On Fusion Nuclear Technology Development Requirements and the Role of CTF toward DEMO

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<u>Note</u>

- Primarily for MFE DEMO (some aspects are relevant to IFE)

Fusion Nuclear Technology (FNT)

FNT Components from the edge of the Plasma to TF Coils **(Reactor "Core")**

1. Blanket Components
2. Plasma Interactive and High Heat Flux Components
    a. divertor, limiter
    b. rf antennas, launchers, wave guides, etc.
3. Vacuum Vessel and Shield Components

Other Components affected by the Nuclear Environment

4. Tritium Processing Systems
5. Instrumentation and Control Systems
6. Remote Maintenance Components
7. Heat Transport and Power Conversion Systems

Short Answers to Key Questions

That we have been asked the past few months

1. Can IFMIF do Blanket / FNT testing? ***No***

IFMIF provides data on "radiation damage" effects on basic properties of structural materials in "specimens".

Blanket Development is something **ELSE**

(IFMIF's role was explained by S. Zinkle. This presentation explains blanket/FNT development)

(No IFMIF report nor any of the material or blanket experts ever said this.)

2. What do we need for Blanket/PFC Development?

A – Testing in non-fusion facilities (laboratory experiments plus fission reactors plus accelerator based neutron sources)

AND B – Extensive Testing in Fusion Facilities

Conclusion from previous international studies
(e.g. FINESSE, ITER Test Blanket Working Group, IEA-VNS):

"The feasibility, operability, and reliability of blanket/FNT systems cannot be established without testing in fusion facilities."

Short Answers to Key Questions (Cont'd)

3. What are the Fusion Testing Requirements for Blankets/FNT?

Based on extensive technical international studies, many published in scholarly journals, the testing requirements are:

Neutron wall load of >1 MW/m^2 with prototypical surface heat flux, steady state (or long pulse > 1000 s with plasma duty cycle >80%), surface area for testing >10 m^2, testing volume > 5 m^3, neutron fluence > 6 MW·y/m^2

4. Can the present ITER (FEAT) serve as the fusion facility for Blanket/FNT Testing? ***No***

- ITER (FEAT) parameters do not satisfy FNT testing requirements

  Short plasma burn (400 s), long dwell time (1200 s), low wall load (0.55 MW/m^2), low neutron fluence (0.1 MW·y/m^2)

- ITER short burn/long dwell plasma cycle does not even enable temperature equilibrium in test modules, a fundamental requirement for many tests. Fluence is too low.

Short Answers to Key Questions (Cont'd)

5. Is it prudent to impose FNT testing requirements on ITER? ***No***
   - Tritium consumption/tritium supply problem, complete redesign is costly, schedule is a problem.
   - The optimum approach is two fusion devices: one for plasma burn; the other for FNT testing. (Conclusion of many studies.)

6. What is CTF?
   - The idea of CTF is to build a small size, low-fusion power DT plasma-based device in which Fusion Nuclear Technology experiments can be performed in the relevant fusion environment at the smallest possible scale and cost.
     - In MFE: small-size, low fusion power can be obtained in a low-Q plasma device.
     - Equivalent in IFE: reduced target yield and smaller chamber radius (W. Meier Presentation).
   - This is a faster, much less expensive approach than testing in a large, ignited/high Q plasma device for which tritium consumption, and cost of operating to high fluence are very high (unaffordable!, not practical).

Short Answers to Key Questions (Cont'd)

7. Is CTF Necessary? Most Definitely, ***but this is not the right question***. The right question is:

   Will ITER plus CTF as the only DT Fusion Facilities be sufficient to have a successful DEMO?

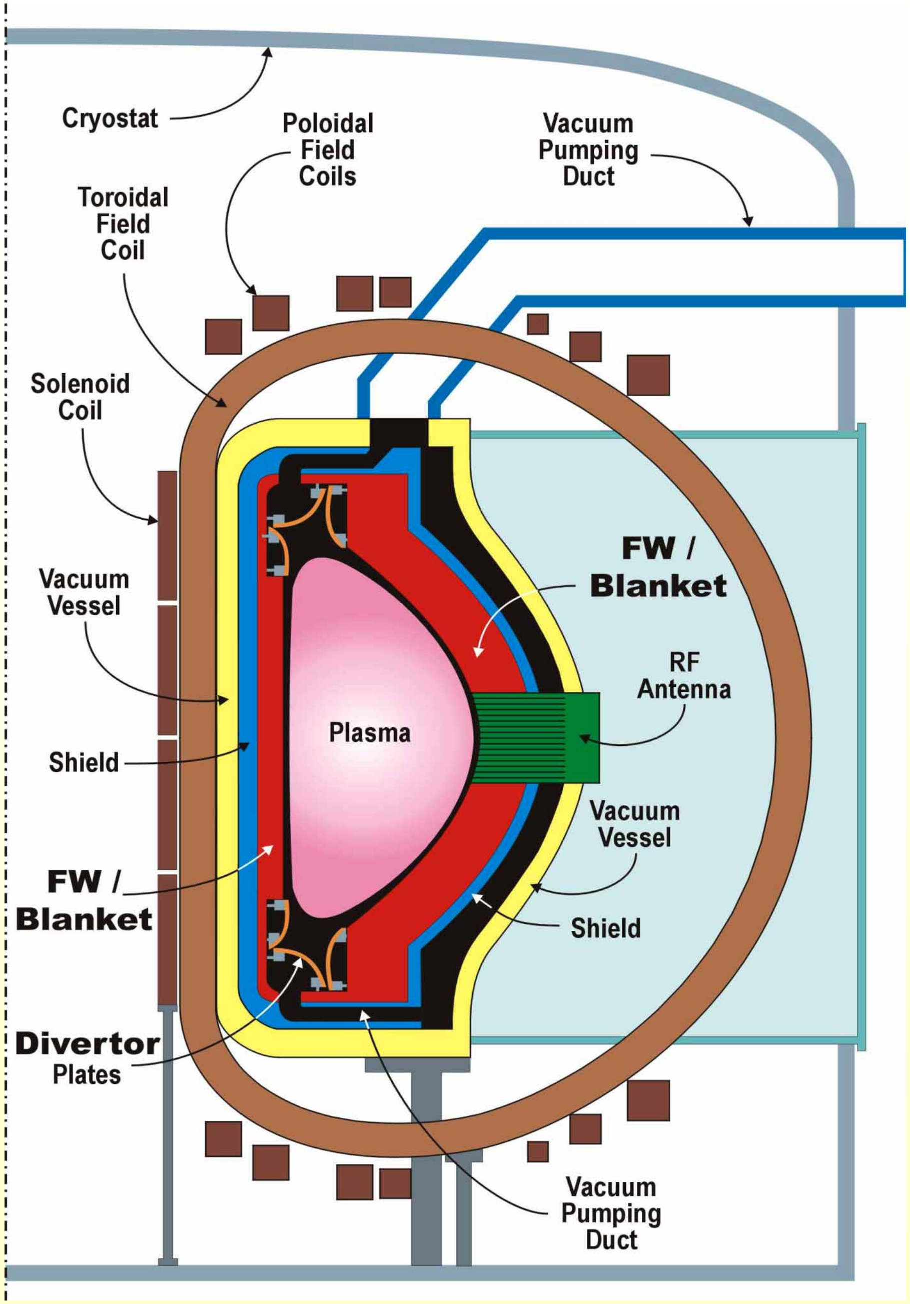
Maybe, but we know for sure that, at a minimum, we need:

- extensive developmental programs on ITER, CTF, and non-fusion facilities.
- this work to begin sooner rather than later, before the tritium supply window closes, to have any hope that DEMO starts in 35 years.

[And remember how many fission test reactors were built.]

Blanket/PFC Concepts, FNT Issues, and Testing Requirements

- **The Vacuum Vessel is outside the Blanket (/Shield). It is in a low-radiation field.**
- **Vacuum Vessel Development for DEMO should be in good shape from ITER experience.**
- **The Key Issues are for Blanket / PFC.**
- **Note that the first wall is an integral part of the blanket (ideas for a separate first wall were discarded in the 1980's). The term "Blanket" now implicitly includes first wall.**
- **Since the Blanket is inside of the vacuum vessel, many failures (e.g. coolant leak from module) require immediate shutdown and repair/replacement.**



Adaptation from ARIES-AT Design

Blanket and PFC Serve Fundamental and Necessary Functions in a DT Fusion System

- **TRITIUM BREEDING at the rate required to satisfy tritium self-sufficiency**
- **TRITIUM RELEASE and EXTRACTION**
- **Providing for PARTICLE PUMPING (plasma exhaust)**
- **POWER EXTRACTION from plasma particles and radiation (surface heat loads) and from energy deposition of neutrons and gammas at high temperature for electric power production**
- **RADIATION PROTECTION**

Important Points

- All in-vessel components (blankets, divertor, vacuum pumping, plasma heating antenna/waveguide, etc.) impact ability to achieve **tritium self-sufficiency**.
- **High temperature** operation is necessary for high thermal efficiency. And for some concepts, e.g. SB, high temperature is necessary for tritium release and extraction.
- All the above functions must be performed **safely** and **reliably**.

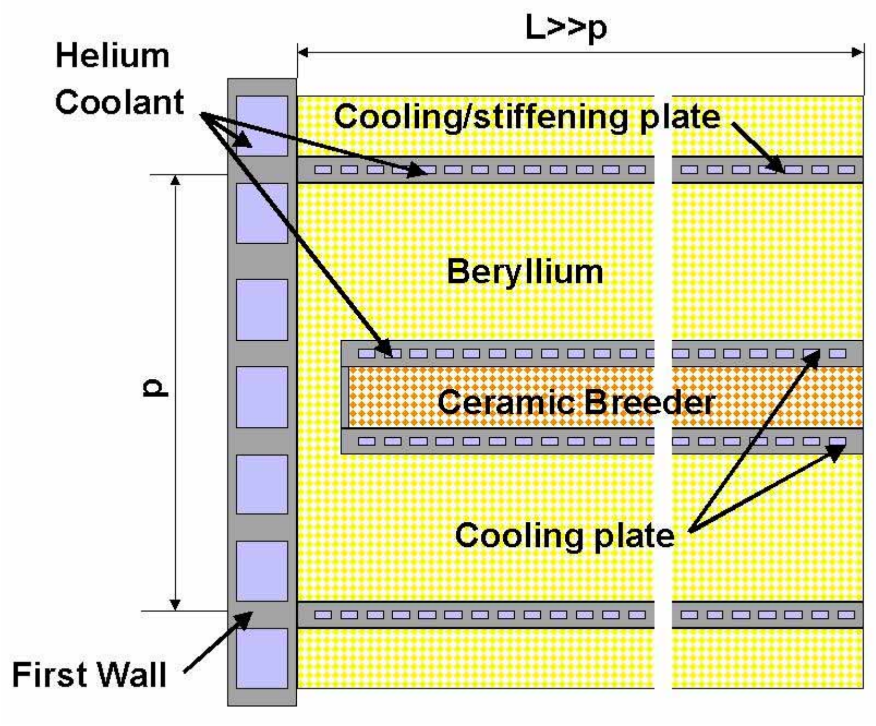
Specific Blanket Options (Worldwide)

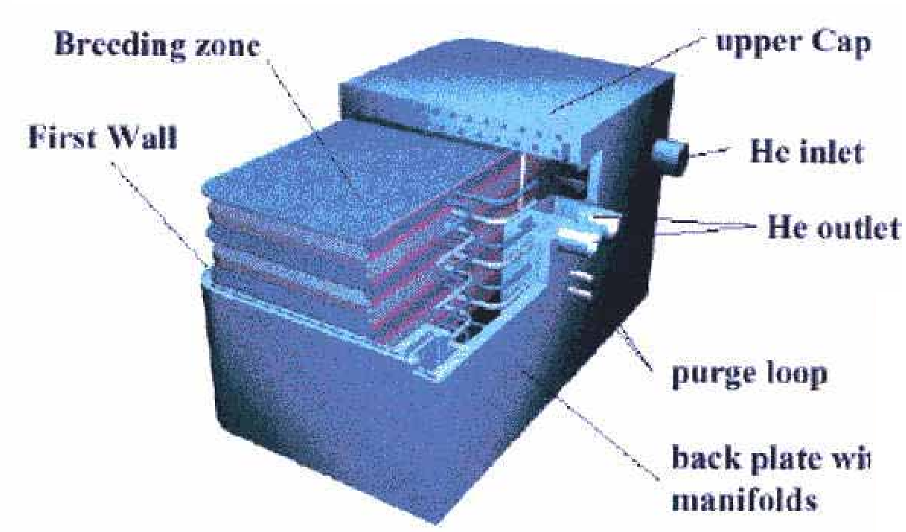
Options	Breeder/Multiplier	Coolant	Purge	Structure	Insulator
EU Demo & 1st generation plants	Pb-17Li	He (8 MPa)	---	Ferritic[+]	
	Li-Ceramic/Be	He (8 MPa)	He 0.13 MPa	Ferritic	
2nd generation plants	Pb-17Li	Pb-17Li & He	---	Ferritic	SiC Insert
	Li-Ceramic/Be	He	He	SiC/SiC	
	Pb-17Li	Pb-17Li	---	SiC/SiC	
JA Demo	$Li_2O(Li_2TiO_3)$/Be	H_2O & He	He	Ferritic	
LHD (Univ.)	Flibe	Flibe		Ferritic	
USA APEX[*] Studies	Li	Li	---	Ferritic/V	Coating
	Flibe(Flinabe)/Be	Flibe/Flinabe		Ferritic	
	Li-Ceramic/Be	He	He	Ferritic	
ARIES Studies	Pb-17Li	Pb-17Li	---	SiC/SiC	
	Pb-17Li	He	---	Ferritic	SiC Insert

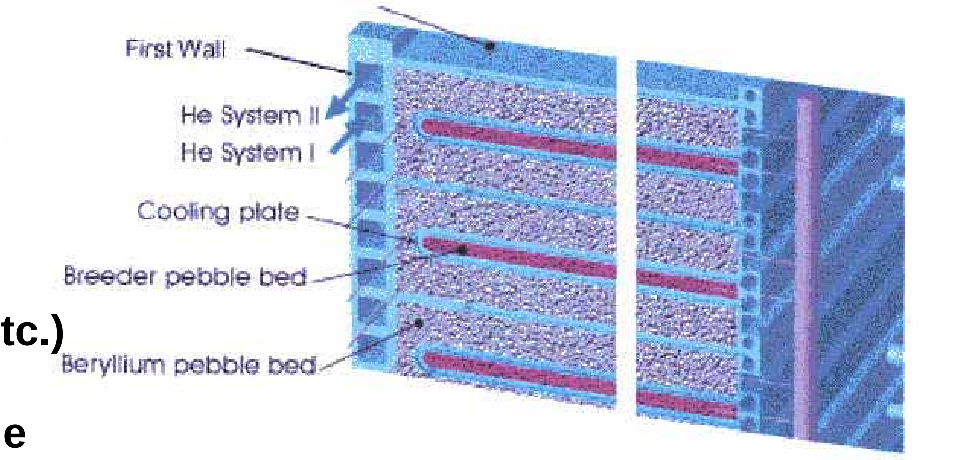
[*] APEX considers both bare solid wall and thin (2 cm) plasma-facing liquid on first wall and divertor

[+] Advanced Ferritic Steels are often proposed for designs using ferritic

A Helium-Cooled Li-Ceramic Breeder Concept is Considered for EU (Similar Concept also in Japan, USA)







Material Functions

Beryllium (pebble bed) for neutron multiplication

Ceramic breeder(Li4SiO4, Li2TiO3, Li2O, etc.) for tritium breeding

Helium purge to remove tritium through the “interconnected porosity” in ceramic breeder

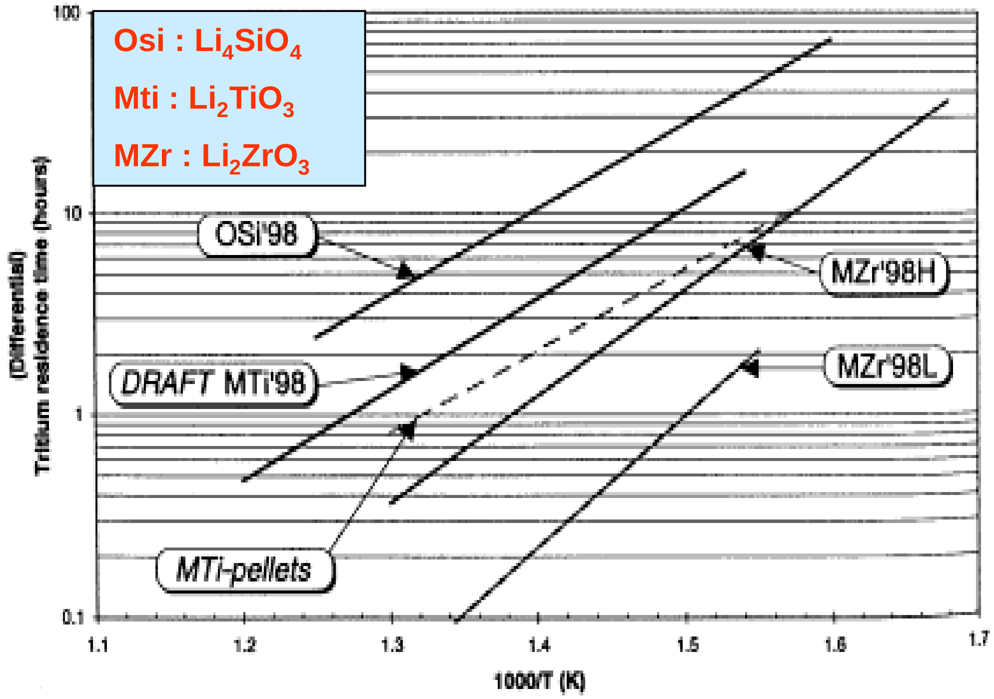
High pressure Helium cooling in structure (advanced ferritic)

Several configurations exist to overcome particular issues

Geometric Configurations and Material Interactions among breeder/Be/coolant/structure represent critical feasibility issues that require testing in the fusion environment

- Configuration (e.g. wall parallel or "head on" breeder/Be arrangements) affects TBR and performance
- Tritium breeding and release
  - **Max. allowable temp. (radiation-induced sintering in solid breeder inhibits tritium release; mass transfer, e.g. LiOT formation)**
  - **Min. allowable Temp. (tritium inventory, tritium diffusion**
  - **Temp. window (Tmax-Tmin) limits and k_e for breeder determine breeder/structure ratio and TBR**

Tritium release characteristics are highly temperature dependent



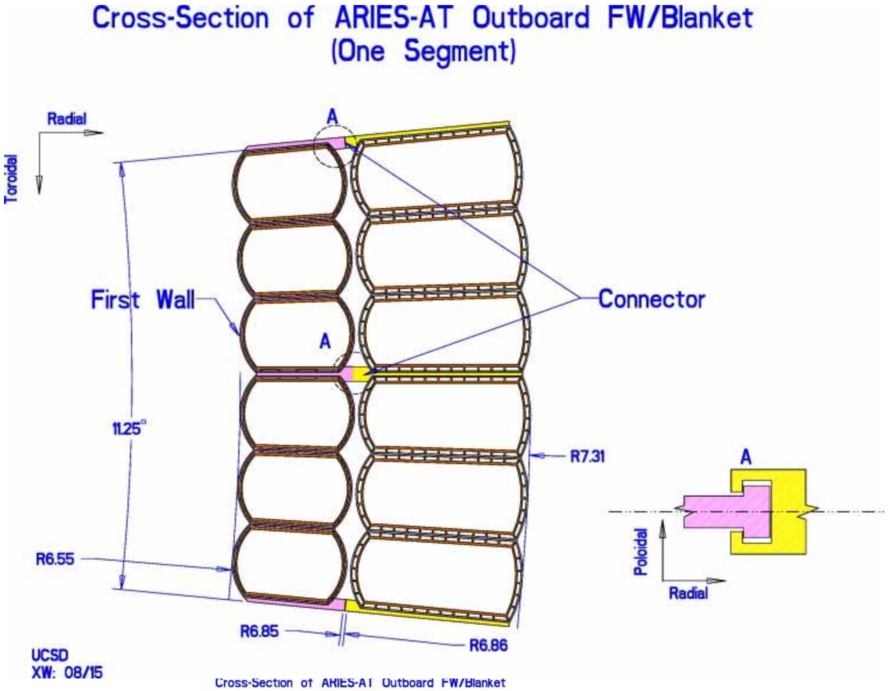
Osi : Li_4SiO_4

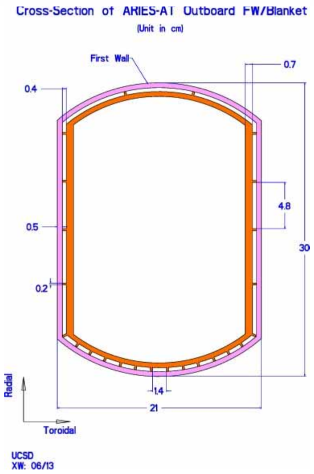
Mti : Li_2TiO_3

MZr : Li_2ZrO_3

- Thermomechanics interactions of breeder/Be/coolant/structure involve many feasibility issues (cracking of breeder, formation of gaps leading to big reduction in interface conductance and excessive temperatures)

ARIES-AT blanket with SiC composite structure and Pb-17Li coolant and tritium breeder

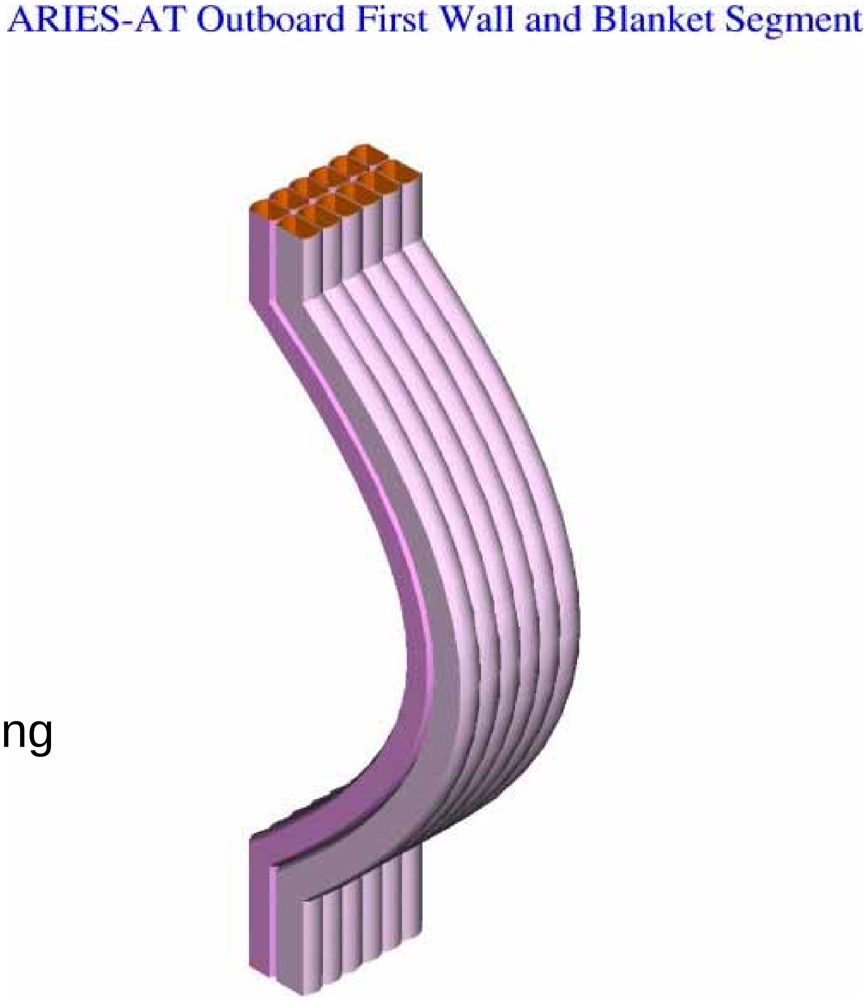




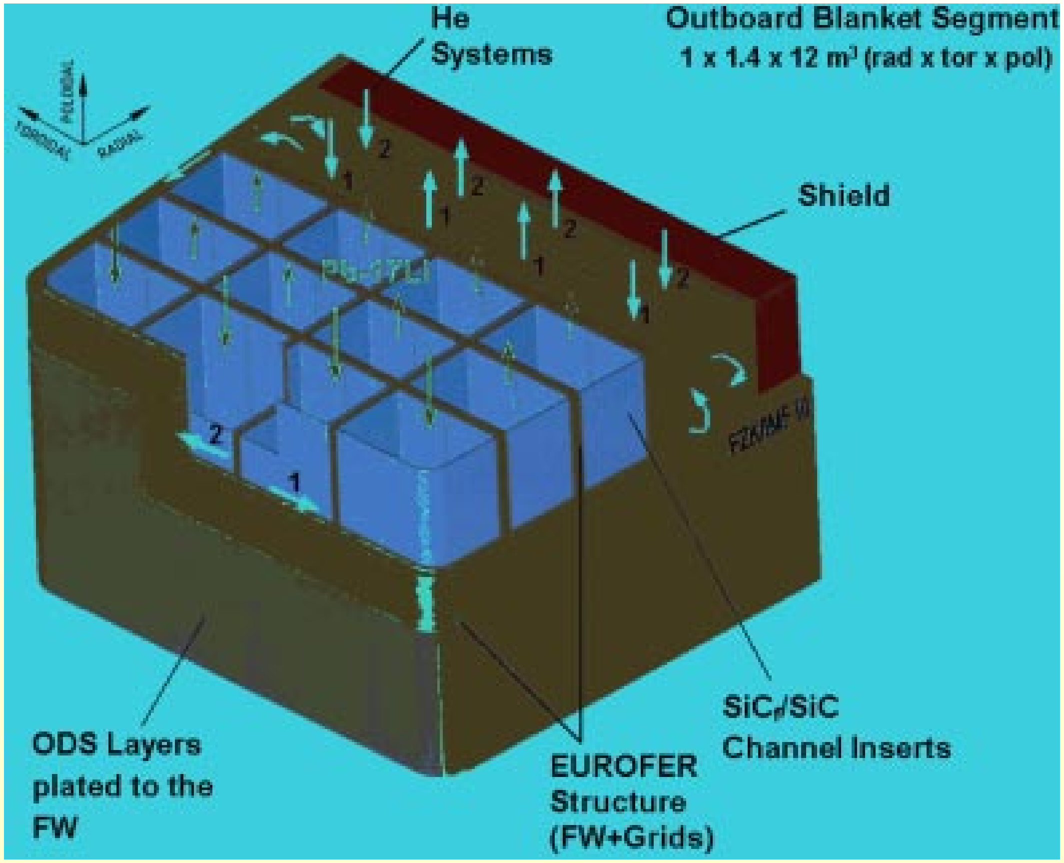
Pb-17Li Operating Temperature

Inlet: 654 ^{o}C

Outlet: 1100 ^{o}C



A Dual-Coolant Concept for EU 2nd Generation Plants (similar to ARIES-ST)



- **Dual coolant: He and Pb-17Li**
- **Coolant temperature (inlet/outlet, ^oC)**
  - 460/700 (Pb-17Li)
  - 300/480 (He)
- **SiC/SiC inserts to allow Pb-17Li operated at temperature greater than the allowable ODS/Pb-17Li corrosion temperature limit**

MHD and Insulators are Critical Issues

Engineering Feasibility will be proven only through Integrated Tests

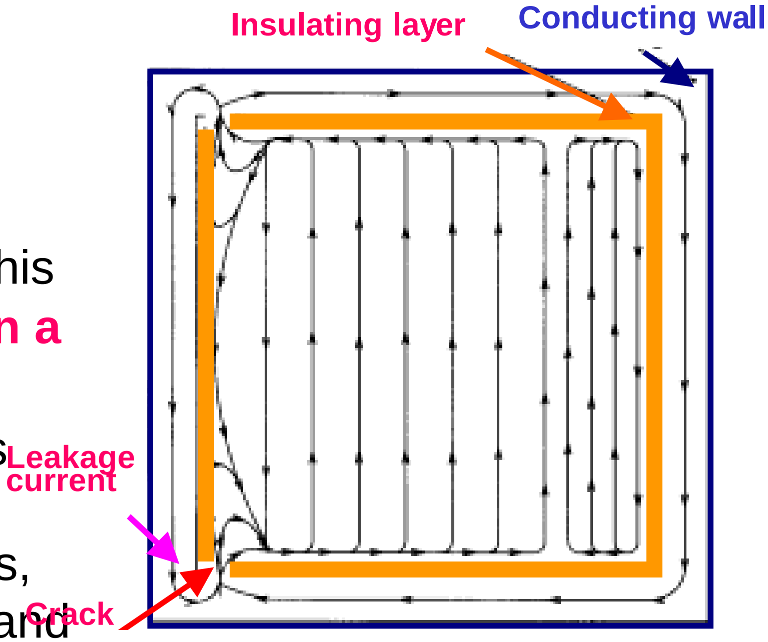
MHD is critical issue for liquid-metal-cooled blankets and PFC's

Insulators are required: Ceramic coatings have been proposed

Key issue: disparate thermal expansion coefficient, low tensile strength and poor ductility of ceramic coatings compared to pipe wall heated under cyclic operations will lead to significant cracking of the coating. Once a crack is generated it forms an electrical circuit for leakage current – leading to critical increase MHD pressure drop.

Therefore, rapid self-healing of coating is mandatory. Healing speed will depend on the details of crack generation rate and size – currently unknown and unpredictable.

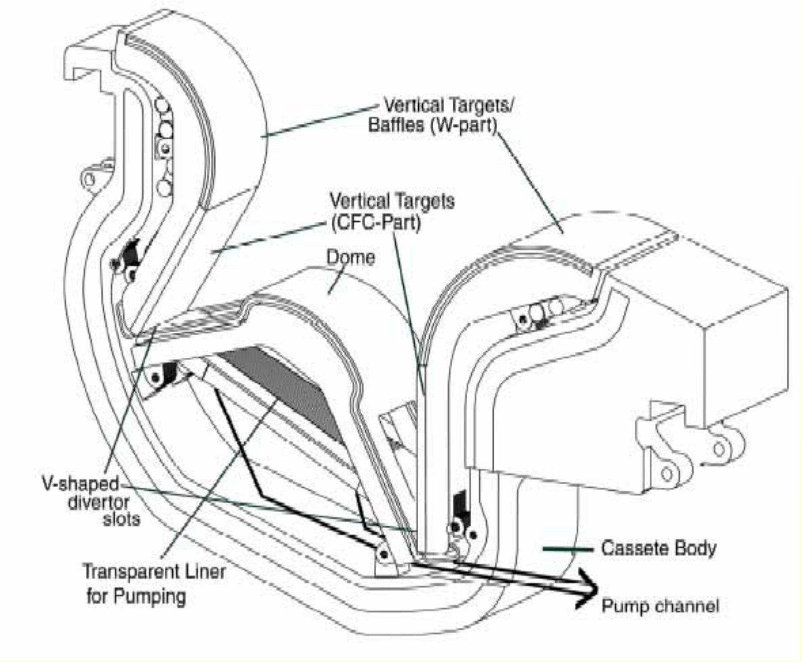
Meaningful testing of the performance of this thin insulating layer **can only be performed in a multi-effect environment** with: (1) high temperature and strong temperature gradients (volumetric nuclear heating), (2) electric and magnetic fields, (3) stress and stress gradients, (4) prototypic material and chemical systems and geometry, and (5) radiation effects.



Leakage of Electric currents in 2D channel with cracked insulator coating

PFC Development

- Highest heat flux component in a fusion device (10-20 MW/m^2)
- Closely coupled to plasma performance
- Cyclic Power excursions (ELMs & Disruptions) erosion lifetime
- Limited materials choices (W, Mo, Ta, Nb?, C?, Liquids: Li, Ga, Sn)
- High neutron fluence
- Tritium retention (C)
- Joining, fabrication, and coolant compatibility issues

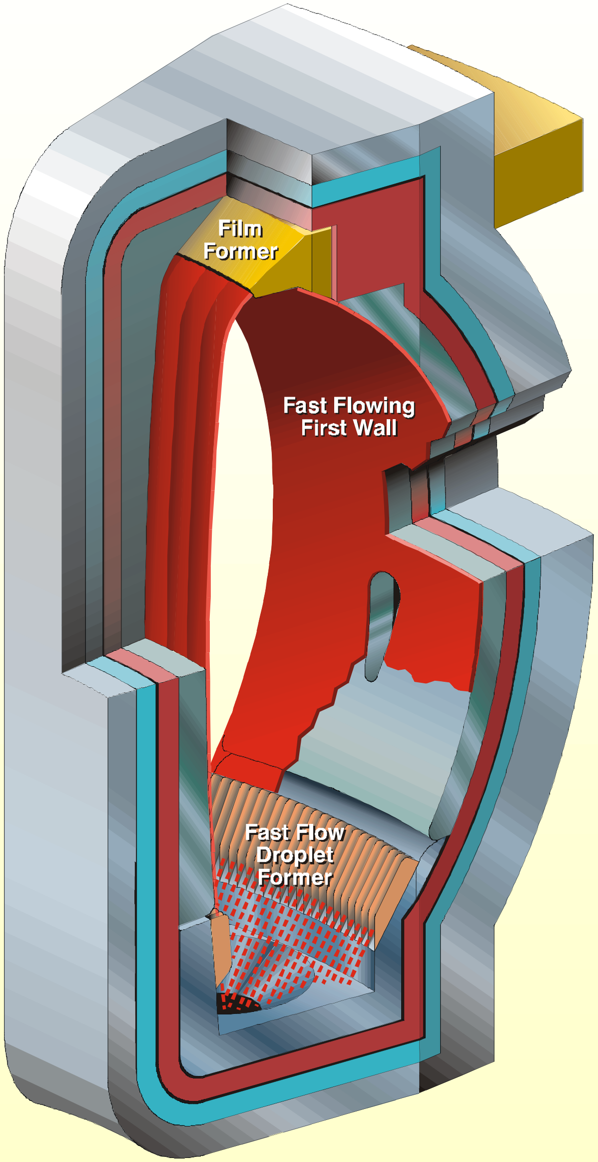


ITER-FEAT Divertor Cassette

Note: PFC, Blanket, rf antennas, and other in-vessel components in reactor "core" must be compatible and they collectively play a major role in key FNT issues, e.g. Tritium Self-Sufficiency.

Role of Liquid Walls in Blanket and PFC Development

- Liquid Walls are being pursued in the US for many potential benefits (removal of high surface heat flux, increased potential for disruption survivability, reduced thermal stresses in structural materials, possible improvements in plasma confinement and stability, etc.)
- The focus of the on-going R&D Program in laboratory experiments and plasma devices is on a thin liquid wall (~2 cm) on the plasma-facing side of the first wall and divertor
- No major changes in Fusion Nuclear Technology Development Pathways are necessary for thin liquid walls. If thin liquid walls prove feasible (e.g. from NSTX liquid surface module), they can be easily incorporated into CTF (and also, hopefully, into ITER at later stages) and DEMO



Summary of Critical R&D Issues for Fusion Nuclear Technology

- D-T fuel cycle **tritium self-sufficiency**

2. **Tritium inventory** and recovery in the solid/liquid breeders under actual operating conditions
3. **Thermomechanical** loadings and response of blanket and PFC components under normal and off-normal operation
4. Materials **compatibility**
5. Identification and characterization of **failure modes, effects, and rates** in blankets and PFC’s
6. Effect of imperfections in electric (MHD) **insulators** in liquid metal cooled blanket and PFC under thermal/mechanical/electrical/nuclear loading
7. **Tritium permeation** and inventory in blanket and PFC
8. **Radiation Shielding**: accuracy of prediction and quantification of radiation protection requirements
9. **Lifetime** of blanket, PFC, and other FNT components
10. **Remote maintenance** with acceptable machine shutdown time.

FNT Testing Requirements

Key Fusion Environmental Conditions for Testing Fusion Nuclear Components

Neutrons (fluence, spectrum, spatial and temporal gradient)

- Radiation Effects
  (at relevant temperatures, stresses, loading conditions)
- Bulk Heating
- Tritium Production
- Activation

Heat Sources (magnitude, gradient)

- Bulk (from neutrons)
- Surface

Particle Flux (energy and density)

Magnetic Field

- Steady Field
- Time-Varying Field

Mechanical Forces

- Normal
- Off-Normal

Thermal/Chemical/Mechanical/Electrical/Magnetic Interactions

Synergistic Effects

- Combined environmental loading conditions
- Interactions among physical elements of components

Table XV*: Capabilities of Non-Fusion Facilities for Simulation of Key Conditions for Fusion Nuclear Component Experiments

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

(1) radiation damage, tritium and helium production, transmutations

(2) nuclear heating in a significant volume

(3) magnetic field, surface heat flux, particle flux, mechanical forces

(4) thermal-mechanical-chemical-electrical interactions (normal and off normal)

* From Fusion Technology, Vol. 29, pp 1-57, January 1996

FNT Development for DEMO:
Need for FNT Testing in Fusion Facilities

Conclusions of International Experts:

--Non-fusion facilities cannot fully resolve any critical issue for blankets or PFC's

--There are critical issues for which no significant information can be obtained from testing in non-fusion facilities (An example is identification and characterization of failure modes, effects and rates)

--The Feasibility of Blanket/PFC Concepts can NOT be established prior to testing in fusion facilities

Note: Non-fusion facilities can and should be used to narrow material and design concept options and to reduce the costs and risks of the more costly and complex tests in the fusion environment. Extensive R&D programs on non-fusion facilities should start now.

Testing in a Fusion Facility is the fastest approach to Blanket and Fusion Development to Demo

A fusion test facility allows SIMULTANEOUS testing of integrated (synergistic) effects, multiple effects, and single effects

- Allows understanding through single and multiple effects tests under same conditions
- Provides “direct” answer for synergistic effects

Specimen

50 cm

100 cm

9 cm

2.5 cm

10.8 cm

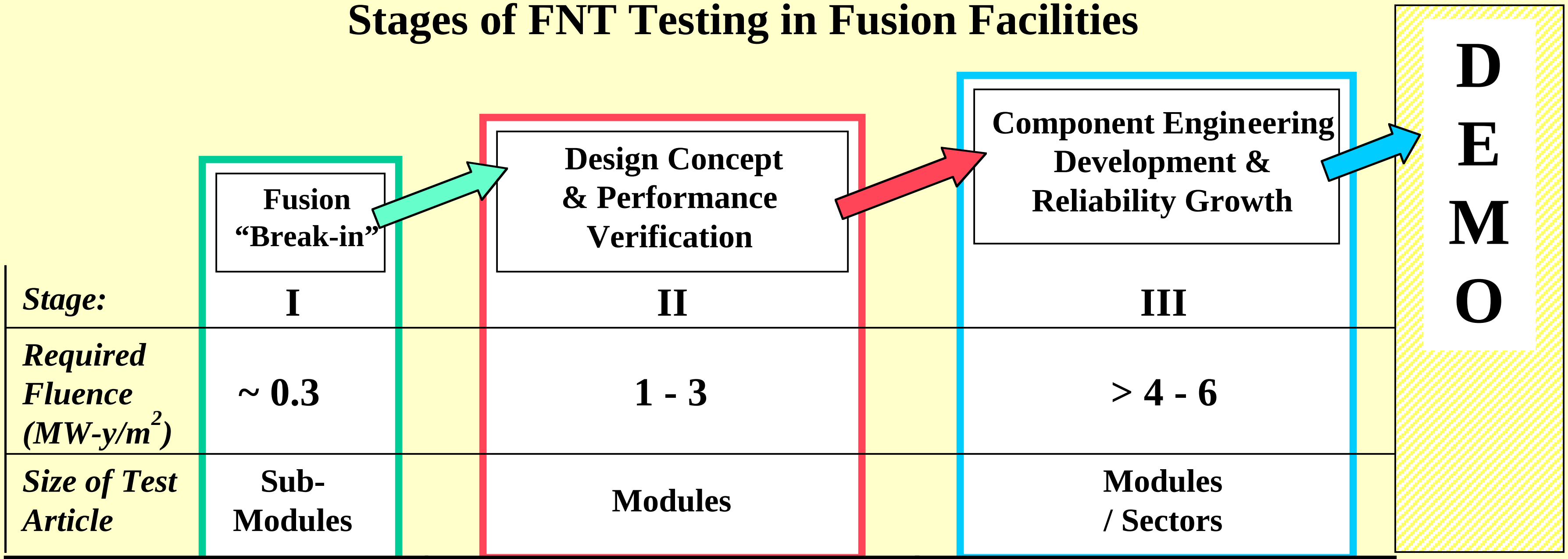
Capsule test

Submodule

Test Module

**** Figures are not to scale. Note Dimensions***

Stages of FNT Testing in Fusion Facilities



	Fusion “Break-in”	Design Concept & Performance Verification	Component Engineering Development & Reliability Growth
Stage:	**I**	**II**	**III**
Required Fluence ($MW\text{-}y/m^2$)	**~ 0.3**	**1 - 3**	**> 4 - 6**
Size of Test Article	**Sub-Modules**	**Modules**	**Modules / Sectors**

D
E
M
O

- Initial exploration of performance in a fusion environment
- Calibrate non-fusion tests
- Effects of rapid changes in properties in early life
- Initial check of codes and data
- Develop experimental techniques and test instrumentation
- Narrow material combination and design concepts
- 10-20 test campaigns, each is 1-2 weeks

- Tests for basic functions and phenomena (tritium release / recovery, etc.), interactions of materials, configurations
- Verify performance beyond beginning of life and until changes in properties become small (changes are substantial up to ~ 1-2 MW · y/m^2)
- Data on initial failure modes and effects
- Establish **engineering feasibility** of blankets (satisfy basic functions & performance, 10 to 20% of lifetime)
- Select 2 or 3 concepts for further development

- Identify failure modes and effects
- Iterative design / test / fail / analyze / improve programs aimed at improving reliability and safety
- Failure rate data: Develop a data base sufficient to predict mean-time-between-failure with sufficient confidence
- Obtain data to predict mean-time-to-replace (MTTR) for both planned outage and random failure
- Develop a data base to predict overall availability of FNT components in DEMO

FNT Requirements for Major Parameters for Testing in Fusion Facilities with Emphasis on Testing Needs to Construct DEMO Blanket

- These requirements have been extensively studied over the past 20 years, and they have been agreed to internationally (FINESSE, ITER Blanket Testing Working Group, IEA-VNS, etc.)
- Many Journal Papers have been published (>35)
- Below is the Table from the IEA-VNS Study Paper (Fusion Technology, Vol. 29, Jan 96)

Parameter	Value
Neutron wall load[a] (MW/m^2)	1 to 2
Plasma mode of operation	Steady State[b]
Minimum COT (periods with 100% availability) (weeks)	1 to 2
Neutron fluence at test module (MW·y/m^2)	
Stage I: initial fusion break-in	0.3
Stage II: concept performance verification (engineering feasibility)	1 to 3
Stage III[c]: component engineering development and reliability growth	4 to 6[c]
Total neutron fluence for test device (MW·y/m^2)	>6
Total test area (m^2)	>10
Total test volume (m^3)	>5
Magnetic field strength (T)	>4

a - Prototypcial surface heat flux (exposure of first wall to plasma is critical)

b - If steady state is unattainable, the alternative is long plasma burn with plasma duty cycle >80%

c - Note that the fluence is not an accumulated fluence on “the same test article”; rather it is derived from testing “time” on “successive” test articles dictated by “reliability growth” requirements

Where to do Blanket/PFC/FNT Fusion Testing?

Options / Scenarios

1. ITER (FEAT)

2. Modified ITER
    - Redesign to satisfy FNT Testing Parameters

3. Defer to DEMO

4. Add Small Size, Small Power Device for FNT Testing (CTF)

    a – CTF parallel to ITER

    b – CTF delayed start relative to ITER

Critical Factors in Evaluating Options

- Tritium Supply Issue
- Reliability/Availability Issue
- Cost
- Risk
- Schedule

ITER (FEAT) Parameters Do NOT Satisfy FNT Testing Requirements

Overall Schedule

- 10 yr construction
- H and D operation: 4 yr
- DT operation (First DT Plasma Phase): 6 yr

Parameters for First DT Phase[a]

Neutron Wall Load: 0.55 MW/m^2
Plasma Burn Time: 400 s
Plasma Dwell Time: 1200 s
Plasma Duty Cycle: 0.25
Neutron Fluence: ~ 0.1 MW•y /m^2

Key Problems are: low wall load (engineering scaling); short plasma burn, long dwell time; very low fluence

[a] - *note: "possibility of second DT Phase will be decided following a review of results of first 10 yr operation"*

Mode of Plasma Operation and Burn/Dwell Times

- This issue was investigated extensively in several studies including the ITER Test Blanket Working Group in both ITER-CDA and ITER-EDA, IEA-VNS. The conclusion reached: need steady state (or if unattainable, long burn/short dwell with plasma duty cycle >80%).
- Extensive Investigation of Blanket Testing Requirements using detailed engineering scaling to preserve phenomena, etc. show that:

  plasma burn time (t_b) > 3 τ_c

  plasma dwell time (t_d) < 0.05 τ_c

  Where τ_c is a characteristic time constant (for a given blanket phenomena)
- Characteristic time constants for various responses/phenomena in the blanket range from a few seconds to a few hours (even days for some phenomena). See Tables in Appendix.
  - Thus the burn time needs to be hours and the dwell time needs to be a few seconds.
- Example of Difficulty: In ITER-FEAT scenario of 400 s burn and 1200 s dwell time, even temperature equilibrium can not be attained. Most critical phenomena in the blanket have strong temperature dependence.

Tritium Consumption in Large and Small Power DT Devices

AND Tritium Supply Issue

AND Impact on the Path to FNT Development

Separate Devices for Burning Plasma and FNT Development, i.e. ITER (FEAT) + CTF is more Cost Effective and Faster than a Single Combined Device

(to change ITER design to satisfy FNT testing requirements is very expensive and not practical)

	NWL	Fusion Power	Fluence (MW·y/m^2)	Tritium Consumption (TBR = 0)	Tritium Consumption (TBR = 0.6)
Two Device Scenario 1) Burning Plasma (ITER)	0.55	500 MW	0.1	5 kg	2 kg
2) FNT Testing (CTF)	>1	< 100 MW	> 6	33 kg	13 kg
Single Device Scenario (Combined Burning Plasma + FNT Testing), i.e. ITER with major modifications (double the capital cost)	>1	910 MW	>6	>305 kg	>122 kg

FACTS

- World Maximum Tritium Supply (mainly CANDU) available for Fusion is 27 kg
- Tritium decays at 5.47% per year
- Tritium cost (if available) is >30 million dollar/kg

Conclusion:

- There is no external tritium supply to do FNT testing development in a large power DT fusion device. FNT development must be in a small fusion power device.

Projections for World Tritium Supply Available to Fusion for Various Scenarios

(Generated by Scott Willms, including information from Paul Rutherford’s 1998 memo on “Tritium Window”, and input from Dai-Kai Sze)

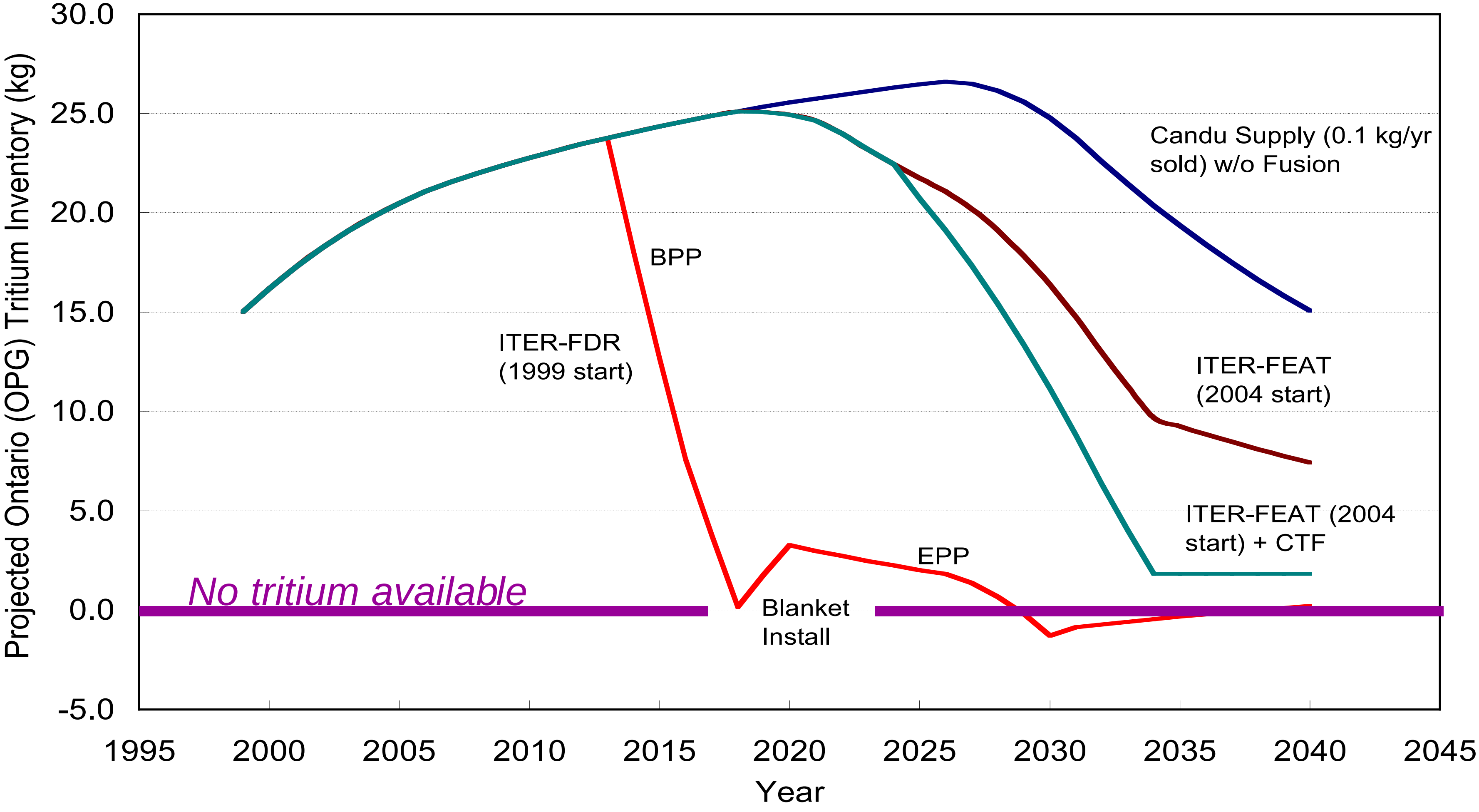
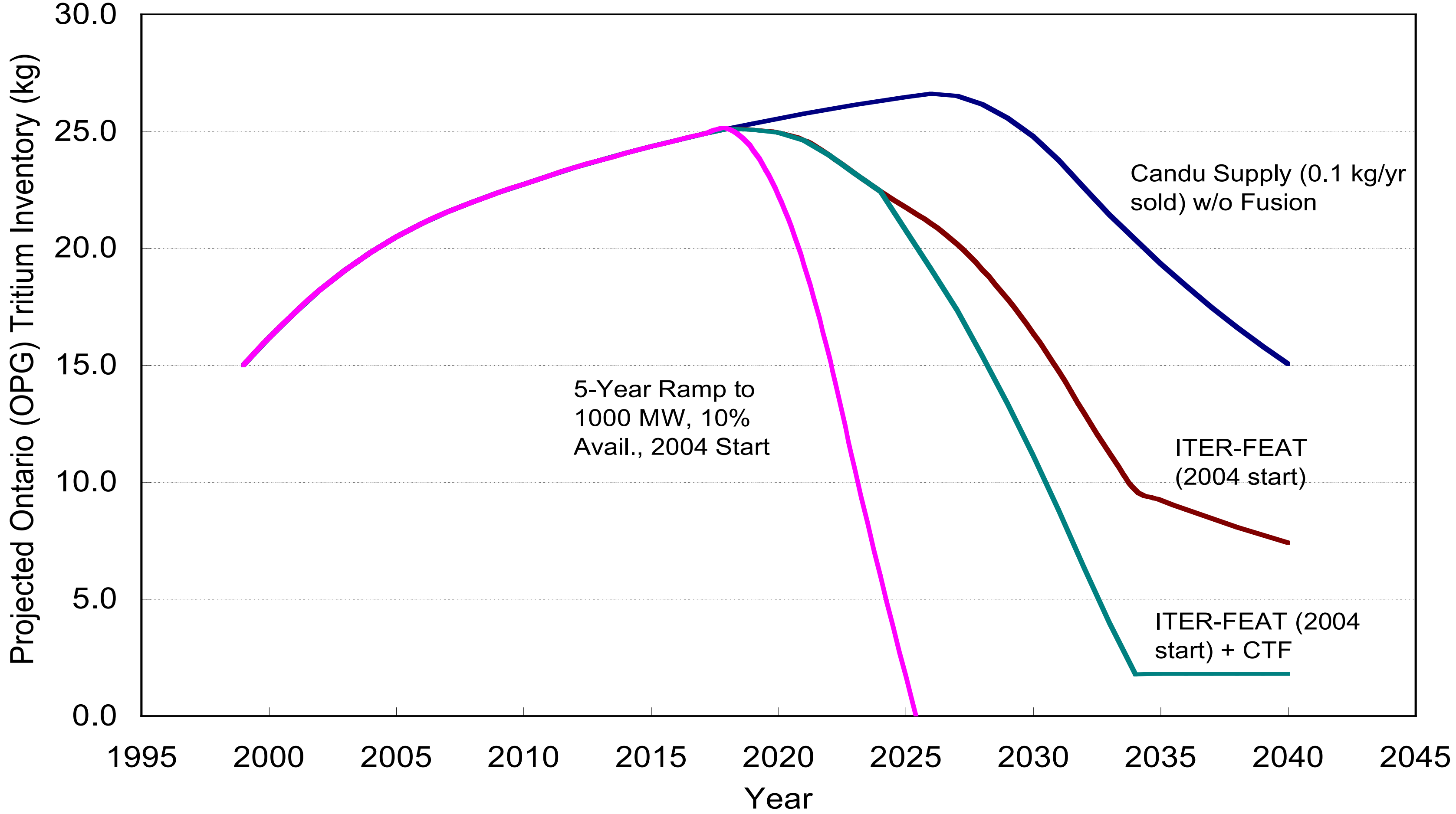


Fig. S/Z 1 (see calculation assumptions in Table S/Z 11)

World Tritium Supply would be Exhausted by 2025 if ITER were to run at 1000 MW fusion power with 10% availability



- Large Power DT Fusion Devices are not practical for blanket/PFC development.
- We need 5-10 kg of tritium as “start-up” inventory for DEMO (can be provided from CTF operating with TBR > 1 at later stage of operation)
- Blanket/PFC must be developed prior to DEMO (and we cannot wait very long for blanket/PFC development even if we want to delay DEMO).

Table S/Z 11

(data used in Fig. S/Z 1 for Tritium Supply and Consumption Calculations)

Tritium Supply Calculation Assumptions:

- Ontario Power Generation (OPG) has seven of twenty CANDU reactors idled
- Reactors licensed for 40 years
- 15 kg tritium in 1999
- 1999 tritium recovery rate was 2.1 kg/yr
- Tritium recovery rate will decrease to 1.7 kg/yr in 2005 and remain at this level until 2025
- After 2025 reactors will reach their end-of-life and the tritium recovery rate will decrease rapidly
- OPG sells 0.1 kg/yr to non-ITER/VNS users
- Tritium decays at 5.47 % / yr

It is assumed that the following will NOT happen:

- Extending CANDU lifetime to 60 years
- Restarting idle CANDU's
- Processing moderator from non-OPG CANDU's (Quebec, New Brunswick)
- Building more CANDU's
- Irradiating Li targets in commercial reactors (including CANDU's)
- Obtaining tritium from weapons programs of "nuclear superpowers"
- Premature shutdown of CANDU reactors

Table S/Z 11 (cont'd)

(data used in Fig. S/Z 1 for Tritium Supply and Consumption Calculations cont'd)

For the ITER-FDR scenario it is assumed:

- Burn 5 kg T/yr for last five years of BPP
- During 2-year install of breeding blanket no tritium burned
- During 10-year EPP will have TBR of 0.8 and require 1.7 kg T/yr from external sources
- Will require about 3 kg T to fill materials and systems (spread over first three years of tritium operations)
- This scenario will not be followed, but is an instructive case study

ITER-FEAT Assumptions:

- Construction starts in 2004 and lasts 10 years
- There are four years of non-tritium operation
- This is followed by 16 years of tritium operation. The first five years use tritium at a linearly increasing rate reaching 1.08 kg T used per year in the fifth year. Tritium usage remains at this level for the remainder of tritium operations.
- There is no tritium breeding (TBR=0)
- There is no additional tritium needed to fill materials and systems

CTF Assumption:

- Will burn 1 kg T/yr for ten years (e.g. 120 MW at 30% availability and TBR = 0.5)
- Begins burning tritium in 2024

Reliability / Maintainability / Availability
Critical Development Issues

$$\mathit{Unavailability} = U(\mathit{total}) = U(\mathit{scheduled}) + U(\mathit{unscheduled})$$

This you design for

This can kill your DEMO and your future

Scheduled Outage:

Planned outage (e.g. scheduled maintenance of components, scheduled replacement of components, e.g. first wall at the end of life, etc.).

This tends to be manageable because you can plan scheduled maintenance / replacement operations to occur simultaneously in the same time period.

Unscheduled Outage: (This is a very challenging problem)

Failures do occur in any engineering system. Since they are random they tend to have the most serious impact on availability.

This is why "reliability/availability analysis," reliability testing, and "reliability growth" programs are key elements in any engineering development.

Availability (Unscheduled): $$A_{un} = \frac{1}{1 + \sum_i \text{Outage Risk}}$$ i represents a component

$$(\text{Outage Risk})_i = (\text{failure rate})_i \bullet (\text{mean time to repair})_i = \frac{MTTR_i}{MTBF_i}$$

MTBF = mean time between failures = 1/failure rate

MTTR = mean time to repair

Notes

- Availability analysis generally tries to allocate outage risks and availability to various components depending on a lot of factors.
- MTTR depends on the complexity and characteristics of the system (e.g. confinement configurations, component blanket design and configuration, nature of failure). Can estimate, but need to demonstrate MTTR in fusion test facility.
- MTBF depends on reliability of components.

One can estimate what MTBF is NEEDED from “availability allocation models” for a given availability goal and for given (assumed) MTTR.

But predicting what MTBF is ACHIEVEABLE requires real data from integrated tests in the fusion environment.

An Example Illustration of Achieving a Demo Availability of 30%

(Table from J. Sheffield's memo to the Dev Path Panel)

Component	Number	Failure rate in hr^{-1}	**MTBF in years**	MTTR for Major failure, hr	MTTR for Minor failure, hr	Fraction of failures that are Major	**Unavailability**	Sum of Unavailability
Toroidal Coils	16	5 x10^{-6}	**23**	10^{4}	240	0.1	**0.098**	0.098
Poloidal Coils	8	5 x10^{-6}	**23**	5x10^{3}	240	0.1	**0.025**	0.123
Magnet supplies	4	1 x10^{-4}	**1.14**	72	10	0.1	**0.007**	0.130
Cryogenics	2	2 x10^{-4}	**0.57**	300	24	0.1	**0.022**	0.152
Blanket	100	1 x10^{-5}	**11.4**	800	100	0.05	**0.135**	0.287
Divertor	32	2 x10^{-5}	**5.7**	500	200	0.1	**0.147**	0.434
Htg/CD	4	2 x10^{-4}	**0.57**	500	20	0.3	**0.131**	0.565
Fueling	1	3 x10^{-5}	**3.8**	72	--	1.0	**0.002**	0.567
Tritium System	1	1 x10^{-4}	**1.14**	180	24	0.1	**0.005**	0.572
Vacuum	3	5 x10^{-5}	**2.28**	72	6	0.1	**0.002**	0.574
Conventional equipment - instrumentation[1], Cooling, turbines, electrical plant ---							**0.05**	0.624

Assuming 0.2 as a fraction of year scheduled for regular maintenance.
Availability = 0.8* (1-0.624) = 0.3

Reliability/Availability is a challenge to fusion, particularly blanket/PFC, development

- Fusion System has many major components (TFC, PFC, plasma heating, vacuum vessel, blanket, divertor, tritium system, fueling, etc.)
  - Each component is required to have high availability
- All systems except the reactor core (blanket/PFC) will have reliability data from ITER and other facilities
- There is NO data for blanket/PFC (we do not even know if any present blanket concept is feasible)
- Estimates using available data from fission and aerospace for unit failure rates and using the surface area of a tokamak show: probable MTBF for Blanket ~ 0.01 to 0.2 yr compared to required MTBF of many years

Aggressive "Reliability Growth" Program

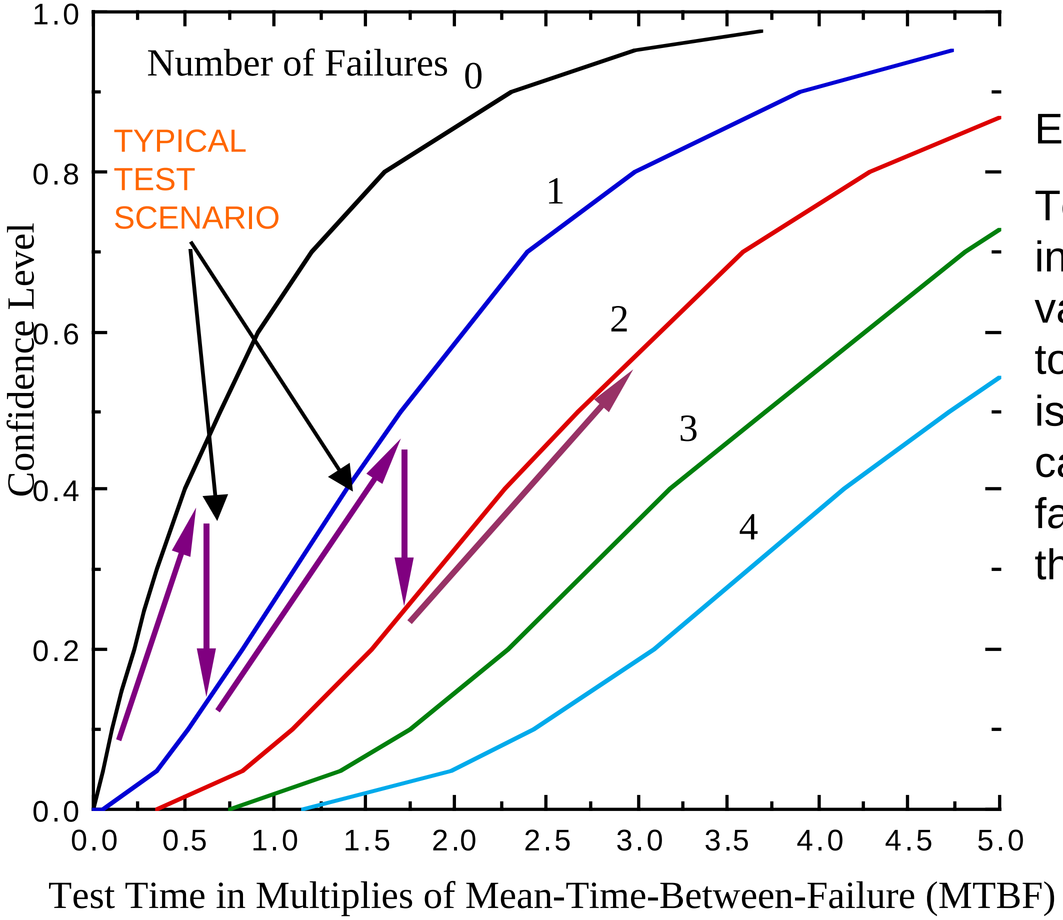
We must have an aggressive "reliability growth" program for the blanket (beyond demonstrating engineering feasibility)

1) All new technologies go through a reliability growth program

2) Must be "aggressive" because extrapolation from other technologies (e.g. fission) strongly indicates we have a serious CHALLENGE

“Reliability Growth”

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

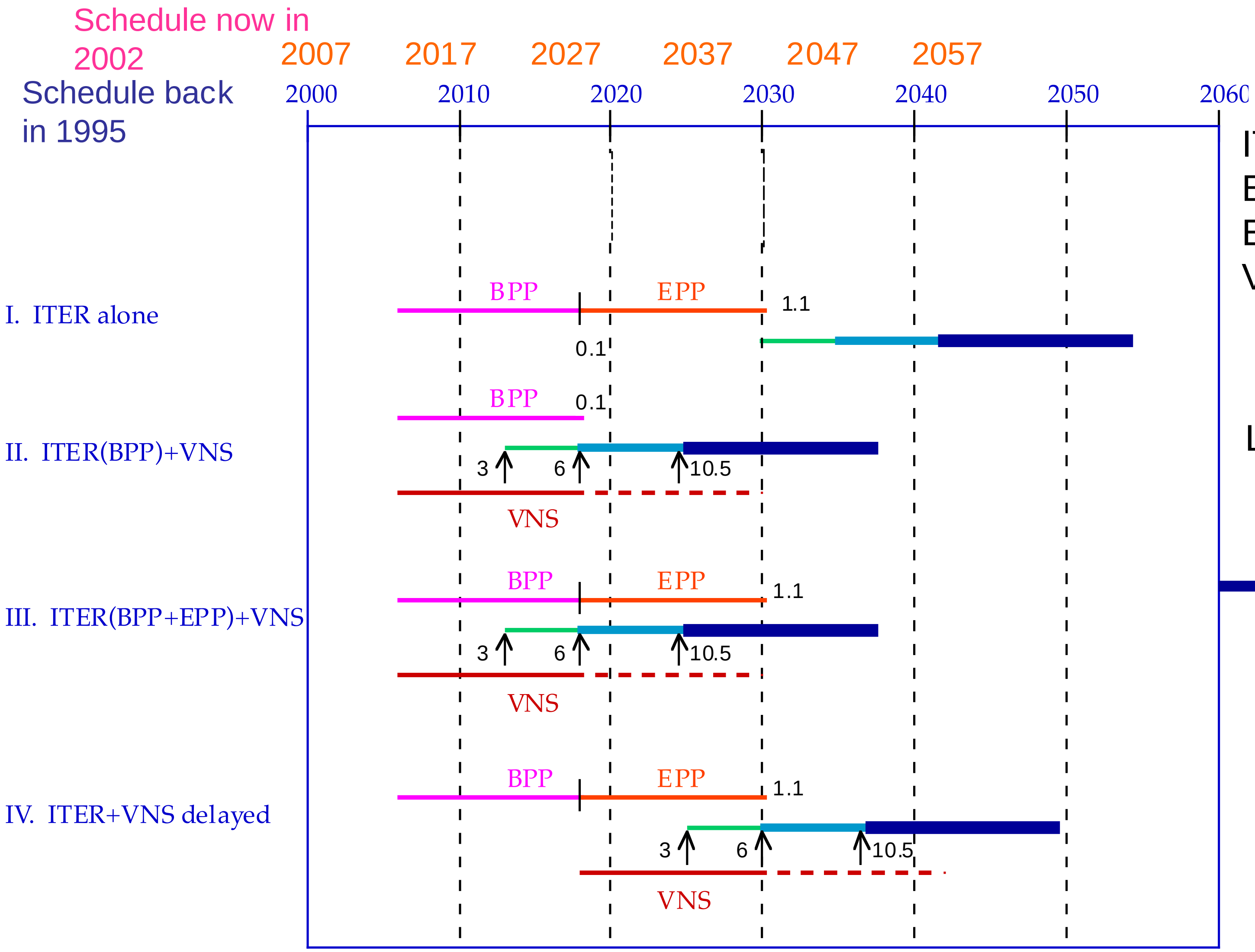


Example,

To get 80% confidence in achieving a particular value for MTBF, the total test time needed is about 3 MTBF (for case with only one failure occurring during the test).

Reference: **M. Abdou et. al., "FINESSE A Study of the Issues, Experiments and Facilities for Fusion Nuclear Technology Research & Development, Chapter 15 (Figure 15.2-2.) Reliability Development Testing Impact on Fusion Reactor Availability", Interim Report, Vol. IV, PPG-821, UCLA,1984. It originated from A. Coppola, "Bayesian Reliability Tests are Practical", RADC-TR-81-106, July 1981.**

Scenarios for major fusion devices leading to a DEMO



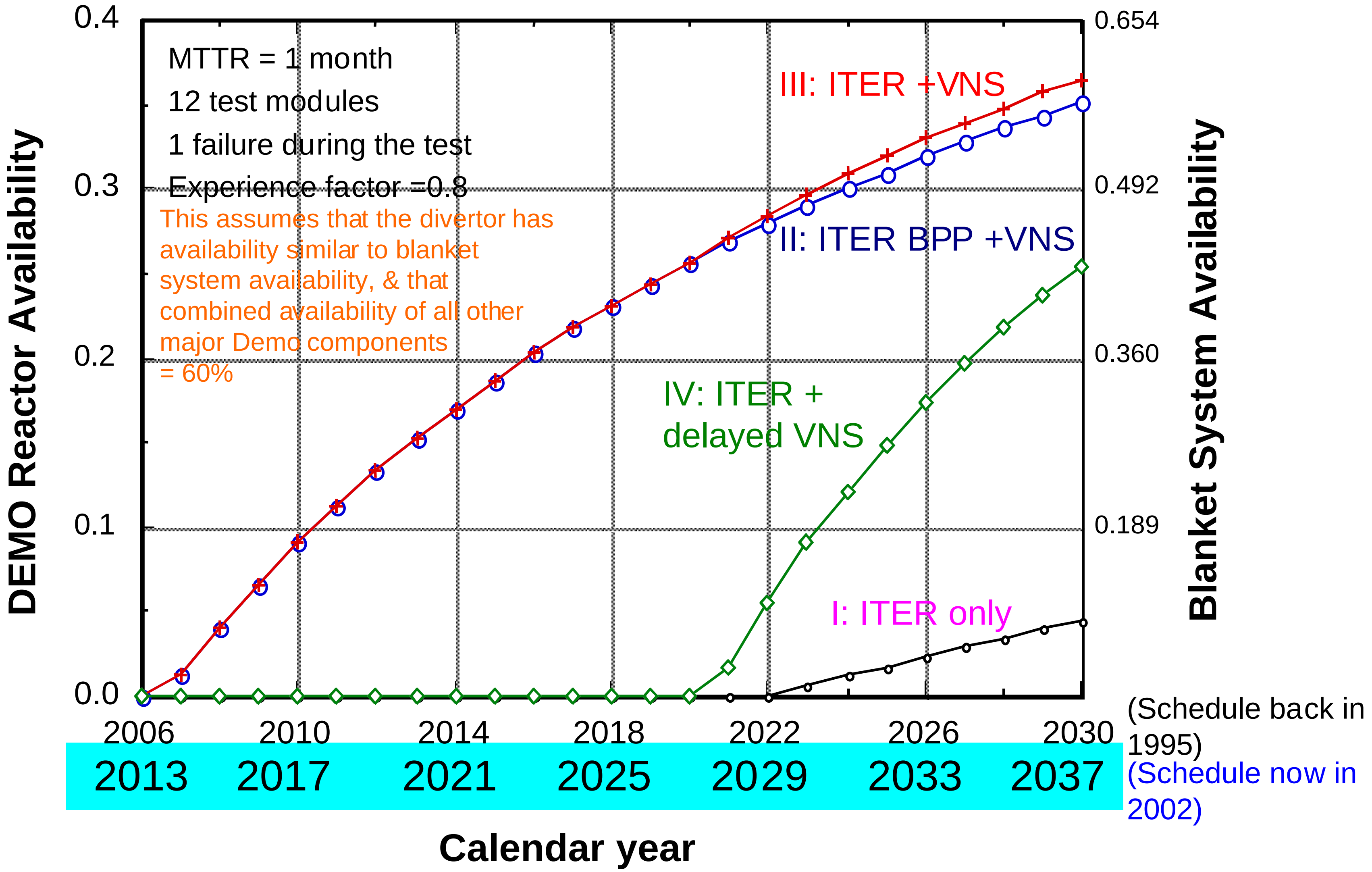
ITER ⇒ ITER-FEAT
BPP ⇒ Phase 1
EPP ⇒ Phase 2
VNS ⇒ CTF

Legend for Demo

🟩 Design
🟦 Construction
■ Operation

Numbers refer to Fluence values in MW•y/m²

DEMO reactor availability obtainable with 80% confidence for different testing scenarios, MTTR = 1 month



Note: ITER in Scenarios I, III and IV assumes fluence of 1.1 MW•y/m^2
(ITER-FEAT 1st phase has 0.1 MW•y/m^2)

Recommendations based on Blanket and PFC Reliability Growth Conclusions

- With ITER alone, even at 1 MW•y/m² fluence (and non-fusion facilities and IFMIF), blanket and PFC tests in ITER alone cannot demonstrate blanket system or PFC system availability in DEMO higher than 4%
  (This also assumes ITER would be modified to a higher wall load and to operate with steady state plasma)
- Blanket and PFC testing in VNS (CTF) allows DEMO blanket system and PFC system availability of ~ 49%, corresponding to DEMO availability ~ 30%
  Note that testing time required to improve reliability becomes even longer at higher availability [e.g. testing time required to increase availability from 30% to 50% is much longer than that needed to improve availability to 30%]

Recommendations on Availability/Reliability Growth Strategy and Goals

- Set availability goal for initial operation of DEMO of ~ 30% (i.e. defer some risk)
  - Operate CTF and ITER in parallel, together with other facilities, as aggressively as possible
  - Realize that there is a serious decision point with serious consequences based on results from ITER and CTF
    - If results are positive proceed with DEMO
    - If not, then we have to go back to the drawing board

How About Reliability/Availability of CTF itself?

- CTF needs to be designed as an experimental, flexible, and maintainable facility
- Must plan an aggressive “Availability Growth” program:
  - improve maintainability
  - “reliability growth” through strategy of test/fail/analyze/fix/improve
  - for both test modules and the device itself
- Is it a Challenge?
  - **Definitely! But, if we do not succeed in CTF in obtaining 25% - 30% availability, how can we succeed in DEMO without CTF?**
  - Blanket/PFC development for DT fusion has high risks. It is more prudent, less costly, and faster to take these risks with smaller, less expensive devices than with large expensive devices
  - To put an “untested, unvalidated” breeding blanket on DEMO has unacceptably high risks, high costs (Impossible?!!). Besides, how would you call that a DEMO? You should call it CTF.

Component Technology Facility (CTF)

MISSION

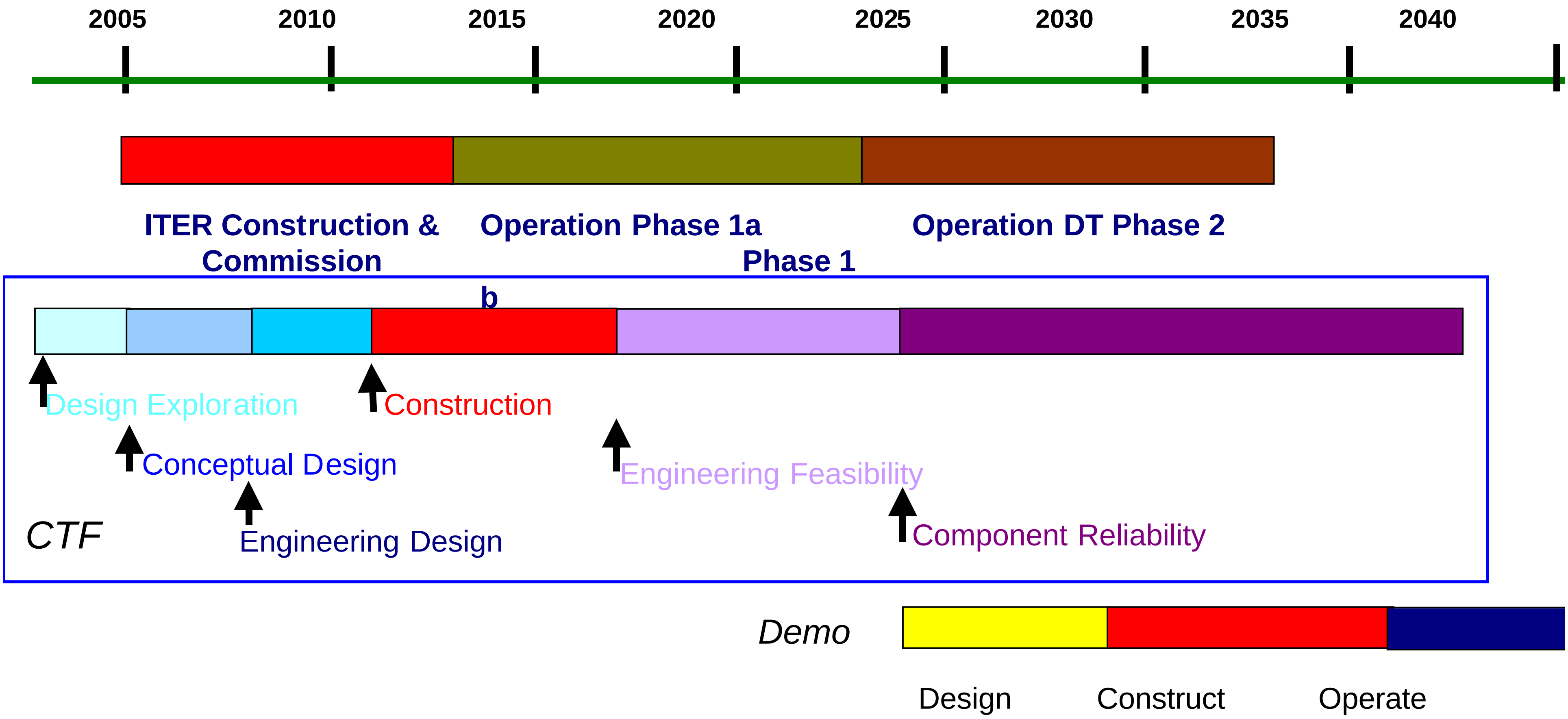
The mission of CTF is to test, develop, and qualify Fusion Nuclear Technology Components (particularly tritium-breeding blankets) for DEMO. And, to provide data and qualification of plasma-facing components.

The CTF facility will provide the necessary integrated testing environment of high neutron and surface fluxes, steady state plasma (or long pulse with short dwell time), electromagnetic fields, large test area and volume, and high neutron fluence.

The testing program and CTF operation will demonstrate the engineering feasibility, provide data on reliability / maintainability / availability, and enable a “reliability growth” development program sufficient to design, construct, and operate blankets, plasma facing and other FNT components for DEMO.

Note: Shorter mission statements can be written if needed.

Proposed CTF Timeline



2005 2010 2015 2020 2025 2030 2035 2040

ITER Construction & Commission

Operation Phase 1a

b

Phase 1

Operation DT Phase 2

CTF

Design Exploration

Conceptual Design

Engineering Design

Construction

Engineering Feasibility

Component Reliability

Demo

Design

Construct

Operate

Time line for ITER is taken from K. Lackner’s presentation at SOFT, 2002

Are there Good Design Options for CTF?

- A key point in the rationale behind CTF is to design a small size, small fusion power (~100 MW), yet achieve a high neutron wall load and steady state plasma operation.

- This can be achieved in MFE by using highly driven plasma (low-Q plasma ~ 1-2).

  [Similar idea in IFE is to use low target-yield to lower the fusion power but make the chamber radius small enough to get higher wall load]

- Several good options for CTF look attractive.

- Dr. Martin Peng will cover options and issues for a CTF device.

Summary

A CREDIBLE Plan for DT Fusion Development MUST include a CREDIBLE Plan for Blanket/PFC Development

- The FEASIBILITY, Operability, and Reliability of Blanket/PFC systems cannot be established without testing in fusion facilities
- The fusion testing requirements for blanket/PFC are:
  - NWL > 1 MW/m², steady state, test area >10m², test volume >5 m³
  - Fluence Requirements: > 6 MW•y/m²

    Engineering Feasibility Phase: 1 – 3 MW•y/m²
    (concept performance verification and selection)

    Engineering Development & Reliability Growth Phase: >4 MW•y/m²
    (not an accumulated fluence on a test article; it is "accumulated test time" on successively improved test articles)
- Tritium Supply considerations are a critical factor in developing a credible strategy for fusion testing and development of blanket/PFC
  - The world maximum tritium supply (from CANDU) over the next 40 years is **27 kg**. This tritium decays at 5.47% per year.
  - Remember: A DT facility with 1000 MW fusion power burns tritium at a rate of **55.8 kg/yr**. Therefore, a large power DT facility must breed its own tritium.

(It is ironic that our major problem is "tritium fuel supply", while the fundamental premise of Fusion is "inexhaustible" energy source)

Summary Cont’d

Options for “Where” to do Blanket/PFC Developments were evaluated:

1 – ITER(FEAT): Not Adequate

- Low fluence, short plasma burn time/long dwell time, low wall load do not provide the required capability

2 – MODIFIED ITER: Too Expensive, Too Risky

- Requires complete redesign. Very Expensive (Think of ITER-EDA cost plus more)
- Tritium is not available to run the large-power ITER for high fluence
- For Modified ITER to have its own tritium breeding blanket with TBR ~1 is very risky and extremely expensive (building unvalidated blanket over 1000 m^2 is costly, frequent blanket failures require costly replacements)

3 – DEMO: “Unthinkable”

- Deferring Blanket/PFC development until DEMO is “unthinkable” because:

  A – All the problems indicated for Modified ITER above (same mistake of doing FNT testing in large power DT device). Plus there is not much external tritium supply left.

  B – This is not a DEMO: a minimum requirement for DEMO is to have at least one validated concept for each component.

So, we have a Serious Problem!

So, what to do?

- Think of What Fission Reactor Developers did as an example:

  They built small-power testing reactors (10-100 MW), but with prototypical local conditions.

  (They were lucky!!)

- Take advantage of the fact that our good fusion engineers have developed and utilized "engineering scaling" to reduce the FNT testing requirements to 10 MW neutron power at 1 MW/m^2 in only 10 m^2 test area (5 m^3 test volume)

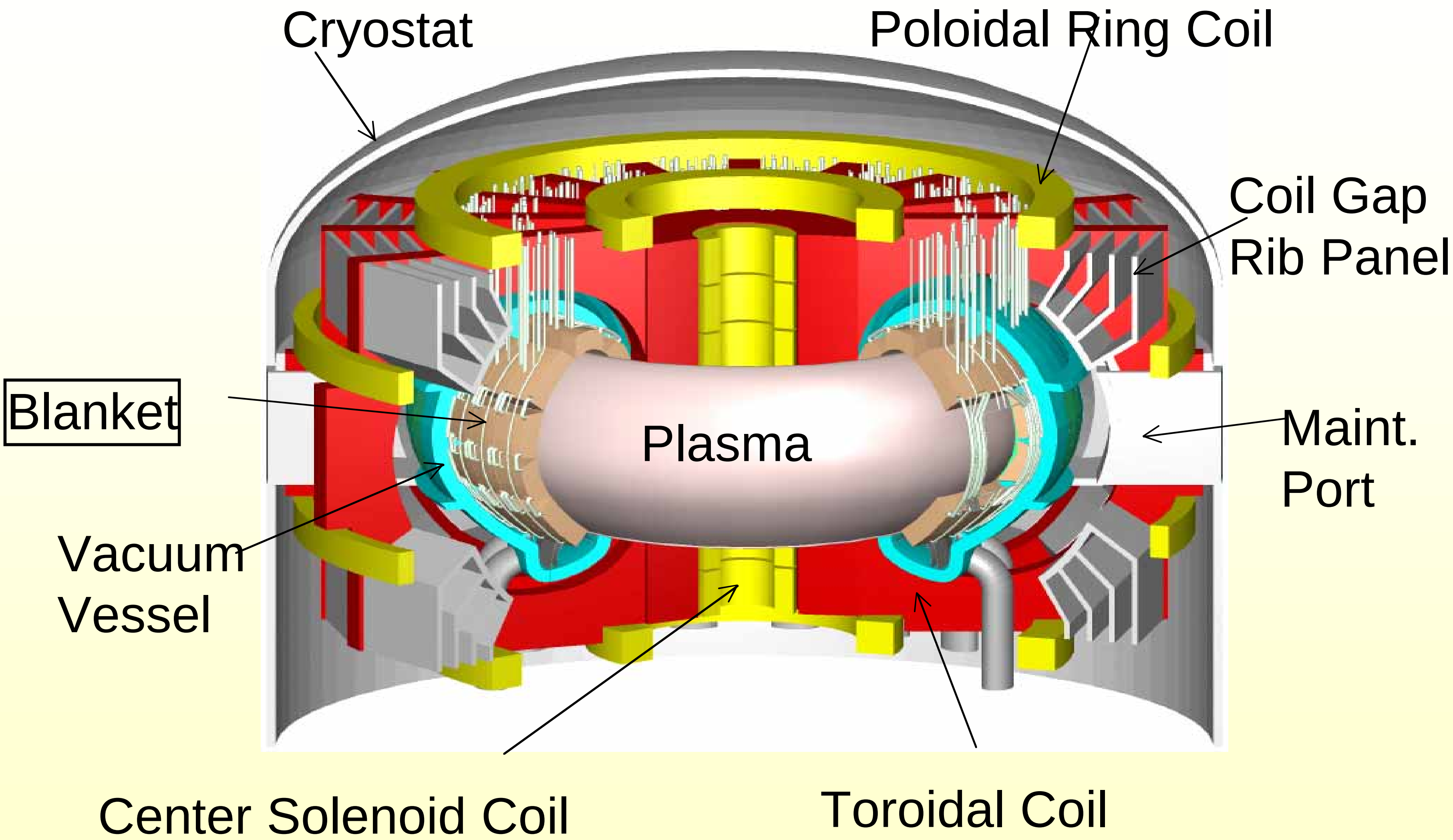
Summary Cont'd

Attractive Logical Solution

- Build a small size, low-fusion power DT plasma-based device in which Fusion Nuclear Technology experiments can be performed in the relevant fusion environment at the smallest possible scale and cost.
  - In MFE: small-size, low fusion power can be obtained in a **driven low-Q plasma device**.
  - Equivalent in IFE: Lower target yield and smaller chamber radius.
- This is a faster, much less expensive and less risky approach than testing in a large, ignited/high-Q plasma device for which tritium consumption, and cost of operating to high fluence are very high and the risk is too great.

APPENDIX

JAERI DEMO Design

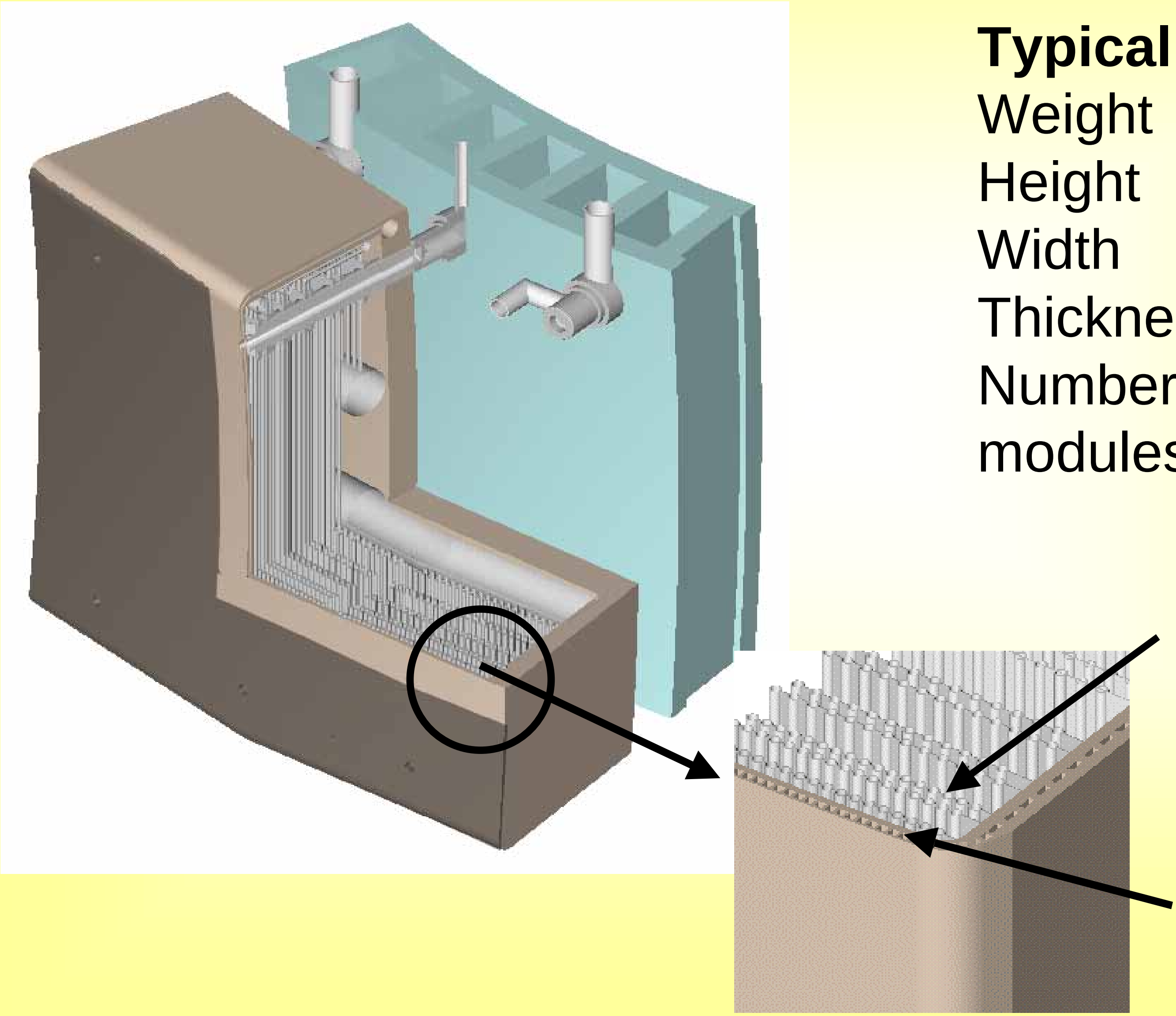


FNT: Components from Edge of Plasma to TFC.

Blanket / Divertor immediately circumscribe the plasma (often called Chamber Technology)

From Akiba, Japan: Typical Blanket Module in DEMO

Schematic of Test Blanket Module



Breeder and Multiplier Pebble bed layers

First Wall with embedded Cooling Channels

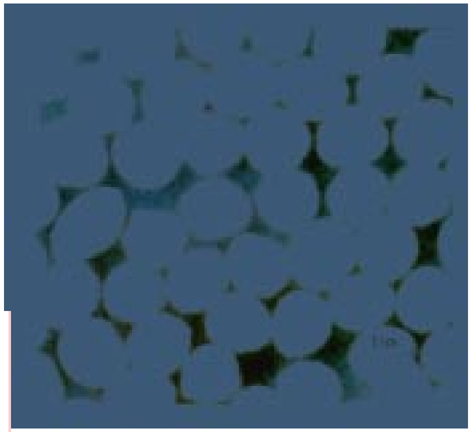
Typical Blanket Module	
Weight	4 ton
Height	1 m
Width	2 m
Thickness	0.6 m
Number of modules	256

Tests for Thermomechanics Interactions of Be/Breeder/He-purge/Structure require "volumetric" heating in complex geometry (fission then fusion)

A Case Study ⟹ HICU Project: A High Fluence Irradiation on Ceramic Breeder Pebble Beds with Mechanical Constraints in Fission Reactor

Project goals:

"the investigation of the impact of neutron spectrum and the influence of constraint conditions on the thermo-mechanical behavior of breeder pebble-beds in a high fluence irradiation"



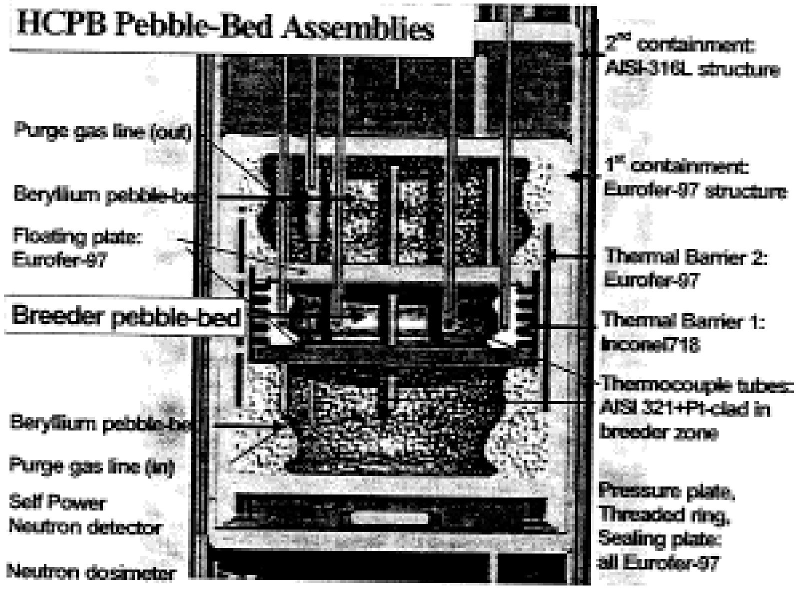
Li$_2$O ceramic breeder

Main critical issues for the "project"

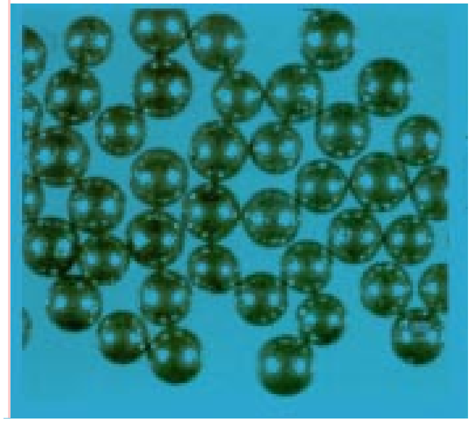
concern the specimen size and the geometry(limited test volume in fission reactor)

Instrumentation

(neutron dosimeter, thermocouples, tritium monitor)



Schematic view of pebble-bed assembly, showing cross-section of test-element, second containment and instrumentation



Beryllium pebble

Table XX.*

Characteristic Time Constants in Solid Breeder Blankets

Process	Time Constant
Flow	
Solid breeder purge residence time	6 s
Coolant residence time	1 to 5 s
Thermal	
Structure conduction (5-mm metallic alloys)	1 to 2 s
Structure bulk temperature rise	
5 mm austenitic steel / water coolant	~1 s
5 mm ferritic steel / helium coolant	5 to 10 s
Solid breeder conduction	
Li_2O (400 to 800ºC)	
10 MW/m^3	30 to 100 s
1 MW/m^3	300 to 900 s
$LiAlO_2$ (300 to 1000ºC)	
10 MW/m^3	20 to 100 s
1 MW/m^3	180 to 700 s
Solid breeder bulk temperature rise	
Li_2O (400 to 800ºC)	
10 MW/m^3	30 to 70 s
1 MW/m^3	80 to 220 s
$LiAlO_2$ (300 to 1000ºC)	
10 MW/m^3	10 to 30 s
1 MW/m^3	40 to 100 s
Tritium	
Diffusion through steel	
300ºC	150 days
500ºC	10 days
Release in the breeder	
Li_2O 400 to 800ºC	1 to 2 h
$LiAlO_2$ 300 to 1000ºC	20 to 30 h

* From Fusion Technology, Vol. 29, pp 1-57, January 1996

Table XXI.*

Characteristic Time Constants in Liquid-Metal Breeder Blankets

Process	Time Constant
Flow	
Coolant residence time	
First wall (V=1 m/s)	~30 s
Back of blanket (V=1 cm/s)	~100 s
Thermal	
Structure conduction (metallic alloys, 5mm)	1 to 2 s
Structure bulk temperature rise	~4 s
Liquid breeder conduction	
Lithium	
Blanket front	1 s
Blanket back	20 s
LiPb	
Blanket front	4 s
Blanket back	300 s
Corrosion	
Dissolution of iron in lithium	40 days
Tritium	
Release in the breeder	
Lithium	30 days
LiPb	30 min
Diffusion through:	
Ferritic Steel	
300ºC	2230 days
500ºC	62 days
Vanadium	
500ºC	47 min
700ºC	41 min

** From Fusion Technology, Vol. 29, pp 1-57, January 1996*

- **To Achieve DEMO Availability = 48%**

	Required Blanket Availability
R. Buende (1989)	97%
IEA-VNS (1996)	90%

- **To Achieve DEMO Availability = 30%**

J. Sheffield (2002): Required blanket availability = 88%

(Assuming Major MTTR = 800 h, Minor MTTR = 100 h)

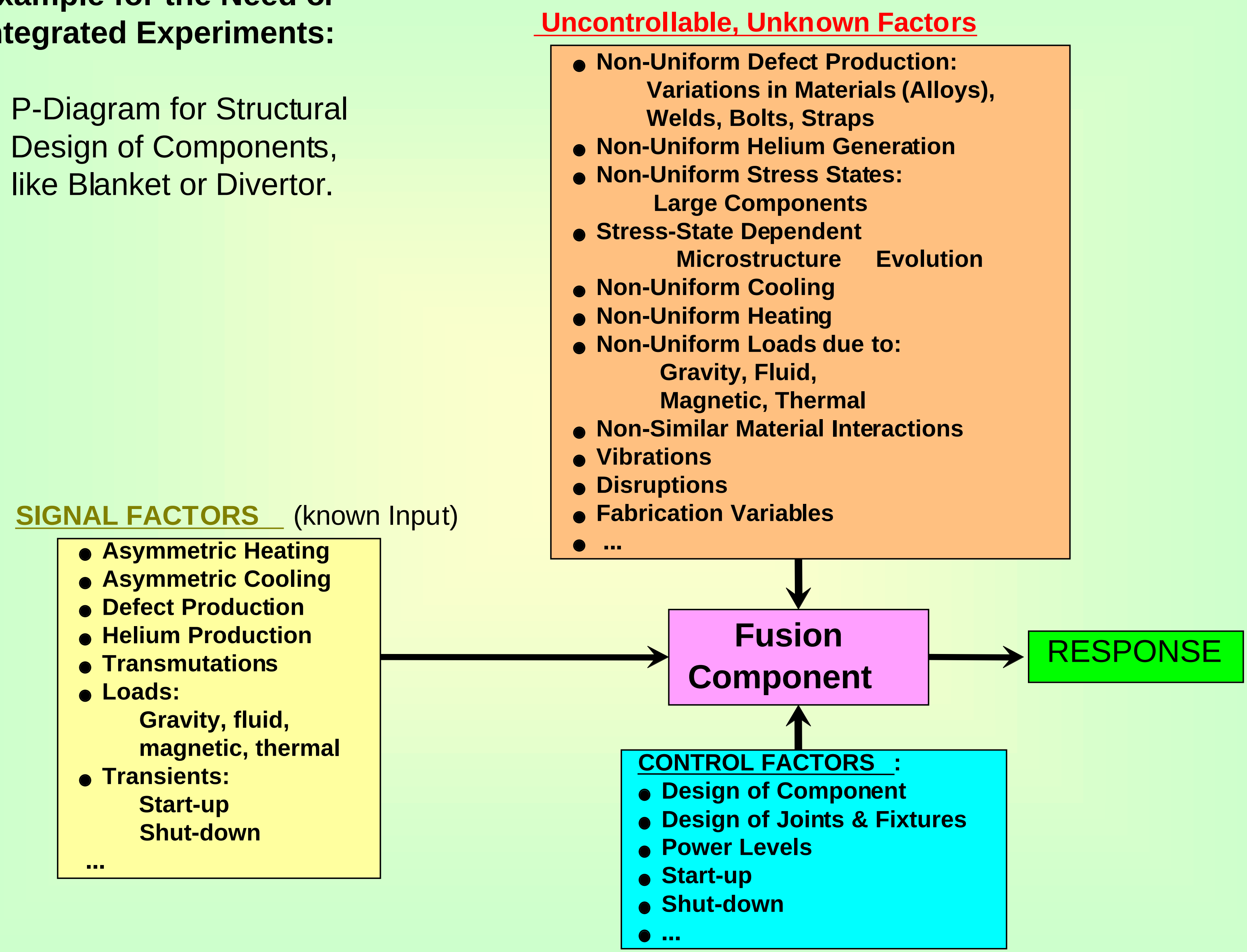
Required MTBF for DEMO Blanket

Depends on availability requirements and MTTR

DEMO Availability	**Required Blanket Availability**	**Required MTBF for a Blanket Module (100 modules, MTTR=1 month)**
30%	**88%**	**60 yr**
48%	**90%**	**75 yr**

Example for the Need of Integrated Experiments:

P-Diagram for Structural Design of Components, like Blanket or Divertor.



Uncontrollable, Unknown Factors

- Non-Uniform Defect Production:
  Variations in Materials (Alloys), Welds, Bolts, Straps
- Non-Uniform Helium Generation
- Non-Uniform Stress States:
  Large Components
- Stress-State Dependent
  Microstructure Evolution
- Non-Uniform Cooling
- Non-Uniform Heating
- Non-Uniform Loads due to:
  Gravity, Fluid, Magnetic, Thermal
- Non-Similar Material Interactions
- Vibrations
- Disruptions
- Fabrication Variables
- ...

SIGNAL FACTORS (known Input)

- Asymmetric Heating
- Asymmetric Cooling
- Defect Production
- Helium Production
- Transmutations
- Loads:
  Gravity, fluid, magnetic, thermal
- Transients:
  Start-up
  Shut-down

...

Fusion Component

RESPONSE

CONTROL FACTORS :

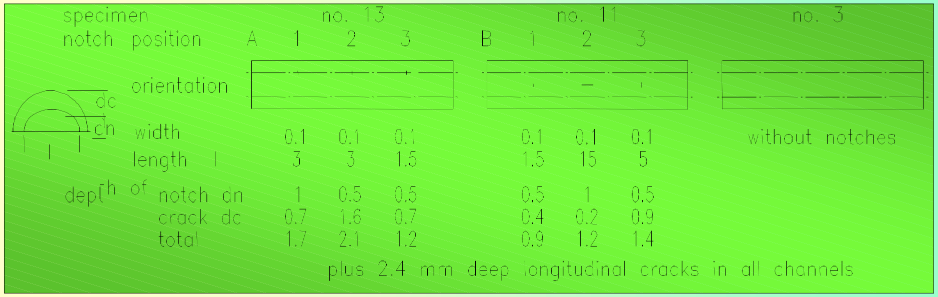
- Design of Component
- Design of Joints & Fixtures
- Power Levels
- Start-up
- Shut-down
- ...

FW-Mock Up Fatigue Testing at FZK

Shows an example of unexpected failure modes that cannot be predicted by models.

(Information from Eberhard Diegele at FZK)

- Thermo-mechanical fatigue test were performed for FW-mock ups from SS 316 L.
  - Loading conditions: about 0.7 MW/m2 heat flux (Fig. 1)
- The specimens were pre-cracked (notched) perpendicular to the coolant tubes at different locations with different sizes (Fig. 2)
- After 75,000 cycles the notched cracks grew to the sizes as indicated.
- **However, unexpectedly there were longitudinal cracks that were initiated in *every channel* - and these cracks grow under fatigue and would have led to failure if the experiment continued.**



specimen	no. 13			no. 11			no. 3
notch position	A 1	2	3	B 1	2	3	
orientation							
width	0.1	0.1	0.1	0.1	0.1	0.1	without notches
length l	3	3	1.5	1.5	15	5	
depth of notch dn	1	0.5	0.5	0.5	1	0.5	
crack dc	0.7	1.6	0.7	0.4	0.2	0.9	
total	1.7	2.1	1.2	0.9	1.2	1.4	

plus 2.4 mm deep longitudinal cracks in all channels

Fig.2:Spark eroded notches and cracks after 75,000 cycles

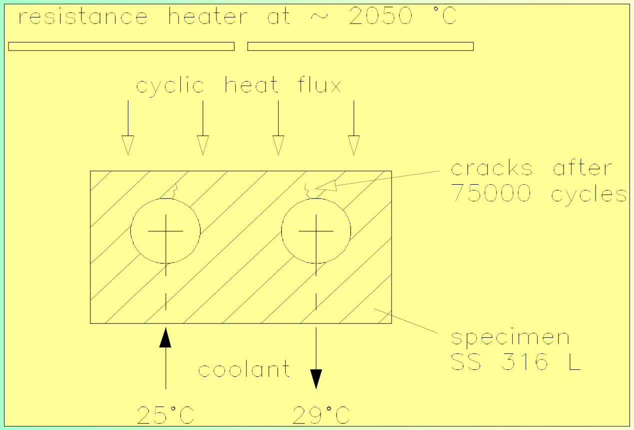


Fig.1: Schematic of FW-Mock Up

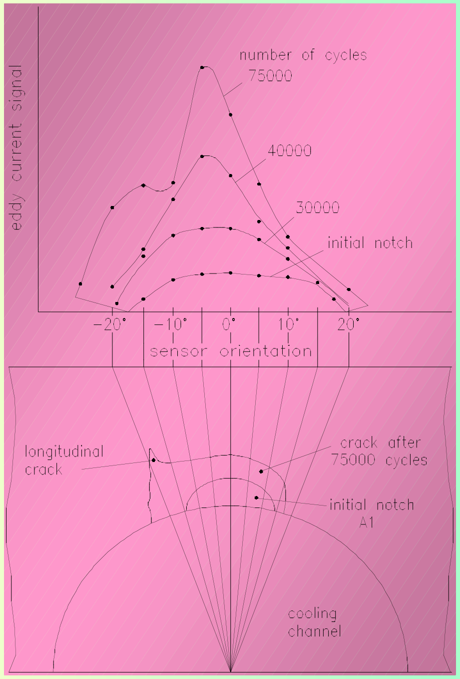


Fig.3: Crack measurements

From elastic-plastic fracture mechanics modeling:

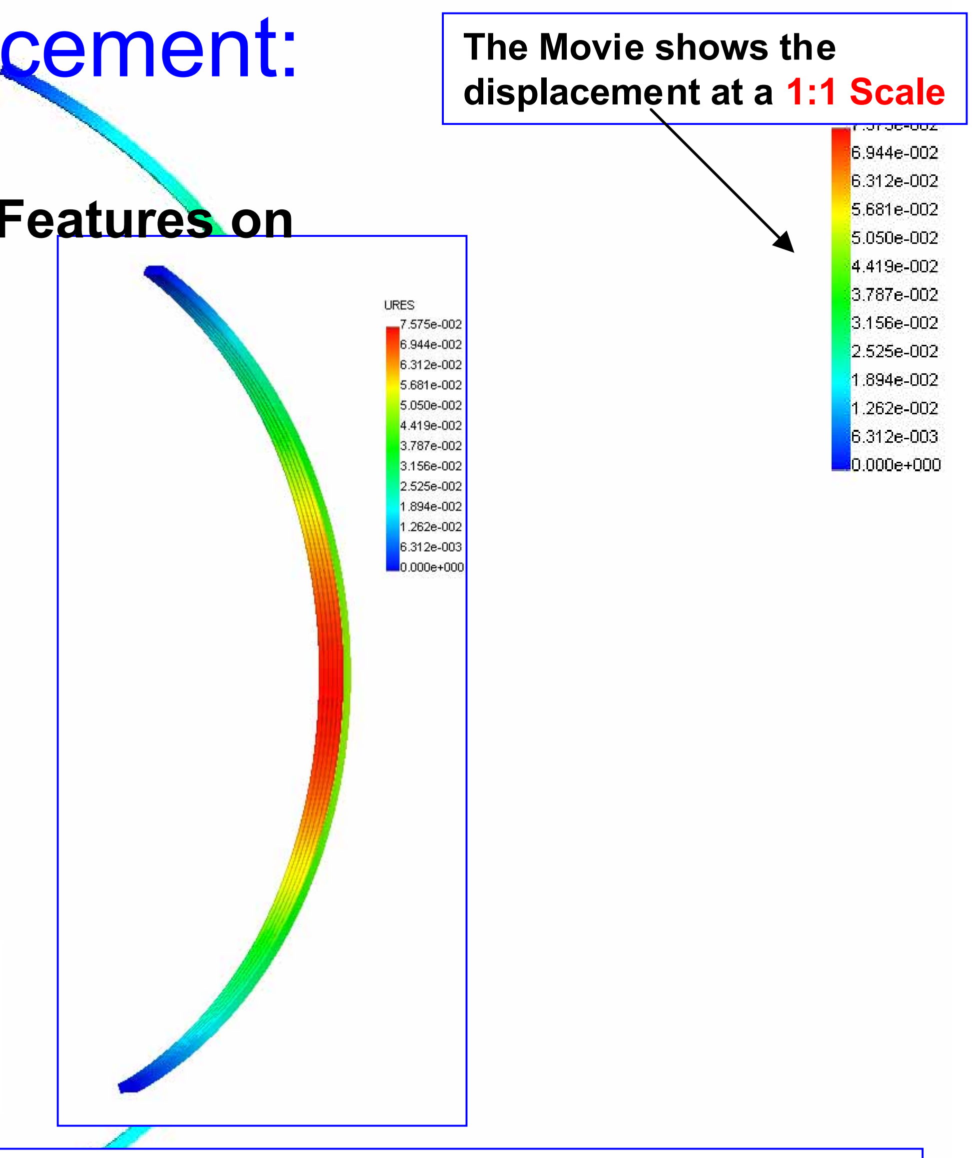
- **Expected the large pre-cracks at the crown of the channel to fail.**
- **Initiation and growth of the longitudinal cracks were not and can not be predicted by models.**

FW-Panel Displacement:

The Movie shows the displacement at a **1:1 Scale**

Effects of 3-D Geometric Features on Displacement:

FW Central Portion Experiences largest Displacement



BC:

Bottom and Top Face are Fixed
No Rotational Freedom along the back

Max Displacement at Center ~ 7.3 cm with no back support. With back support, these displacements must be accommodated through higher stresses

Notes from M. Abdou and D. Sze in response to a question received on 10/25/2002.

Is “Batch” Processing together with “low temperature blanket” a good “transition” option?

Batch Processing

--Evaluated in the 1970s

--Conclusion: Not Practical for the “complex” fusion devices

1. In large systems like a tokamak: It takes a long time to remove/reinsert blankets. You still have to go through the vessel, the shield, and the magnet support. (for example: several months in ITER); therefore you cannot do it frequently (once every two years?!).
2. In 1000 MW Fusion Power Device, the tritium consumption is 55.8 kg per full power year. So, for 20% availability, tritium inventory accumulated in 2 years is >22 kg (in addition to the “hold up” inventories in PFCs and other in-vessel components).
3. Safety experts have suggested much lower targets for tritium inventory (~2 kg). Note also that tritium will decay at 5.47%/year and you will have to provide external start up inventory, plus inventory for duration of “first batch”.
4. And “there is really no effective way to recover tritium from the blanket using a batch process.”

Low-Temperature Blanket?

Evaluated during INTOR, ITER-CDA, ITER-EDA

Assessment:

-- It is still high risk because we use technologies unvalidated in the fusion environment.

-- There is no good low-temperature breeding blanket option. You can have only “partly” low-temperature.

-- “Partly” low-temperature breeding blankets have their added complications and issues for which an additional R&D program is needed.

Options for Low-Temperature Blanket?

- All self-cooled liquid metal options require high temperature (>300°C) because of high melting point. We do not know if any of them are feasible in the fusion environment because of issues such as insulators, tritium barriers, etc.

- Separately-cooled LiPb requires either Helium or water, both above 300°C. Practically all feasibility issues for “reactor-type” blankets are the same and must be resolved by extensive testing first in the fusion environment.

Options for Low-Temperature Blanket? (cont'd)

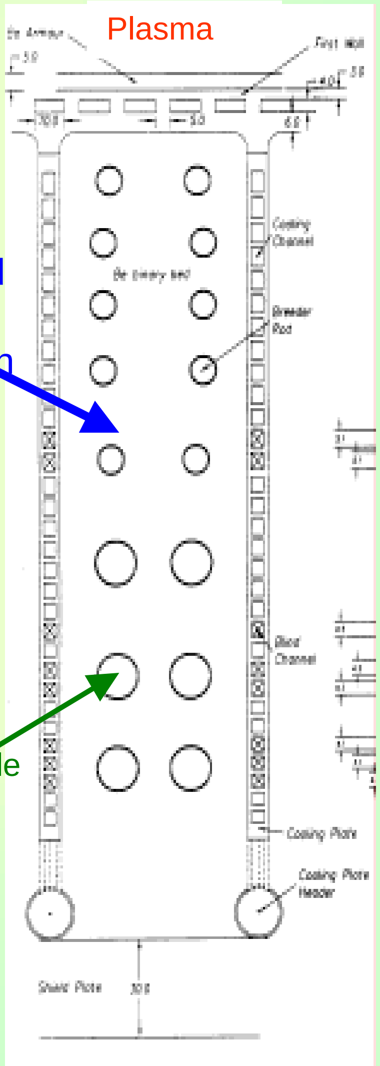
- **Solid Breeder Options were evaluated in INTOR, and ITER-CDA, ITER-EDA**

-- Breeder must run at high temperature

-- Only the coolant can be low temperature

-- All the feasibility issues with the breeder and multiplier are essentially the same as those for reactor-type blanket. But with the added complexity of providing "thermal resistance" between the low-temperature coolant and the hot solid breeder.

-- Both stainless steel and ferritic steel have severe embrittlement problems at low-temperature (ITER can use low-temperature coolant in the present non-breeding design only because of the very low fluence).



Beryllium pebble bed is used as a temperature barrier in a low temperature breeding blanket design

Breeder pebble bed rod