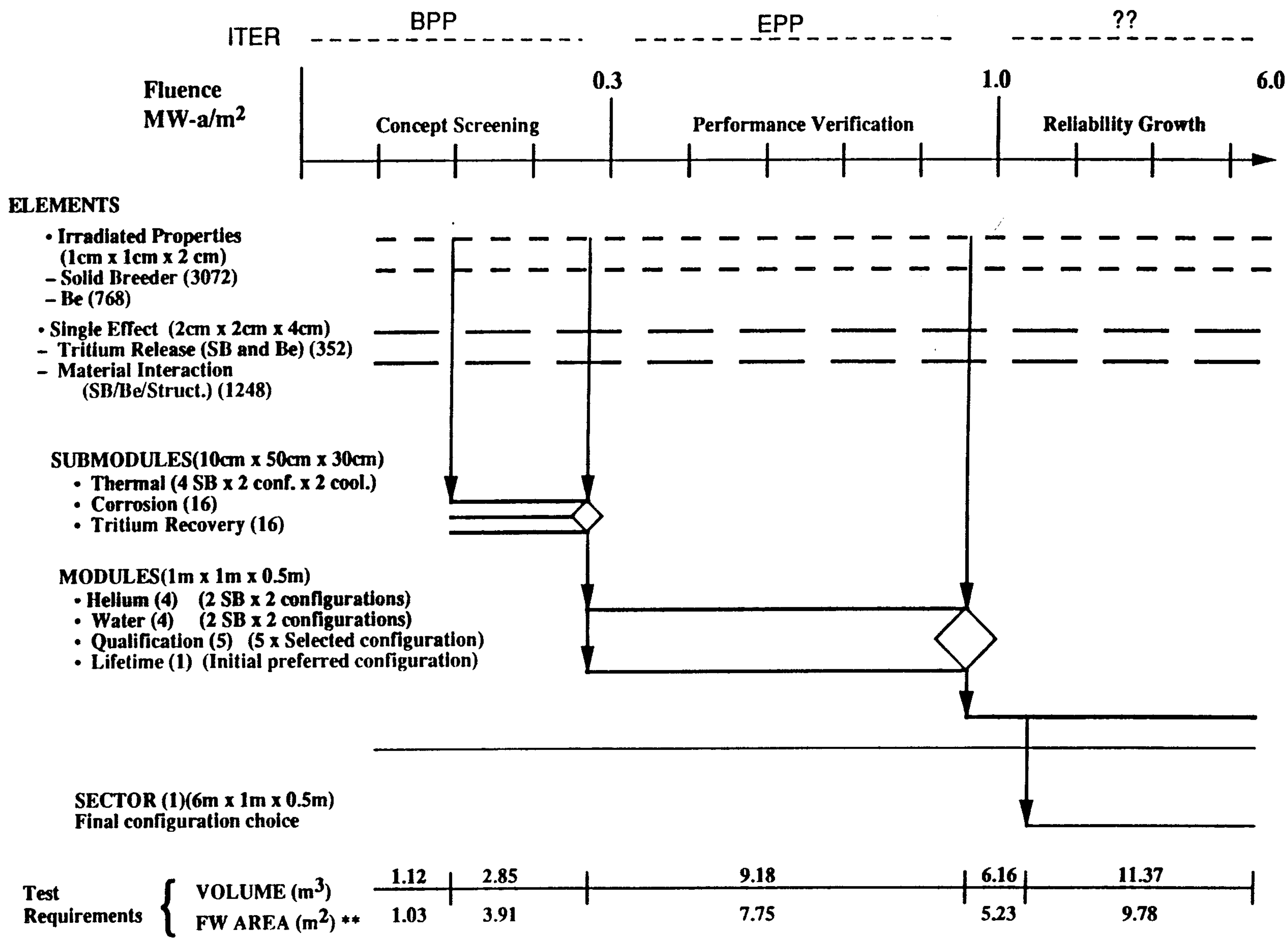
Tests	Number of Test Articles						Total Number	Element Size (Test Size)	Volume m^3	FW Area m^2
	SB (SBxformxpor)	Be Form (formxpor)	Structure	T	Fluence	Dupl.				
Basic Tests										
Solid breeder irradiated properties (4 properties)	4 x 2 x 3			4	4	2	3072	1 x 1 x 2 cm (2 x 2 x 3 cm)	0.037	0.077
Be 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

Solid Breeder Blanket Test Matrix, cont'd.

Tests	**SB**	**Be**	**Structure**	**Config.**	**Total (Test size)**	**Element Size m^3**	**Volume m^2**	**FW Area***
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.

Example Test Sequence for Solid Breeder Blankets



ITER: BPP, EPP, ??

Fluence MW-a/m^2: 0.3, 1.0, 6.0

Concept Screening | Performance Verification | Reliability Growth

ELEMENTS

- **Irradiated Properties (1cm x 1cm x 2 cm)**
  - Solid Breeder (3072)
  - Be (768)
- **Single Effect (2cm x 2cm x 4cm)**
  - Tritium Release (SB and Be) (352)
  - Material Interaction (SB/Be/Struct.) (1248)

SUBMODULES(10cm x 50cm x 30cm)

- Thermal (4 SB x 2 conf. x 2 cool.)
- Corrosion (16)
- Tritium Recovery (16)

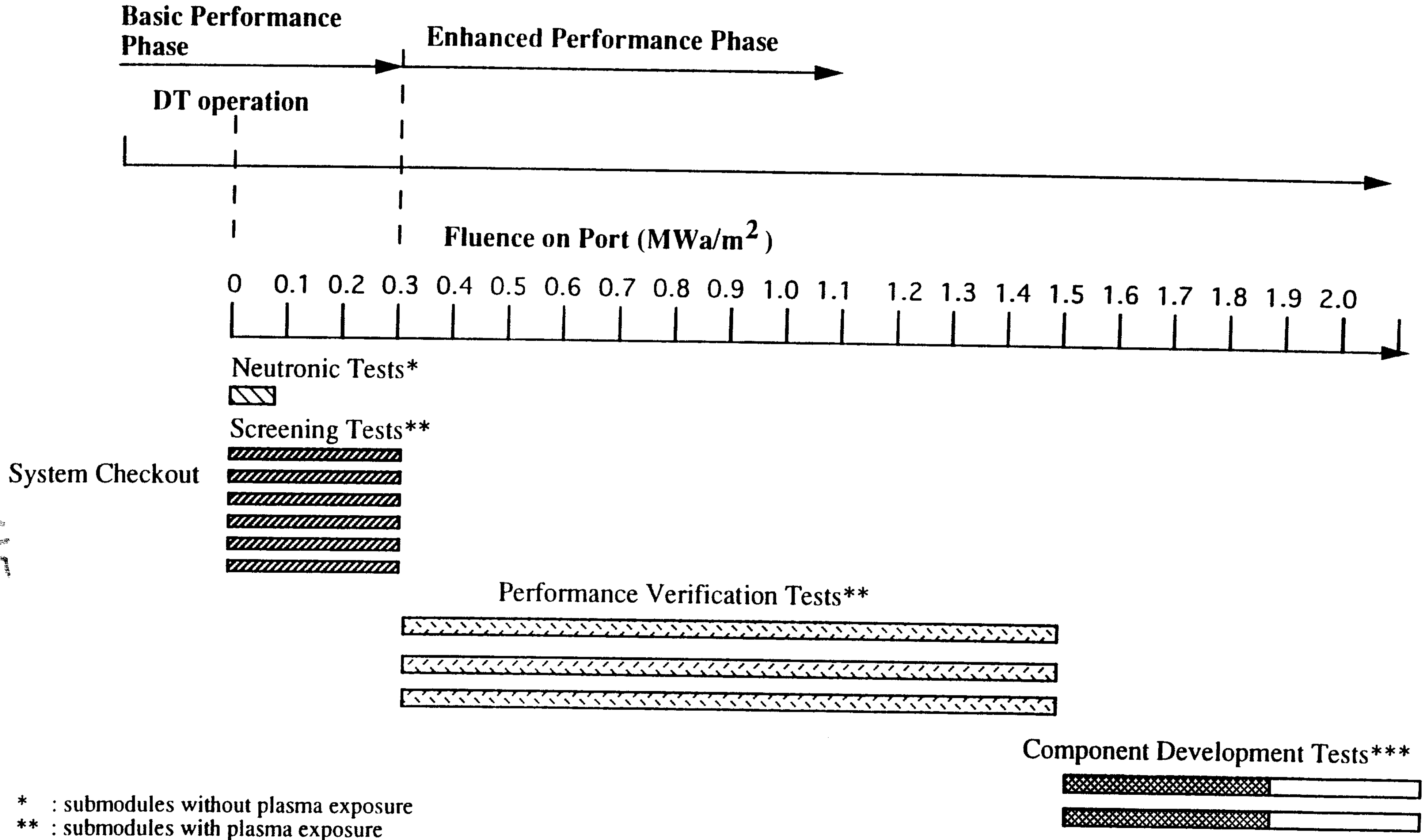
MODULES(1m x 1m x 0.5m)

- Helium (4) (2 SB x 2 configurations)
- Water (4) (2 SB x 2 configurations)
- Qualification (5) (5 x Selected configuration)
- Lifetime (1) (Initial preferred configuration)

SECTOR (1)(6m x 1m x 0.5m)
Final configuration choice

Test Requirements					
VOLUME (m^3)	1.12	2.85	9.18	6.16	11.37
FW AREA (m^2) **	1.03	3.91	7.75	5.23	9.78

** total area will be larger to account for boundary conditions



* : submodules without plasma exposure
** : submodules with plasma exposure
*** : modules of half segment with plasma exposure

Testing Schedule for Heilum- and Water-Cooled Solid Breeder Blankets

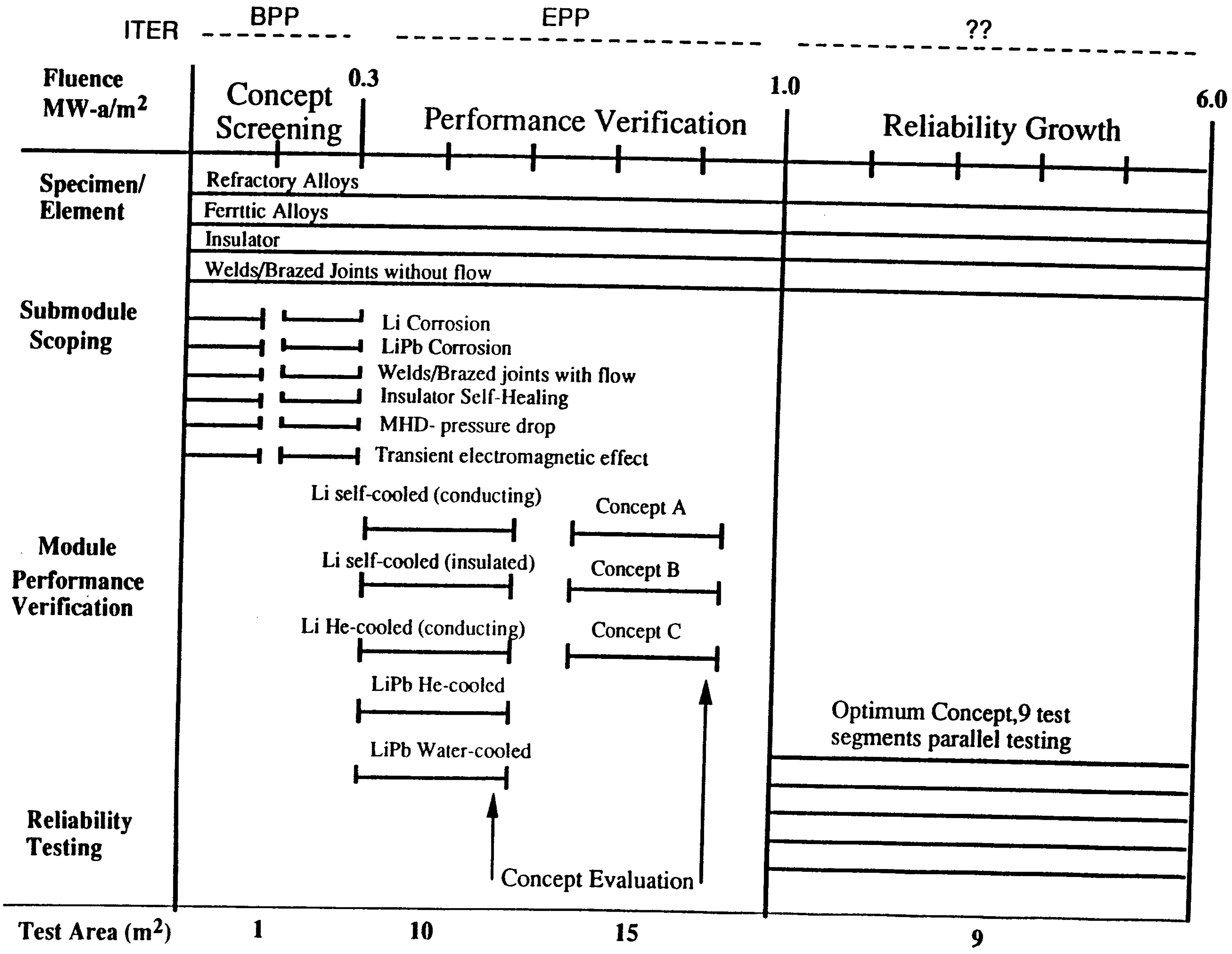
Liquid Metal Blanket Test Matrix

Tests	Typical Test Article Sizes (Toroidal x Poloidal x Radial; cm)	Number of Test Articles
Basic scoping 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 screening tests (Submodule)		
Corrosion verification	25 x 25 x 25	2 x 2 x 3 (material x velocity x temperature x redundance)
Welds/Brazed joints with flow	25 x 25 x 25	5 x 2 x 3 x 3 (geometry x velocity x temperature x redundance)
Insulator self-healing	25 x 25 x 25	5 x 2 x 3 x 3 (geometry x velocity x temperature x redundance)
MHD pressure drop	25 x 100 x 25	5 x 3 x 3 (geometry x velocity x redundance)
Transient electromagnetic effect	Variable x 25 x 25	5 x 3 (toroidal dimension x redundance)
Performance Verification (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

Summary of Space Requirements:

Concept Screening	**10 m^2**
Performance Verification	**15 m^2**
Reliability Growth	**9 m^2**

Example Test Sequence for Liquid Metal Blankets



Overview
Characteristics of Solid Breeder Test Program

- Test Phases & Decision Points
- Measurements
- Test Module Design and Physical Hardware

Objectives of Solid Breeder Blanket Testing

I. Calibration and Screening Phase:

- Calibrate fusion environment against results from nonfusion facilities
- Characterize and quantify the submodule blanket performance during operation for all relevant parameters and issues such as:
  - Tritium release rate
  - Thermomechanical performance
  - Thermalhydraulic performance
- Evaluate and screen concepts for further performance verification

II. Performance Verification Phase:

- Characterize performance and verify design details for the concepts identified
- Select best concept(s) for engineering development and reliability growth

III. Component Development and Reliability Growth

Criteria for Decision Points

A concept will be evaluated according to:

- Basic performance - such as tritium breeding recovery and thermal efficiencies
- Available safety margin
- Failure modes
- Environmental and safety features

A Large Number of Submodule Screening Tests is Needed

Breeder Materials

Li_2O, Li_2ZrO_3, Li_4SiO_4, $LiAlO_2$

Multiplier

Beryllium

Breeder/Multiplier Form

Pebble bed or Sintered product

Coolant

Helium
Water

Purge

Helium + %H_2

Structure

Ferritic/martensitic steels
Vanadium alloy
SiC

Configuration

- Beryllium mixed with breeder or separate
- BIT, BOT
- Different zones, coolant arrangement

Engineering Scaling

- Several of each one focusing on a group of issues

Types of Experiments Proposed for ITER Solid Breeder Tests During BPP

- Integrated Submodule Experiments With Plasma Exposure
  - To provide testing results for DEMO blanket concept selection and improvement
  - To evaluate accommodative performance of blankets to poloidal wall load distribution and thermo-mechanical integrity of large blanket structure

- Partially-Integrated Submodule Experiments With Plasma Exposure
  - Each submodule reproduces a critical section or unit cell of a blanket module
  - To characterize and quantify the submodule blanket performance during operation in the following aspects:
    - Tritium release rate
    - Thermomechanical performance
  - To evaluate and screen concepts for further performance verification

Conditions to be Simulated

- DEMO- like conditions

Example Solid Breeder Blanket Submodule Configurations to be Tested (with plasma exposure)

Material	Configuration/ Reference	Test configuration/ Frontal surface
Helium-Cooled Solid Breeder		
Li_2ZrO_3+Be+Ferritic	Packed bed in zone	Submodule/0.2x0.5
Li_2ZrO_3+Be+SiC	Packed bed in zone /ARIES	Submodule/0.2x0.5
Li_2O+Be+Ferritic	Sintered block	Submodule/0.2x0.5
Li_4SiO_4+Be +Martensitic	Packed bed	Submodule/0.2x0.5
Water-Cooled Solid Breeder		
Li_2O+Be+Ferritic	Sintered block	Submodule/0.2x0.5
Li_2ZrO_3+Be +Martensitic	BOT/BCSS (homogeneous SB/Be mixture)	Submodule/0.2x0.5

Note

- The U.S. believes intelligent concept screening requires fusion testing.
- A robust development program would test several conditions.

Measurements Required to Address Critical Blanket (Performance) Issues

Performance Issue	Measurements to be Performed	Number of Diagnostics per module	
		In-situ	ex-situ
Integrated tritium retention, release and recovery	Tritium concentration and gas species in purge stream	1	
	Purge gas flow rate, control	1	
	Post-examination of tritium concentration in breeder, multiplier and structure		X
Integrated mechanical interactions	Breeder/structure, breeder/multiplier, multiplier/structure deformation and strain	5-10	
	Post-examination of structural thermomechanical behavior		X
	Post-examination of material microstructure		10
Thermal performance for breeder, multiplier, conductance gap and interfaces	Temperature in breeder, multiplier, structure and coolant	10-20	
Tritium permeation	Coolant flow tritium concentration	1	
Structural response of the blanket module	Structural deformation, stress and strain	5-10	
	Post-examination of structural thermomechanical behavior		X
Material interactions	Purge chemistry, coolant chemistry, PIE	1	

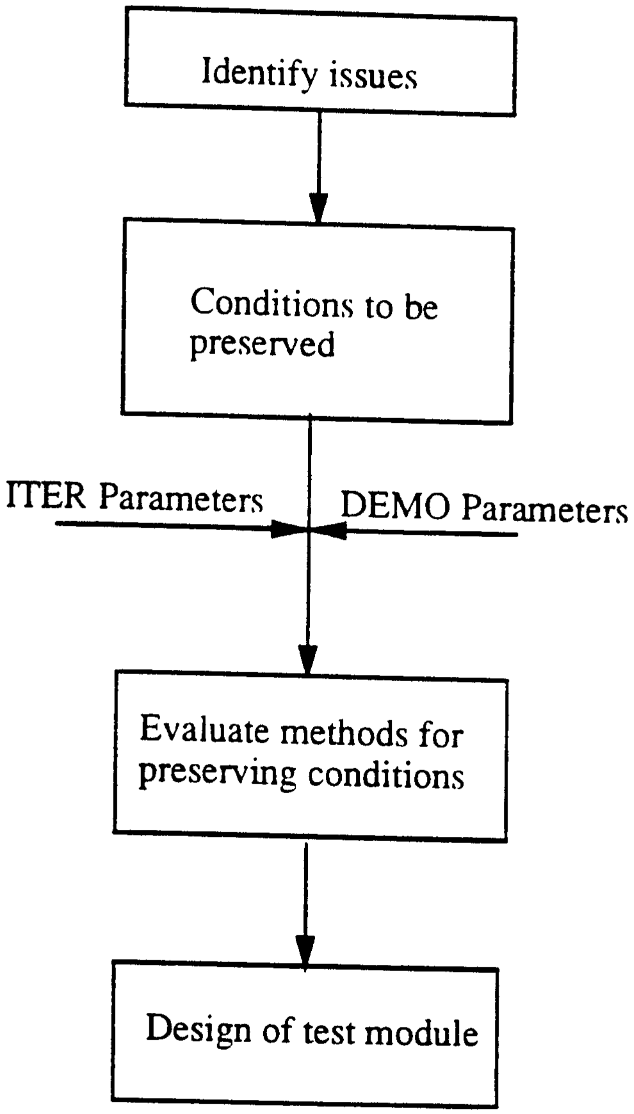
Test Article Design

- ITER testing is limited because of the environmental conditions and test port configuration.
- It is necessary to maximize the test benefit.
- 3 types of test article design:
  - DEMO Look-Alike (useful only for neutronics)
  - DEMO Act-Alike (majority of tests)
  - ITER optimized blanket concept (useful during BPP to test basic breeding blanket for EPP)

Act-Alike Design Strategy

The test article to be tested in ITER is designed to preserve aspects of DEMO blanket behavior by using an engineering scaling process.

Example: Partially Integrated Submodule Tests



Identify issues

Conditions to be preserved

ITER Parameters

DEMO Parameters

Evaluate methods for preserving conditions

Design of test module

- Tritium release and inventory
- Thermomechanical performance

- Breeder/multiplier/structure temperature and temperature difference
- Purge gas characteristics and chemistry
- Coolant operating temperature and pressure
- Breeder/multiplier/structure thermomechanical boundary

- Breeder/multiplier needs to be 4-sides cooled
- The scaling law of preserving $\bar{T}$ in the case of same temperature difference in the breeder region requires that:

$$(T_c + \Delta T_{film} + \Delta T_{interface} + \Delta T_{clad} + \Delta T_{gap})_{DEMO} = (T_c + \Delta T_{film} + \Delta T_{interface} + \Delta T_{clad} + \Delta T_{gap})_{ITER}$$

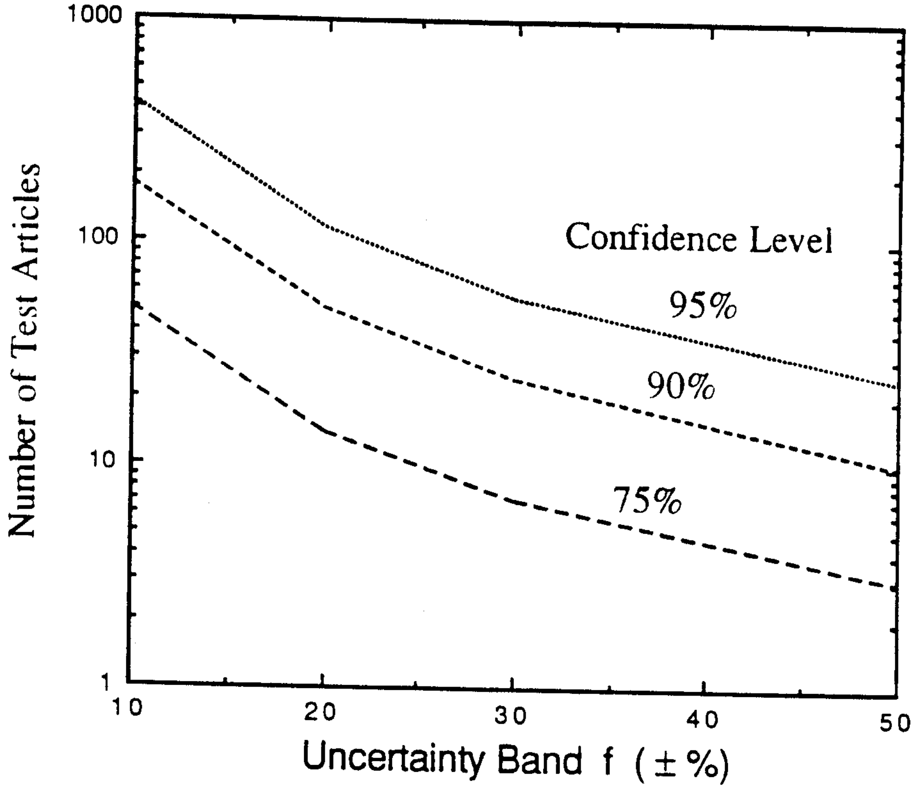
- Alter material thickness to account for a lower heat generation rate

$$\Delta_{ITER} = \Delta_{DEMO} \times [\dot{Q}_{vDEMO}/\dot{Q}_{vITER}]^{0.5}$$
$$= \Delta_{DEMO} \times [N_{DEMO}/N_{ITER}]^{0.5}$$

How Many Test Modules (per Concept)?

- When the number of test modules are small, it is difficult to resolve whether the observations are real or practically significant. Furthermore, a small sample size makes the statistics too dependent on the precise value of a few individual observations or a high uncertainty interval in estimating both mean and variance.

Example: A mean value of TBR for a blanket design option is to be estimated within ± *f* % at some confidence level



Number of test articles required as a function of required uncertainty band for different confidence levels

Additional Issues of Test Module Design

1. The need of plasma exposure

   - Surface heat flux is crucial.

   - The blanket first wall and the first few centimeter blanket zone away from the first wall represent the most critical and challenging areas for blanket designers, which must be addressed at the early stage of the fusion testing.

2. Boundary conditions and poloidal and toroidal effects are important and should be reproduced to the extent possible.

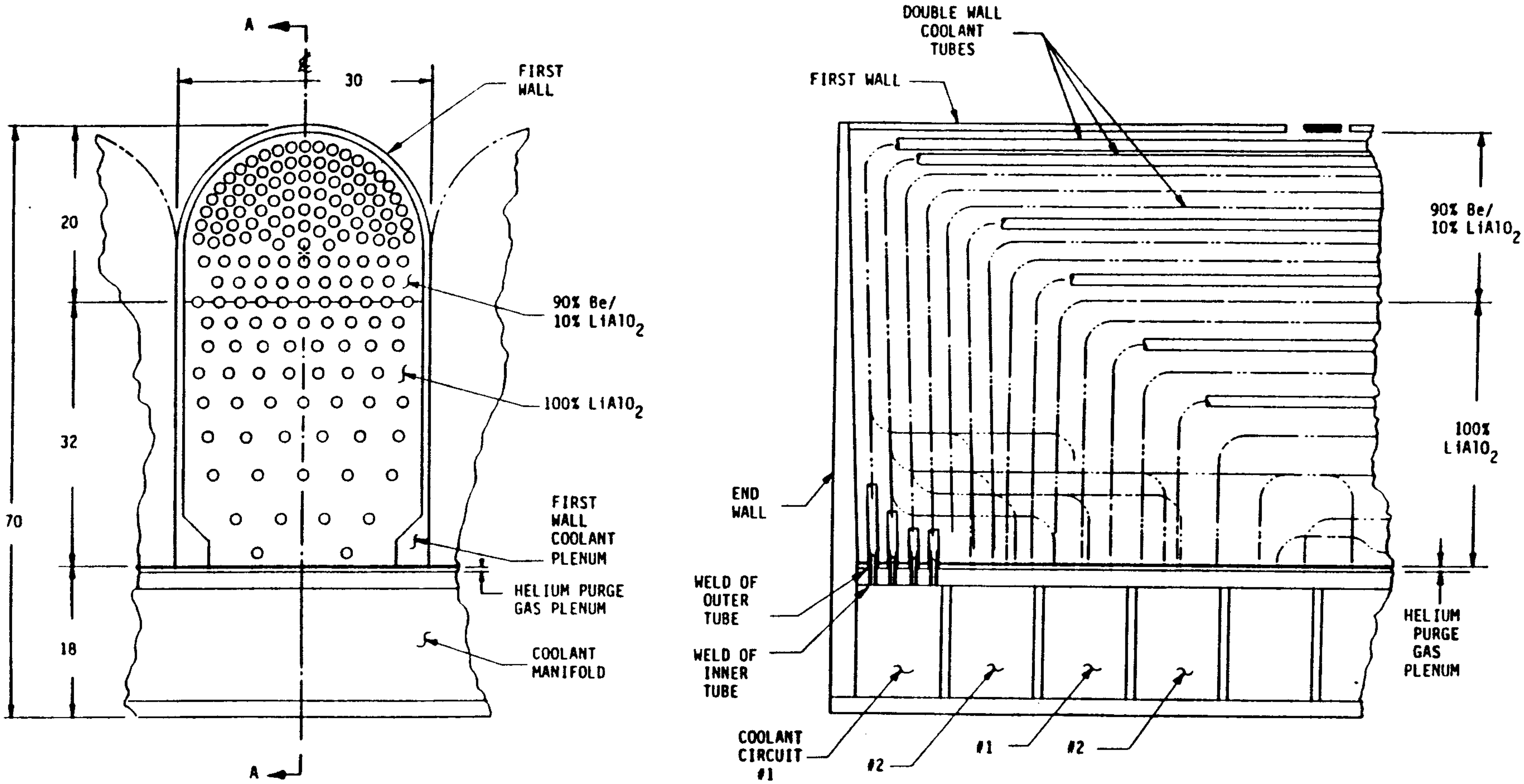
3. Test data and instrumentation issues

   - limits on the amount of local data and possible accuracy
   - degradation/survival of sensors under irradiation
   - interference of the sensors with the test conditions

4. Support structure

Operating Conditions for Solid Breeder Test Modules

Breeder material	Li_2O	Li_2ZrO_3
Breeder form	Sintered	Pebble
Breeder temperature		
Maximum	800°C	1000°C
Minimum	350°C	400°C
Temperature gradient	~300°C	~400°C
Breeder density	80%	90% (80% packing)
Structure	FS	FS
Coolant	Water	Helium
Coolant flow dir.	Toroidal	Poloidal
Coolant temp. range	280/320°C	300/500°C
Coolant pressure	15 MPa	5-6 MPa
Multiplier	Beryllium	Beryllium
Purge gas	Helium	Helium
Purge gas pressure	0.1 MPa	0.2 MPa
Additives	H_2	H_2
Test article size		
Toroidalx poloidal x radial	0.2x6x0.6	0.2x6x0.6
Number of test articles	3	3
Plasma exposure	Yes	Yes
Test phase	BPP	BPP



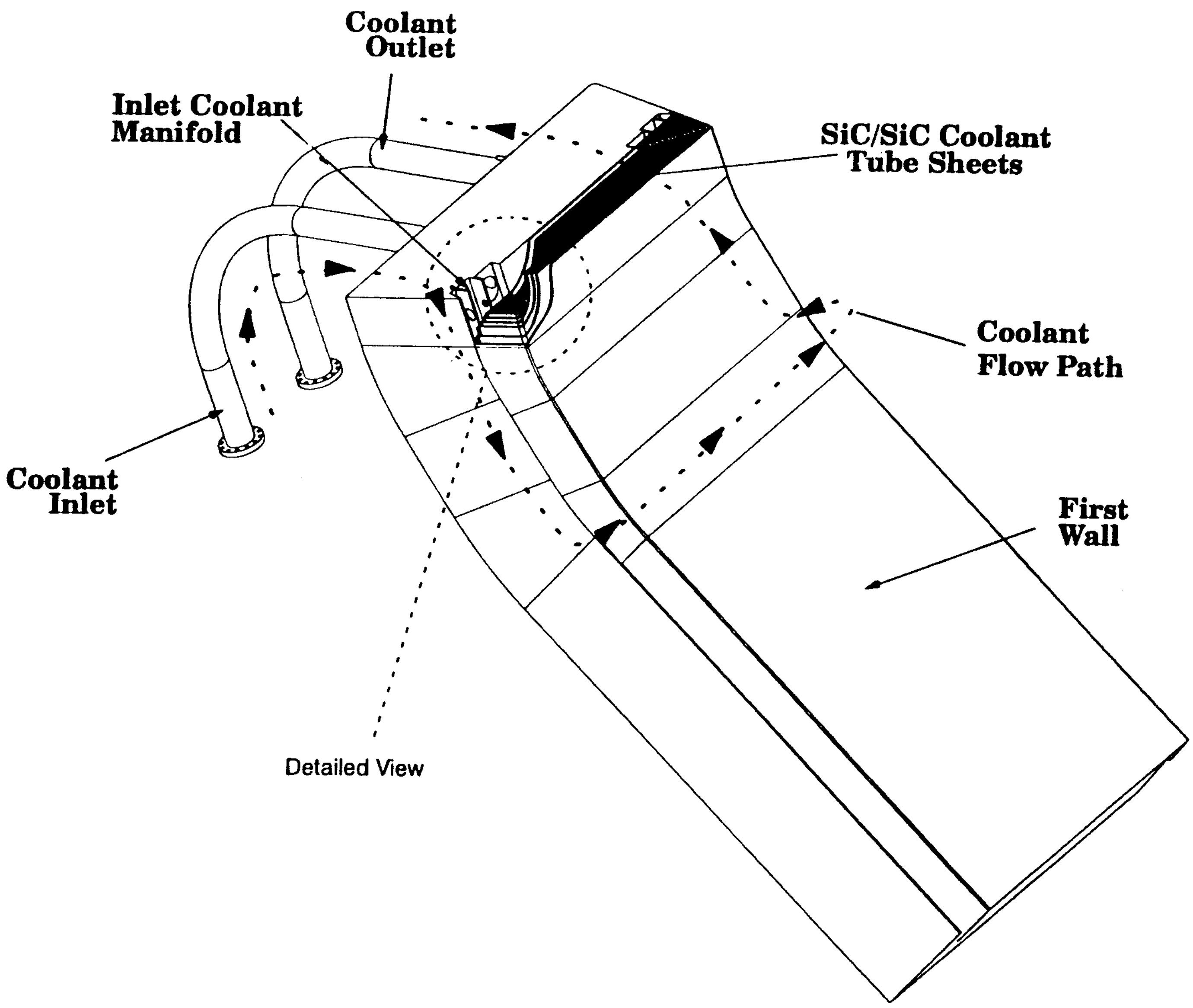
CROSS SECTION THROUGH BLANKET MODULE--LOOKING IN TOROIDAL DIRECTION

VIEW A-A (LOOKING IN POLOIDAL DIRECTION)

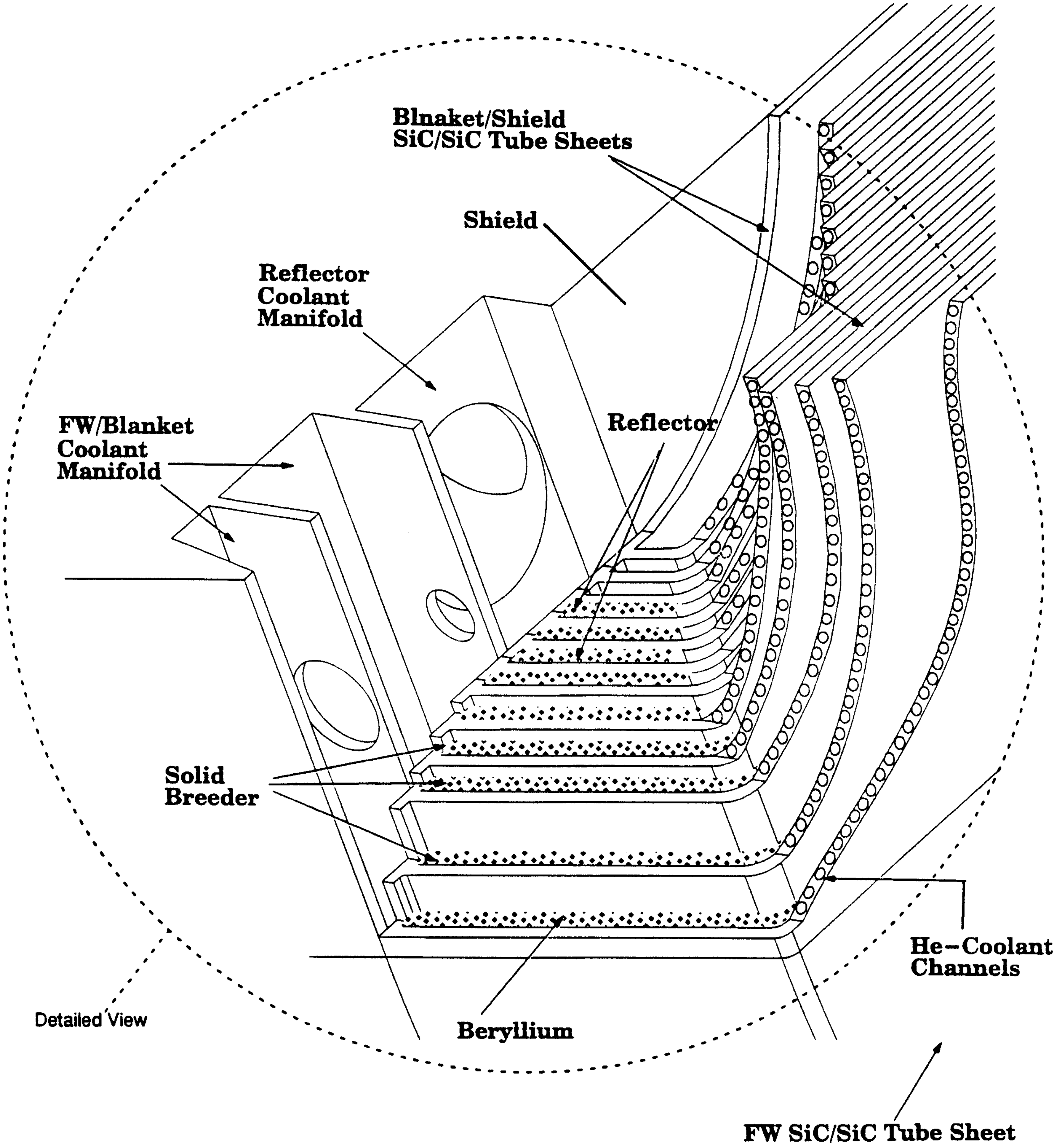
(ALL DIMENSIONS IN CM)

Fig. 9.4-1. Reference design configuration for $LiAlO_2/H_2O/FS/$ Be concept-tokamak

Candidate SiC/SiC Composite Solid Breeder Toroidally-Cooled Blanket/Shield Module



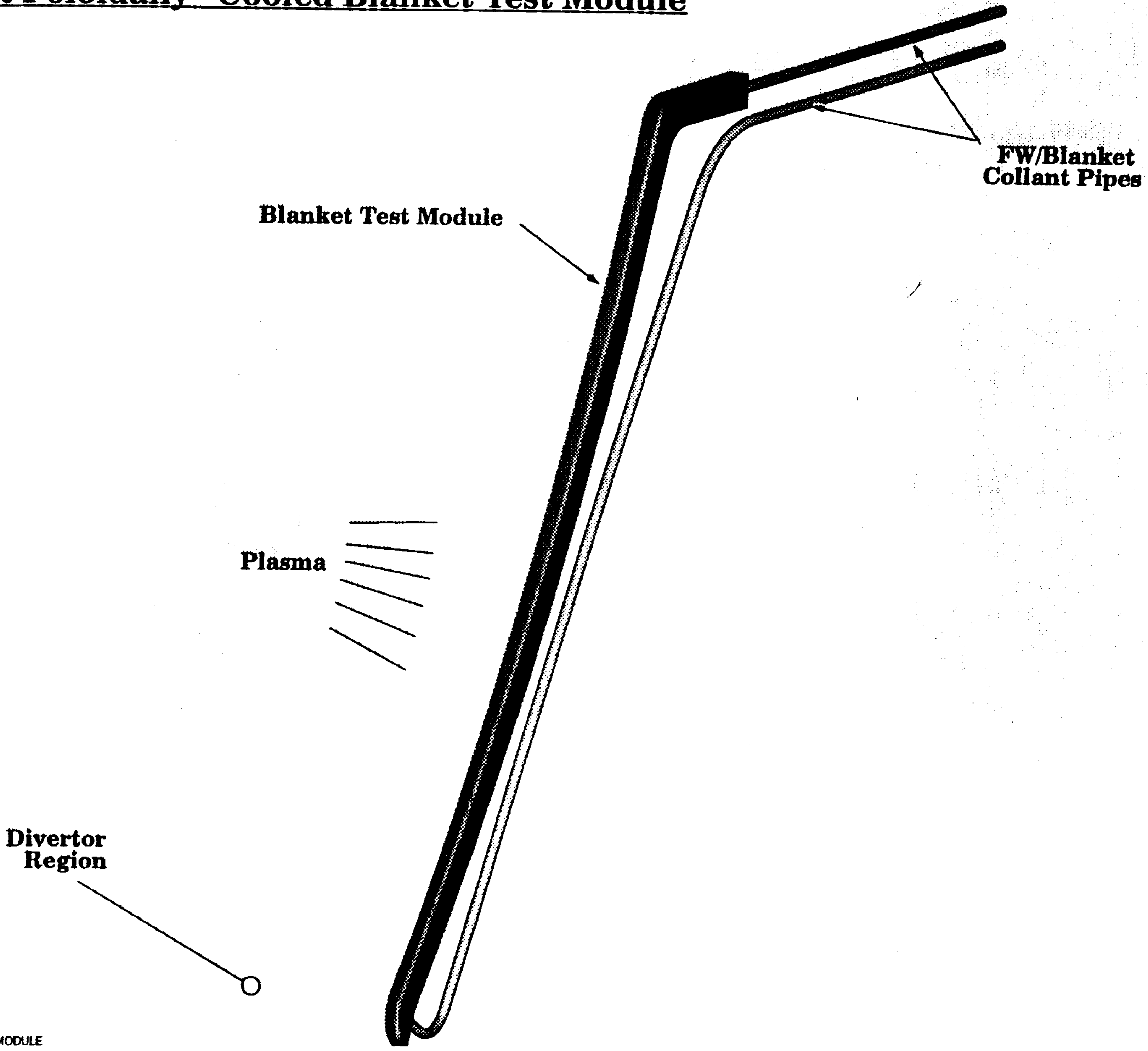
Candidate SiC/SiC Composite Solid Breeder Toroidally–Cooled Blanket/Shield Module



UCLA
SS: A1_FPC_C4_9404

62

ITER Poloidally–Cooled Blanket Test Module



FW/Blanket Collant Pipes

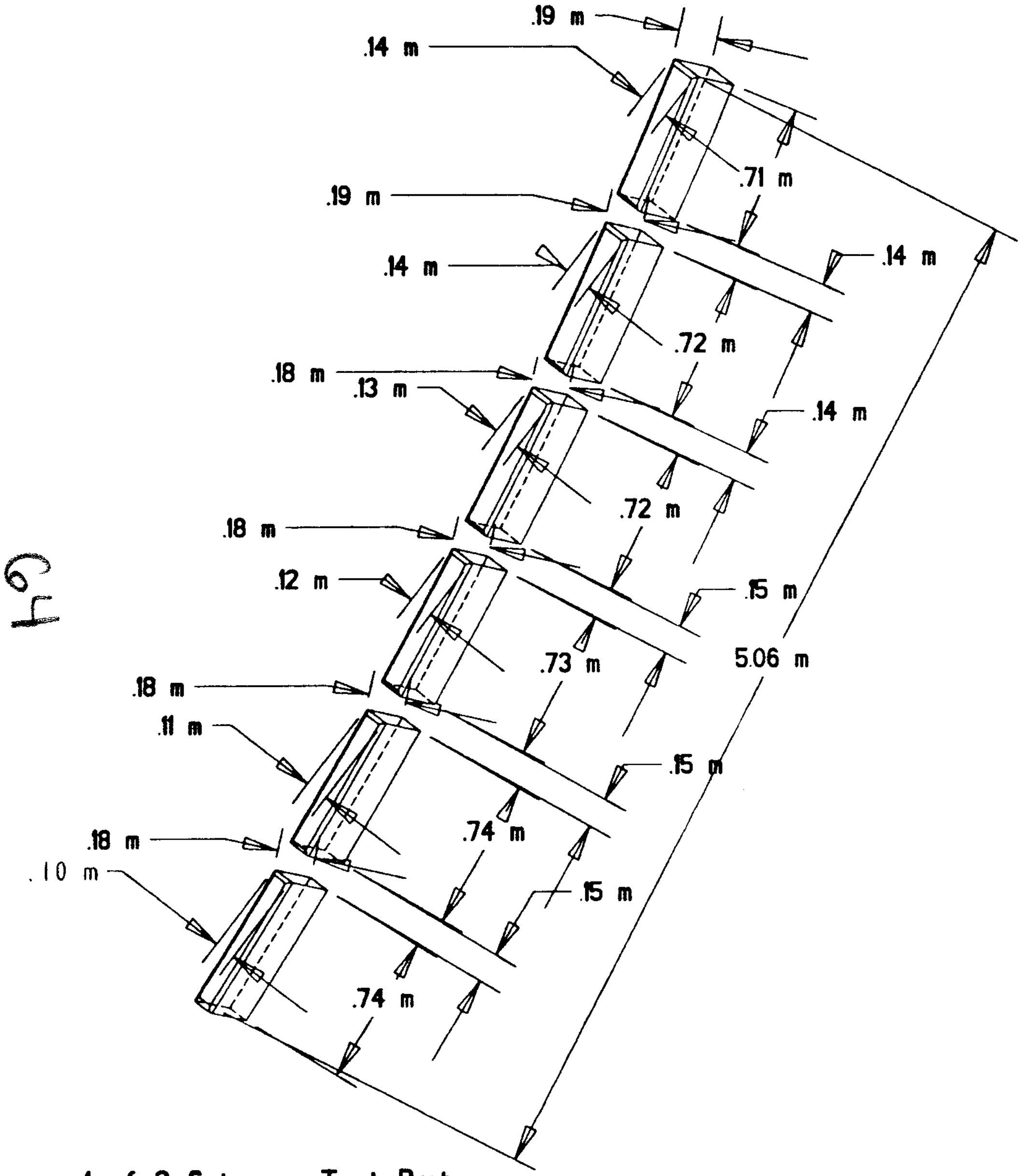
Blanket Test Module

Plasma

Divertor Region

UCLA
SS9404 T MODULE

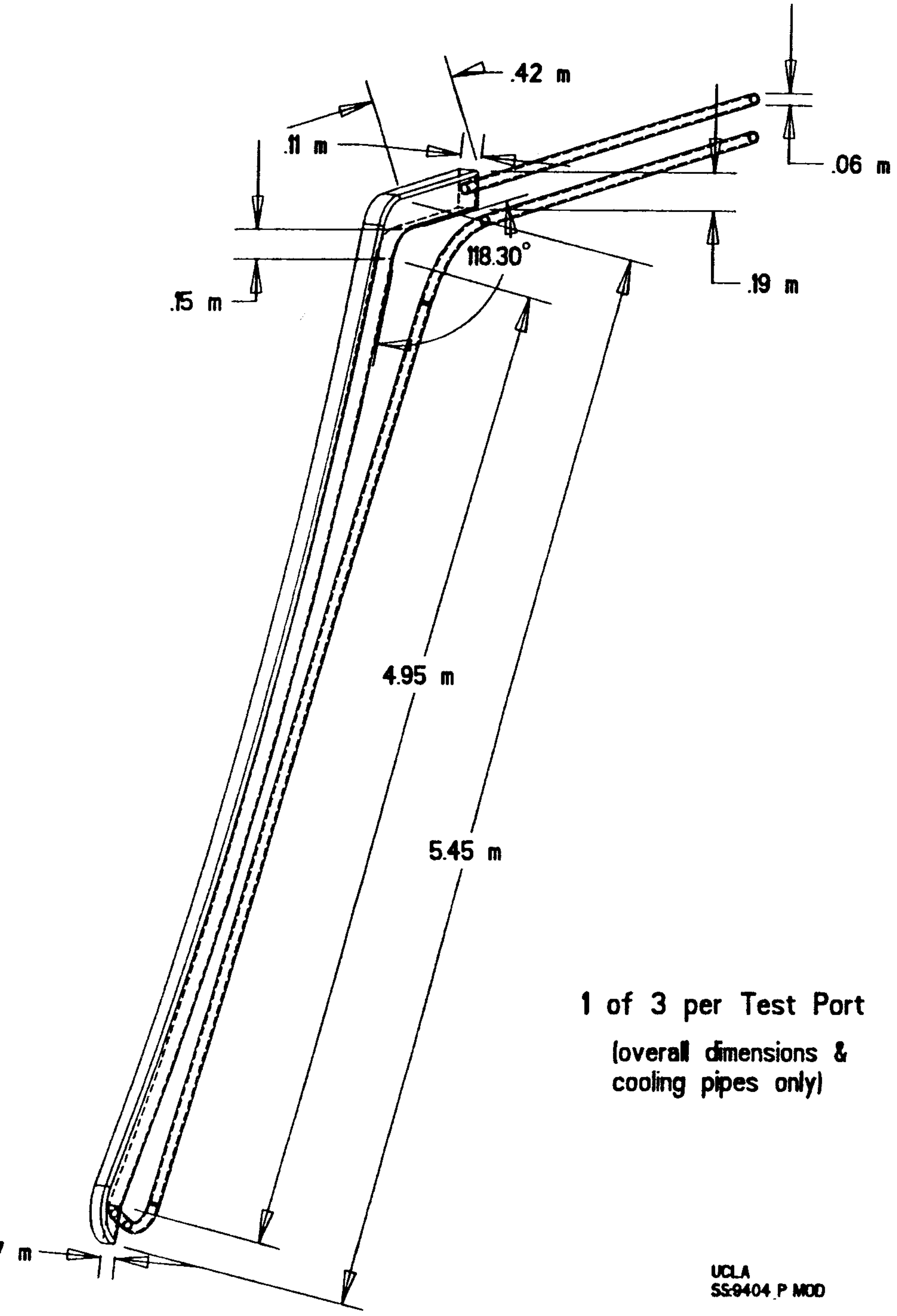
ITER Blanket Test Submodules



1 of 2 Sets per Test Port

(overall dimensions only)

ITER Poloidally-Cooled Blanket Test Module



1 of 3 per Test Port

(overall dimensions &
cooling pipes only)

UCLA
SS9404_P MOD

Testing of Liquid Metal Blankets

- Primary Option
  - Self-cooled Li/V
  - Poloidal flow

- Differences from ITER Liquid Metal Option
  - Operating temperature
  - Flow geometry
  - TBR > 1
  - Advanced structural alloy and insulator coating

- Important Features of Fusion Test Environment
  - Bulk heating
  - Large test volume
  - Magnetic field distribution
  - Neutron spectrum

- Testing Approach
  - Tests of liquid metal modules can begin at the beginning of the BPP.
  - Initial tests can be done in the absence of the plasma.
    - magnetic field only
  - Tests can be performed during H or D plasma operation.
  - First wall heat flux.
  - Fully integrated tests can be performed during D-T plasma operation.

Role of Test Temperature

- The Li outlet temperature in an electric power producing blanket will be 500-600°C.
  - 300°C for ITER blanket option.

- The thermodynamic equilibria and reaction rates between materials will be significantly different.

- At 300°C there is little concern of interstitial transfer in bi-metallic loops, but his could be a concern at 500-600°C.

- The kinetics of insulator coating growth will be faster.
  - Consider other candidate coatings.

- Permeation and solubility levels of H isotopes will be different.

- Alloy strength changes at high temperature.
  - Optimize V-alloys for high temperature strength.

Test Types for Liquid Metal Blankets

- **MHD Pressure Drop and Flow Behavior**
  - Validate out-of-reactor test predictions.
- **Heat Transfer**
  - First wall heat flux alone.
    Validate out-of-reactor test predictions.
  - First wall and bulk heating.
- **Short-term Integrated Performance**
  - Influence of fusion irradiation on insulator coating.
  - Thermal cycling.
- **Tritium Permeation and Recovery**
- **Neutronics**
  - TBR.
  - Activation.
- **Long-term Integrated Testing**
  - Reliability.
  - Corrosion/mass transfer.

Questions/Concerns

- Limit on Li Volume
- Inert Environment
- Interface with Base Blanket
- Space for Auxiliary Equipment
- Exposed First Wall
  - Consequences of a failure.
- Testing Time
  - Burn time
  - Dwell time
  - Fluence
- Number of Simultaneous Test Modules

Neutronics Tests

1. Dedicated Neutronics Tests

Objectives
a.) Verify Codes and Data
b.) Obtain Safety Factors

Test Vehicles: Look-Alike Test Modules

Requirements:

- Reproductible and Stable Neutron Field
- Special Boundary Regions around the test module to preserve prototypicality and allow accurate calculations
- Very low fluence

Special Case: Tritium Self Sufficiency
(discussed later)

2. Supplementary Neutronics Tests

Measurements performed in test modules (or submodules) used for other non-neutronics tests (e.g. solid breeder of liquid metal thermomechanics submodules)

Objectives:

1.) Additional information to support dedicated neutronics tests
2.) Provide the source terms and associated uncertainties (e.g. heat generation and tritium production rate) for non-neutronics tests (e.g. tritium recovery, theromechanics, safety tests)

Dedicated Neutronics Test Matrix

	Source characterization	In-Module Neutronics Parameters		Out-of-Module Neutronics Parameters
Neutronics Parameters	Neutron Yield	TPR, Heating Rate, Neutron Spectrum, Gamma Spectrum Reaction Rates	H, He, dpa Rates Breeder Burn-Up	Dose Behind Test Module Shield
Type of Test	Out-of-Module	In-Module, Integrated (at a Location)	In-Module, Integrated (at a Location)	Out-of-Module Integrated
Test Module Conditions: **Material, Geometry Test Module Size**	N/A	A sub module (0.3 x 0.3 x 1 m) or module (2 x 1 x 1 m) is sufficient to perform these tests as long as the geometrical details surrounding the test module are accurately considered in the calculational model. It is however preferred to apply these test in modules. Typical materials and configuration of FW/B/S are needed		
Device Operation Conditions **Fluence**	⇐ 1 W.sec/m^2 to 1 MW.sec/m^2 ⇒ Any linear combination of wall load and operating time that results in this range of fluence is suitable to perform the tests. Typically, 20 sec of operation at 5 x 10^{12} n/cm^2.sec is adequate		< 0.1 MW.yr/m2 This relatively larger fluence is required to accumulate reasonable and detectable level of damage to the FW and burn-up of the breeding material	Same as for in-module parameters but the higher end (1MW.sec/m2) is preferable
Operating Scenario	Steady State or pulsed operation is acceptable provided the accumulated required fluence is reached			
Operating Phase	Second year of SD&PT phase S & CV phases. Could be continued during RG phase	Second year of SD&PT phase and S phase. Could Be continued during CV phase.	S & CV phase. Could be continued to first two years of the RG phase.	Concurrent with in-module neutronics tests

* SD&PT Phase= Shakedown and Physics Testing Phase

* S Phase = Scoping Phase, CV Phase = Concept Validation Phase, RG Phase = Reliability Growth Phase

Supplementary Neutronics Measurements For Non-Neutronics Tests

	In-Module Neutronics Parameters			Out-of-Module Parameters
Neutronics Parameters	• Local TPR • Zonal TPR	• Local Heating Rate • Zonal Heating Rate	• FW damage parameters • Breeder damage parameters	Σ Neutron and Gamma leakage behind shield to I/B and O/B at test module
Related Issues	• Tritium generation and inventory	• Thermomechanical response • Tritium permeation and recovery • Power generation	• Component lifetime • Material properties under irradiation	• Radiation damage to Magnet (S/C or N/C) • Neutron streaming and peaking factors • Personnel protection
Type of Test	In-Module, Integrated			Out-of-Module, integrated
Test Module Conditions: **Material,** **Geometry,** **Test Module Size**	The size required is determined from the test matrix size requirement for other tests. This could be a full test module (2 x 1 x 1 m) or smaller test sub modules. Material selection is also dictated by the other tests			
Device Operating Conditions: **- Fluence** **- Operating Scenario**	Fluence requirements could be governed by other non-neutronics tests performed in or out-of-test module. The neutronics test themselves require very low to low fluences (1 W.sec/m2 up to 1 MW.sec/m2) except for damage parameters and burn-up tests which require longer fluences (0.5 to 1 MW.yr/m2). Steady state or pulsed operation are acceptable as long as fluence requirements are met			
- Operating Phase	First year of Concept Validation (CV)Phase. Could be extended or repeated during the remaining years of CV* Phase		Last year of Scoping (S*) Phase and first two years of CV* Phase. Could be extended for another year	Same as local and Zonal TPR and heating rates in the test modules

* S Phase = Scoping Phase, CV Phase = Concept Validation Phase

Materials Test Program

Role of Material Tests:

- Support ITER Component tests
- Obtain Fission / Fusion Correlations
  (at low to moderate fluence)
- Surveillance Program - ITER Materials
- Engineering Data
  (at low to moderate fluence)

Types of Material Tests:

- Advanced Structural Materials
- Surveillance Structural Materials
- Solid Breeder Materials
- Neutron Multiplier (Be)
- Insulators for Liquid Metals
- Special Purpose Materials
  - -PFC Materials
  - -Magnet Materials

Materials Tests (cont'd)

Operating Temperature Range:

- Cryogenic Temperature for Magnet Materials
- 100 - 400 °C for Surveillance
- Up to 800 - 1000 °C for Advanced Materials

Types of Tests:

- Passive

  -Control of irradiation condition is minimal. It may include at most the irradiation temperature.

- Active

  -Test conditions are varied continuously during the irradiation and in-situ material behavior is collected during irradiation.

  -Much more complex than passive tests; should be limited to critical areas.

Summary of Number of Specimens for Material Tests

• Structural Materials Four Different Alloys (SiC, Valloy, Ferritic, developmental)	25000
• Surveillance Structural Materials (Assume three different heats of ITER Structural Materials)	1500
• Solid Breeder Materials Three materials with 3 different product form / conditions	1500
• Surveillance and Advanced Special Purpose Materials	4000
Total	32000

Representative Materials Test matrix for ITER

Program Element	Test Description	Specimen Configuration	Size (mm)	Material Variables	Irradiation Environment Temp.	Fluence	Flux	Stress	Multi-plicity	Total Specimens	Vol./Spec. (cm^3)	Total Vol. (cm^3)
Advanced Structural Alloys	Charpy-v	1/3 CVN	(3.3 × 3.3 × 23.6)	4	7	4	1	0	8	896	0.26	235
	Tensile	Flat	(0.76 × 25.4 × 5.0)	4	7	4	1	0	15	1680	0.10	162
	Creep	Tube	(4.57 dia.×23.0)	4	7	1	1	6	1	168	0.38	63
	Swelling	Disc	(3.18 dia. × 5.0)	144	7	4	1	0	6	24192	0.002	48
	Fracture Toughness	Compact Tension	(160 dia. × 2.5)	4	7	4	1	0	16	1792	0.5	901
	Stress Corrosion Cracking	CERT SS-3	(0.76 × 25.4 × 5.0)	4	7	4	1	0	24	2688	0.10	259
	Fatigue	Constant Amplitude/High Cycle	(6.35 dia. × 38)	4	7	4	1	0	3	336	1.2	404
Surveillance Structural Alloys	Charpy	CVN	(9.9 × 9.9 × 24.4)	3	3	4	2	0	7	504	2.39	1207
	Tensile	Round	(12.5 dia. × 48)	3	3	4	2	0	4	288	5.89	1696
		Tube	(6.35 dia. × 50.8)	3	3	4	2	0	4	288	1.61	463
	Creep	Tube	(6.35 dia. × 28.2)	3	3	1	2	6	1	108	0.89	96
	Fracture Toughness	Compact Tension	(30.4 × 31.8 × 12.7)	3	3	4	2	0	2	144	12.29	1770

Representative Materials Test matrix for ITER, cont'd

Solid Breeder Materials	Breeder Material Performance (PIE)	Cylinders	(6.35 dia. × 50.8)	4	5	4	2			480	1.61	772
Surveillance and Advanced Special Purpose Materials	Ceramic: Mechanical	Cylinders	(12.7 dia. × 50.8)	4	7	4	2		3	672	6.45	4328
	Ceramic: Thermal/Electrical	Plates	(25.4 × 25.4 × 25.4)	4	7	4	4		2	896	2.05	1835
	High Heat Flux	Plates	(25 × 25 × 6.35)	6	4	4	1	0	1	96	3.97	381
	Tensile	Flat	(0.76 × 25.4 × 5.0)	4	7	4	1	0	15	1680	0.1	162
	Swelling	Disc	(3.18 dia. × 0.25)	16	7	4	1	0	6	672	0.002	5
	Creep	Tube	(4.57 dia. × 23.0)	4	7	1	1	6	1	168	0.38	63
	Magnets	Plates	(25 × 25 × 6.35)	4	2	4	4	0	1	128	3.97	508
	Magnet Material	Plates	(25 × 25 × 6.35)	4	2	4	1	0	2	64	3.97	254

Materials Test Program (cont'd)

Interface With the Machine

- Temperature Control is Crucial
  Need constant temperature for a given period
  - Dwell Time and COT issues
  - Providing controlled environment (coolant streams, etc.)
- Isolation from First Wall is acceptable
  - However, dose drops rapidly with depth behind first wall.
- Material Examination Intervals
  - 100 days to 1 year
- Turnaround time for specimens
  (reconstituting the material test module)
  - ~2 weeks
- Other requirements on maintenence and test vehicle design

Observations on HHFC Testing in ITER

Base Machine Operation

Observation of basic divertor and HHFC operation is an important part of the test program

Testing in the Divertor Region

Divertor ports (similar to blanket ports) should be considered

Test articles with the same plasma-facing material as the basic divertor should be allowed

The conditions available in the divertor "throat" region may allow for high-heat-flux testing of **first wall** test modules.

Testing in the FW/Blanket Test Ports

Non-PMI issues for PFC materials (e.g., radiation effects) can be tested in a "blanket test port" with plasma exposure

Testing Issues for Plasma Interactive Components

1. **Particle exhaust, erosion and recycling**

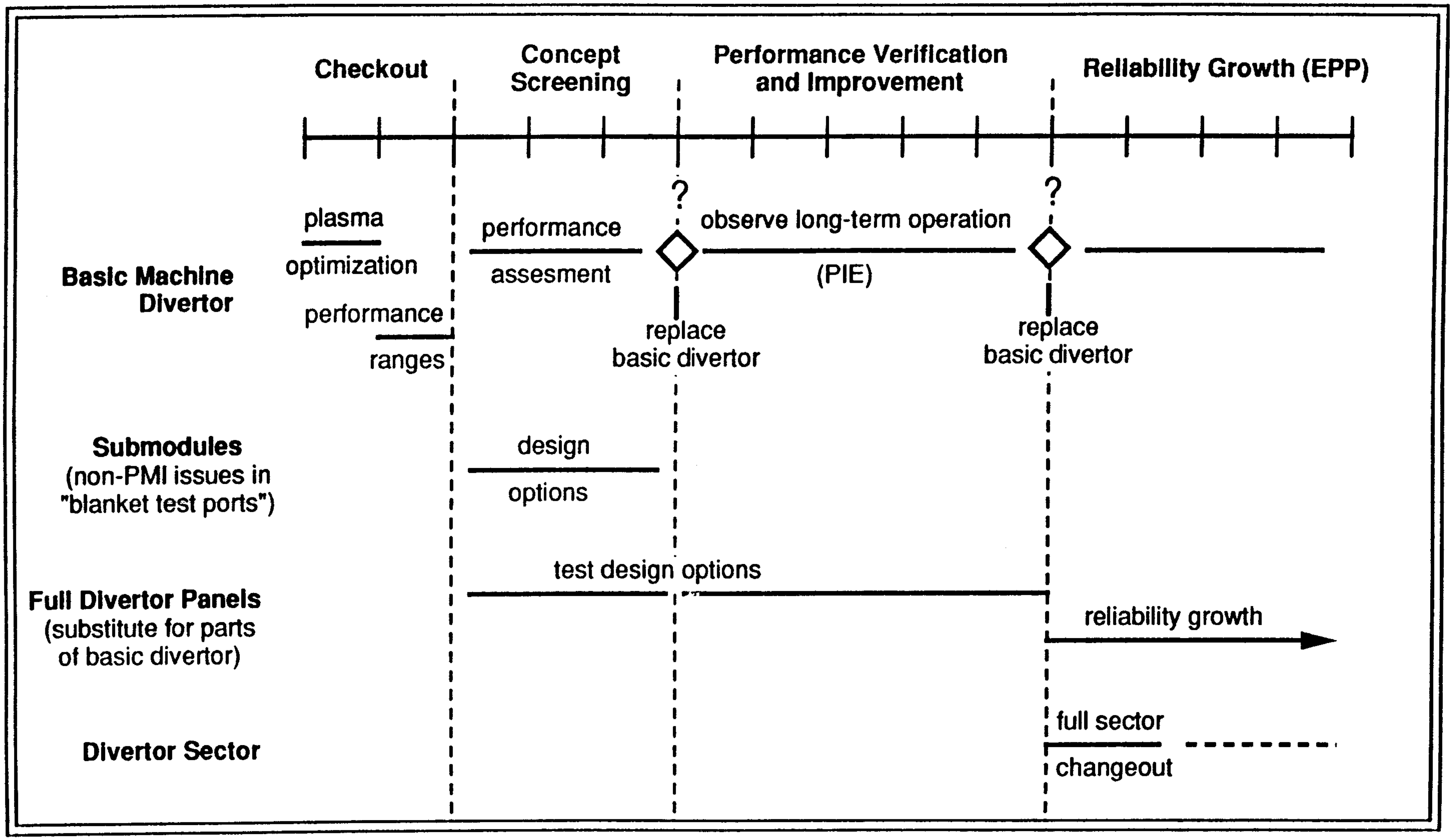
2. **High heat flux removal and thermomechanical response**
   - heat transfer limits
   - flow distribution and stability (especially for liquid metals)
   - corrosion and chemistry (including coatings)
   - thermal fatigue
   - bond integrity
   - heat source characterization

3. **Disruptions (thermal and electromagnetic effects)**

4. **Tritium permeation and retention**

5. **Irradiation effects on component behavior**
   - short-term (e.g., thermal conductivity)
   - long-term (swelling, embrittlement, etc.)

Example Test Program for Divertors



Checkout | **Concept Screening** | **Performance Verification and Improvement** | **Reliability Growth (EPP)**

Basic Machine Divertor
- plasma optimization
- performance ranges
- performance assesment
- ?
- replace basic divertor
- observe long-term operation (PIE)
- ?
- replace basic divertor

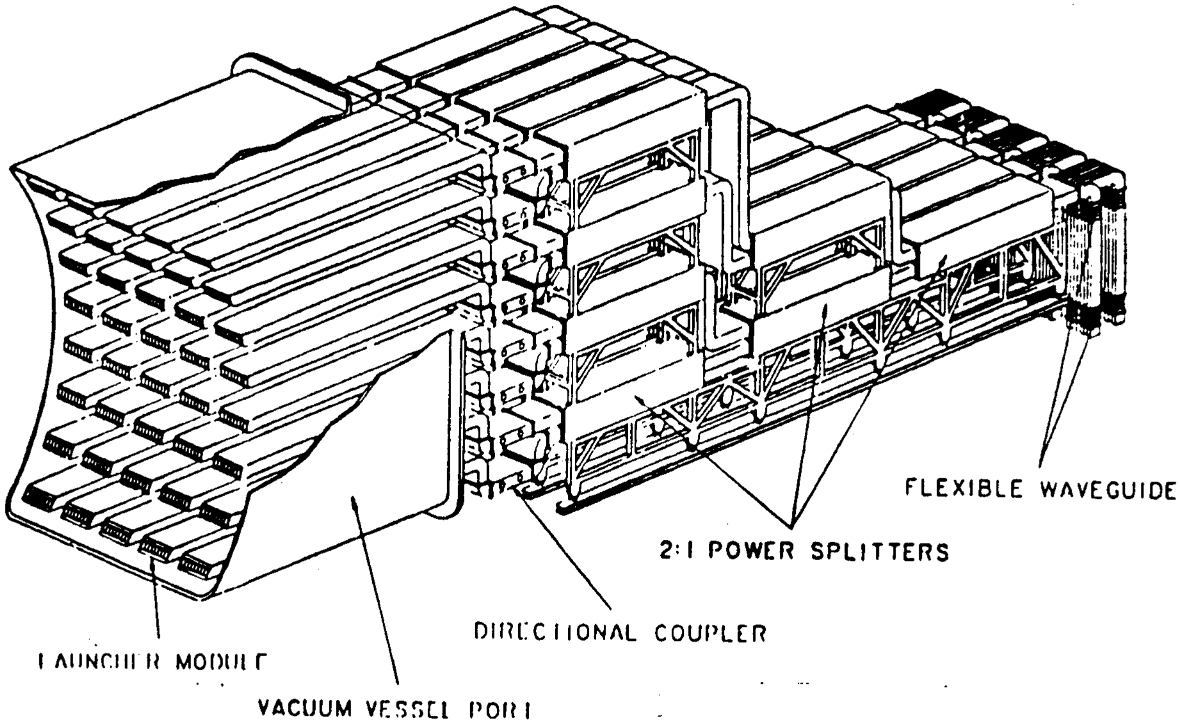
Submodules (non-PMI issues in "blanket test ports")
- design options

Full Divertor Panels (substitute for parts of basic divertor)
- test design options
- reliability growth

Divertor Sector
- full sector changeout

Heating and Current Drive Systems Test Program

- **Many engineering/nuclear issues need to be tested.**
- **An example is the launcher array for lower hybrid current drive**



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

Ancillary Equipment for ITER Test Program

Large Amount of Complex Ancillary Equipment Intimately Tied into the Testing Program

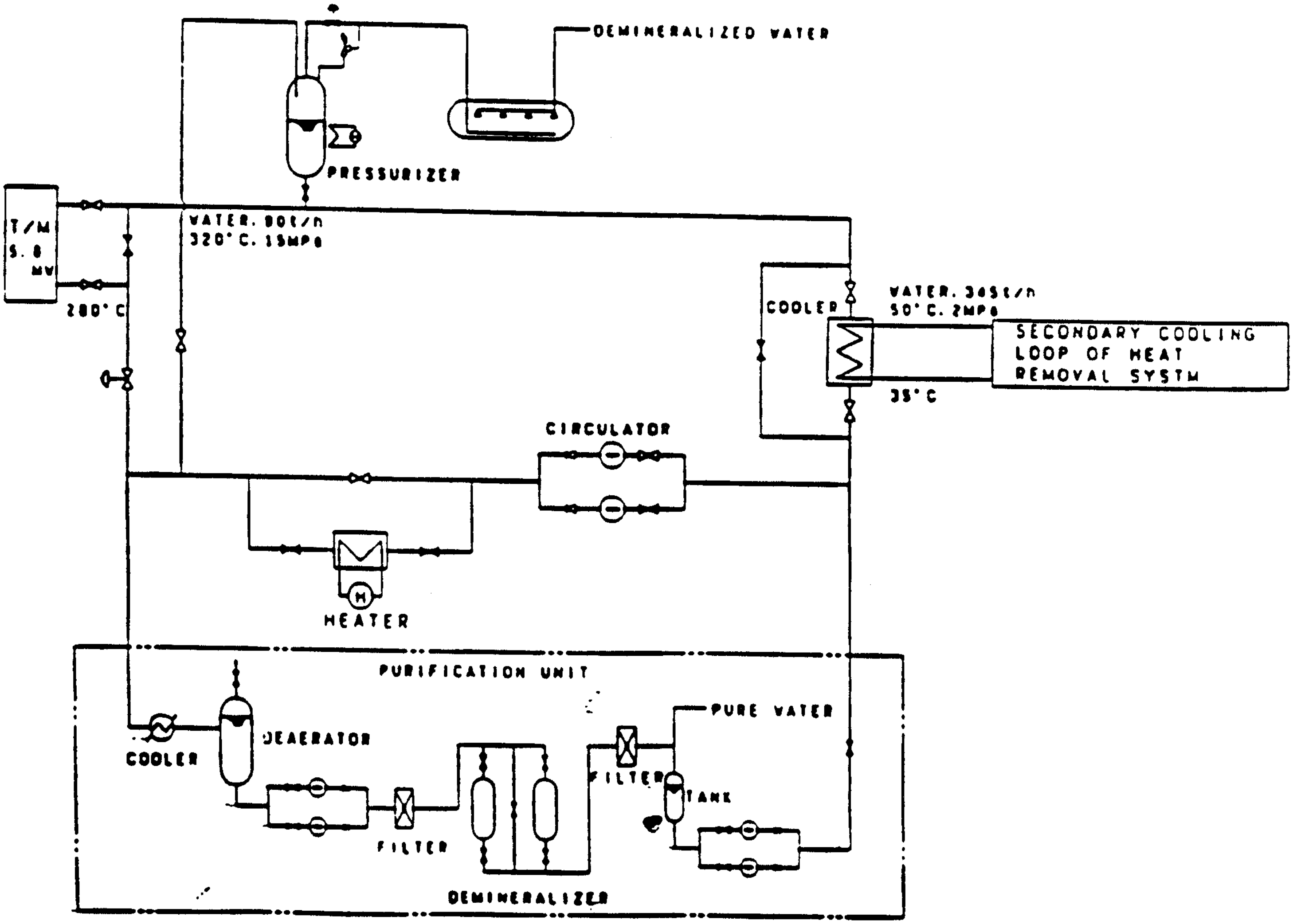
Needed Ancillary Equipment:

- Heat Rejection
- Tritium Recovery Systems and Test-Specific Intermediate Tritium Processing
- Chemical (Impurity) Control Systems
- Coolant and Purge Fluid Storage, Start-up, and Volume Control Systems
- Emergency and Safety Systems
- Remote Handling Equipment
- Test Rooms and Hot Cells for Examinations
- Control and Data Acquisition Systems

The ancillary equipment requirement has several serious issues:

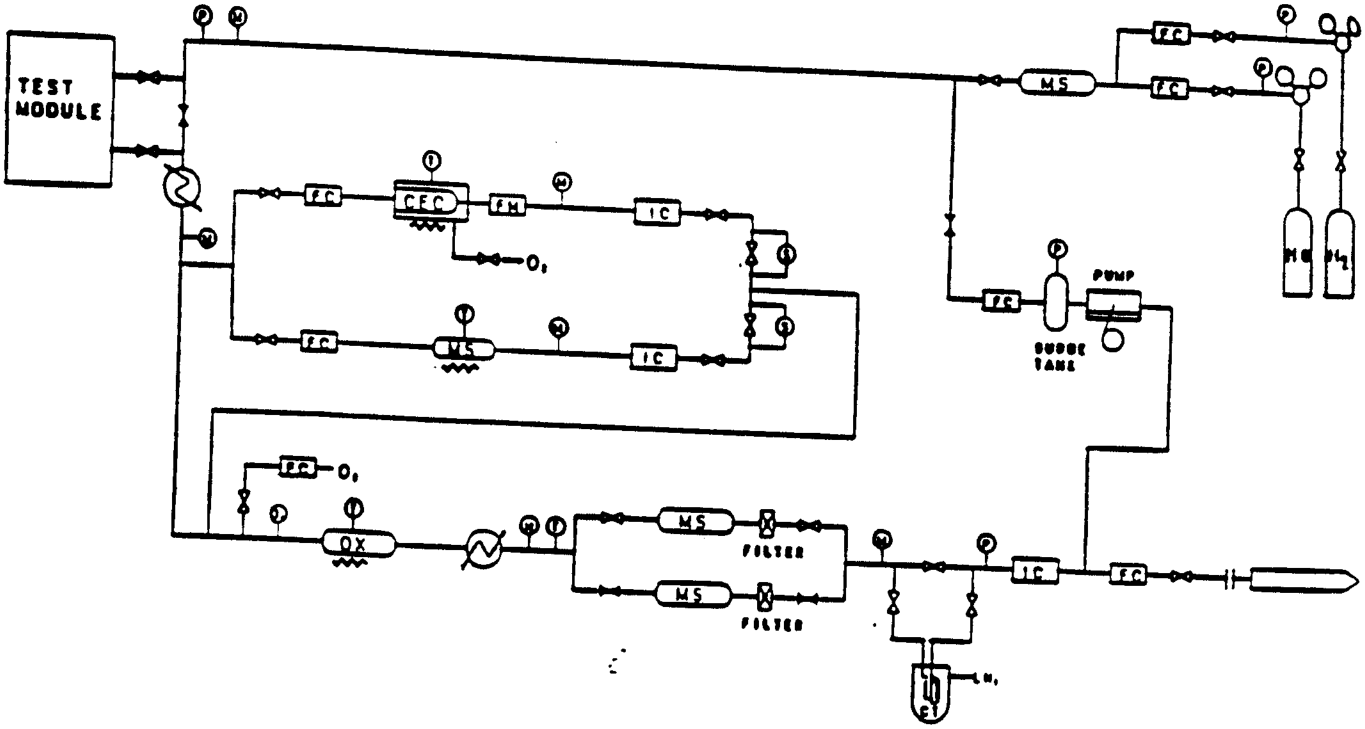
- Space requirement
- Access lines
- Maintenance/removal requirements
- Cost
- R&D

Example Cooling System for a Single Water-Cooled Solid Breeder Blanket Test Module



Tritium Recovery System for Solid Breeder Blanket Test Module

- A tritium recovery process for solid breeder test modules involves: measure, merge and process



Tritium Analysis

IC: Ionization chamber
M: Hygrometers
S: Gas sampling lines
CEC:Cermaic electrolysis cell
FM: Flow meter
FC: Flow controller
P: Pressure gauge
T: Thermometer

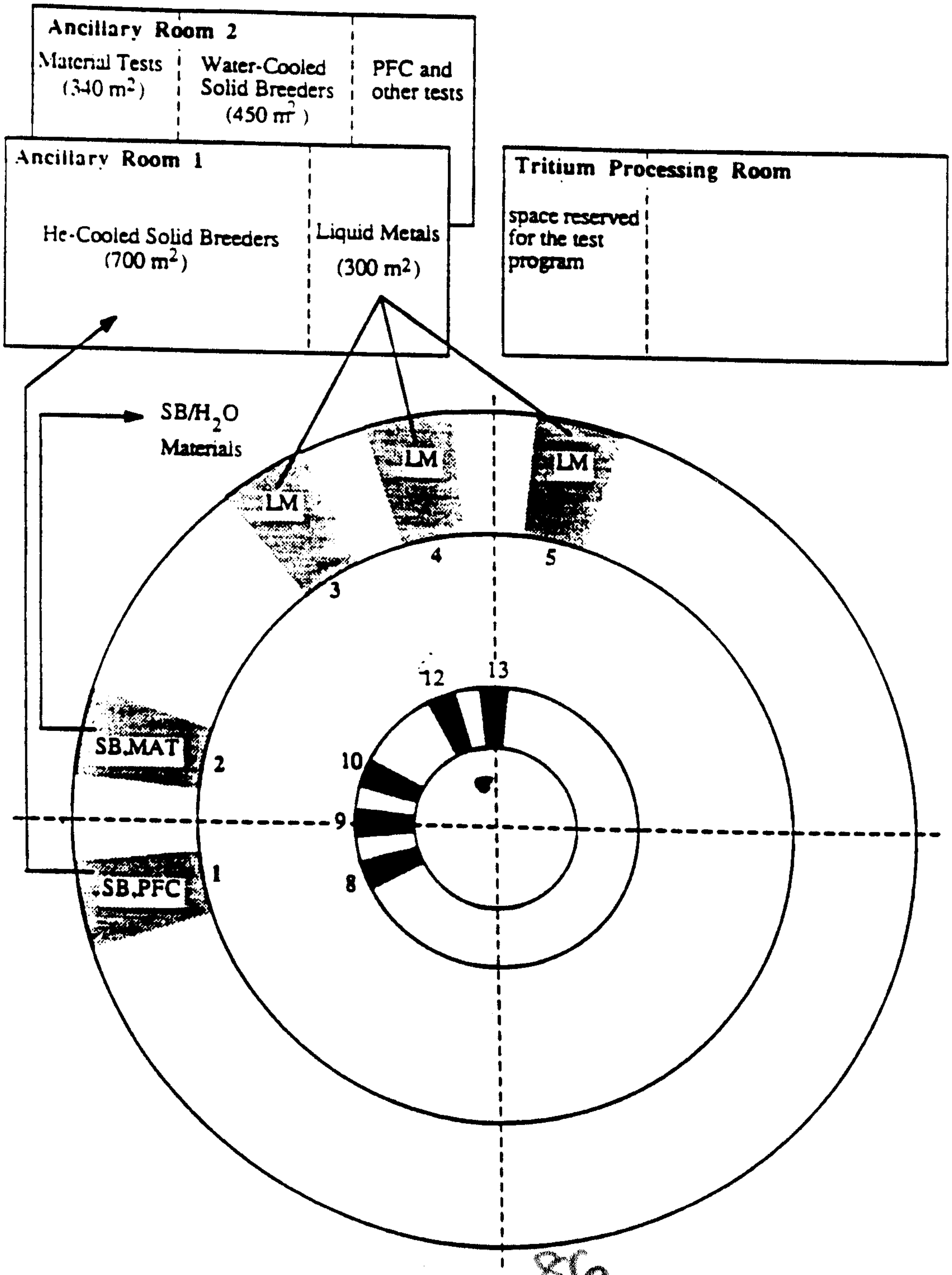
Tritium Recovery

MS: Molecular sieve Beds
CT: Cold trap
OX: Catalytic oxidizer

In Order to Ensure That the ITER Design can Accommodate the Test Program

Need to Discuss Ancillary Equipment Arrangements for EDA with JCT and Parties Involved in Testing

FIG. 4.2.4 - Space Allocation During the Technology Phase



Need to Develop the Space Requirements After an International Test Program Agreement is Reached.

TABLE 4.2.4. ESTIMATE OF ANCILLARY EQUIPMENT SPACE REQUIREMENTS

Port	Test Article Type	Space Requirements (Area x Height, m^{2}xm) behind test port	ancillary rooms	plant services*
SB/gas				
	3 submodules		730 x 11	300 x 11
	full module or segment		370 x 11	130 x 11
SB/H2O				
	3 submodules		450 x 11	150 x 8
	full module or segment		150 x 11	50 x 5
LM/self				
	4 submodules	300 x 11		
	full module or segment	300 x 11		
LM/H2O				
	2 submodule	50 x 11	100 x 11	
	full module	100 x 11	100 x 11	
	segment	100 x 11	200 x 11	
Materials				
	Test assembly	120 x 5**	220 x 11	525 x 11
TOTAL FLOOR AREA		400-500 m^2	1600 m^2	975 m^2

* plant services include space allocated in the main tritium processing hall and post-irradiation examination rooms (hot cells)

** pneumatic system for test specimen insertion/extraction. may be located in ancillary room

International Aspects
of ITER Test Program

Collaboration in the ITER Test Program

Collaboration on the test program is fundamentally different from collaboration on the basic device:

- R&D for ITER construction is specific to ITER and of common interest to parties
- The test program is tightly coupled to and plays a key role in R&D programs for DEMO and commercial reactor development

Difficulties may arise due to:

- differences in design choices
- differences in the overall strategies for fusion development
- differences in the approaches to testing

At present, there is no formal framework or agreement on collaboration on the test program

Need a mechanicsm to address parties' interests and collaboration on the test program

- (R&D)
- design and construction of test modules
- operation and sharing of information from the test program

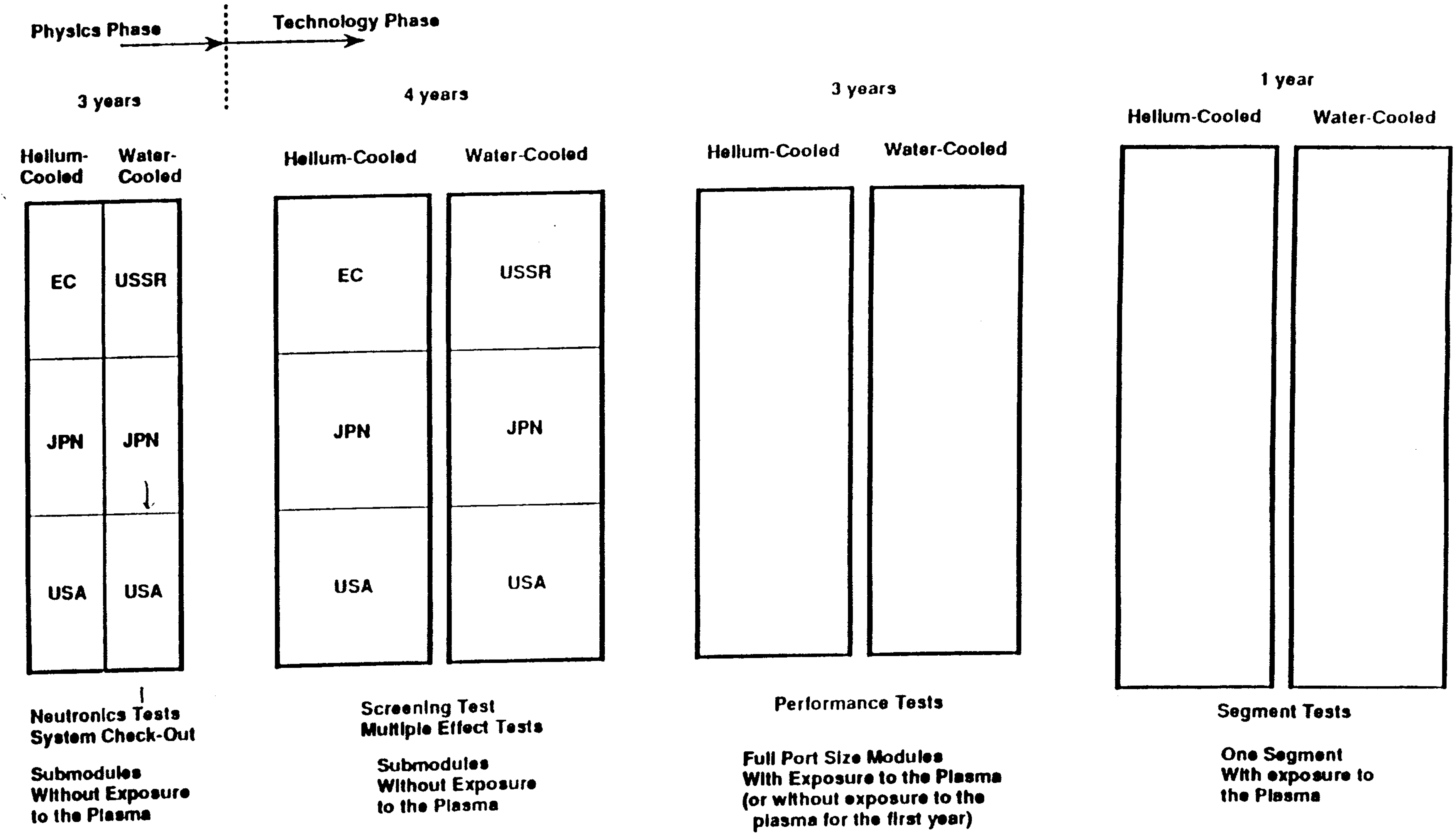
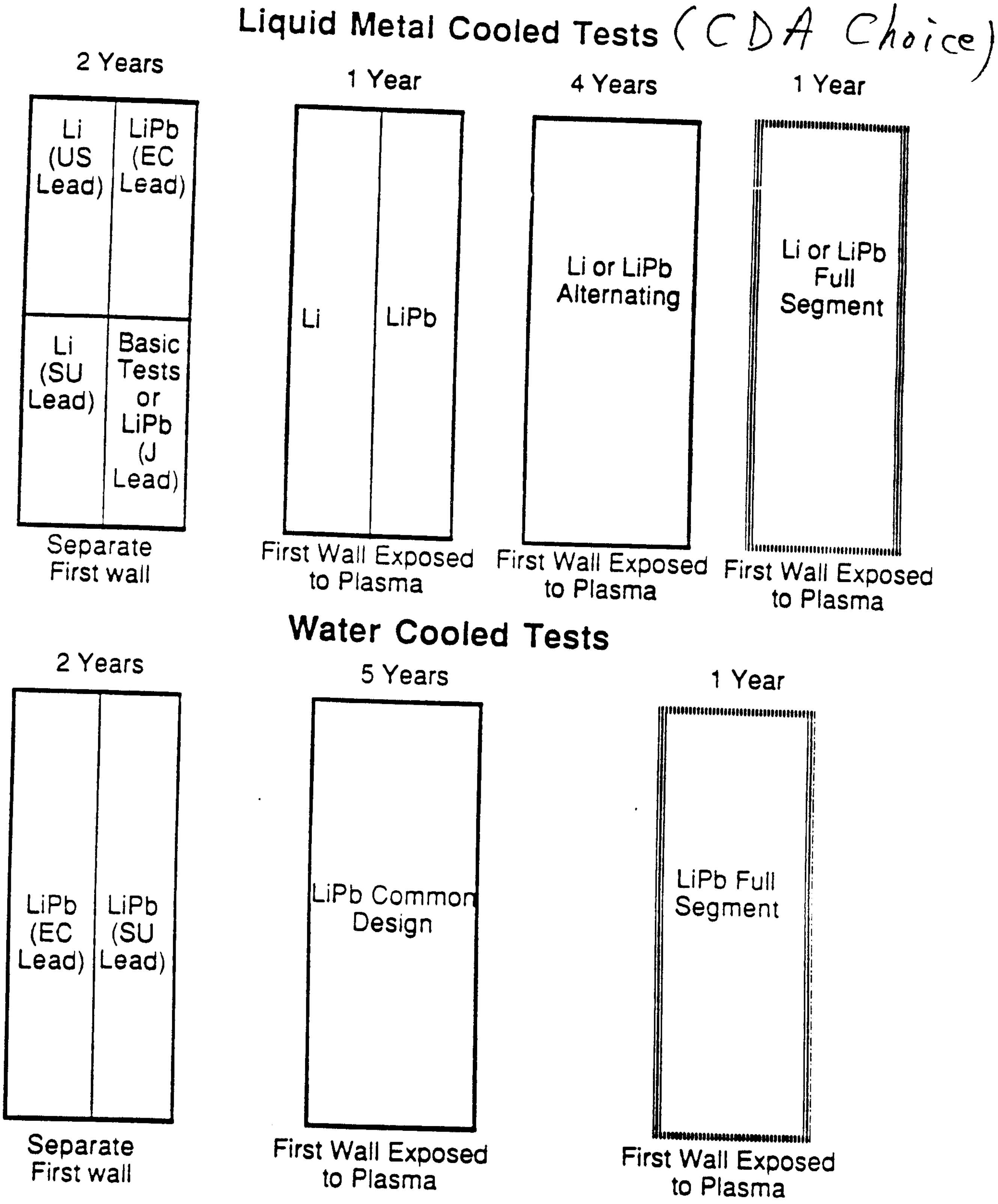


Fig. 1 Test Port Allocation to Helium- and Water-Cooled Solid Breeder Blankets

(CDA Choice)

Fig 2 Test Sequence for Liquid Metal Blankets



Options for the International Test Program

	CDA choice	*EDA choice*
1. Allocation of available testing spaces to parties		
– fully independent		
– lead role given to individual parties		
– spaces assigned to international groups	X	
– fully common test program		
2. Design of testing spaces and ancillary equipment		
– generic test spaces capable of testing any concept		
– single-coolant test spaces	X	
– custom-designed test spaces		