Fusion R&D Strategy from A Technology Viewpoint

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The Region Immediately Surrounding the Plasma
Divertor / First Wall / Blanket /Vacuum Vessel / Shield

Names

Fusion Nuclear Technology (FNT)
Fusion Power Technology
Reactor Core
Plasma Exterior
In-Vessel System (components)

- FNT embodies a majority of the most challenging issues in the development of an attractive fusion energy source
- Despite Meager Resources for FNT R&D, remarkable progress has been made (witness this conference)

What Have We Learned?

Realizing the fusion promise of an attractive energy source for future generations requires, among other top priorities, advances in engineering sciences and innovative research to develop advanced fusion nuclear technology

Challenging Fusion Nuclear Technology Issues

1. Heat Removal at High Temperature and Power Density

2. Tritium Fuel Self Sufficiency

3. Failure Rate

4. Time to Recover From A Failure

Heat Extraction

(Power Handling)

At High Temperature, High Power Density

A. How high a power density (neutron wall load) is needed for fusion to be competitive?

B. What is the wall load capability of present FW / Blanket concepts?

Power Density and Heat Flux in Fission Reactors

	PWR	BWR	HTGR	LMFBR	ITER-Type
Equivalent Core Diameter(m) **Core Length (m)**	3.6 3.8	4.6 3.8	8.4 6.3	2.1 0.9	30 15
Average Core Power Density (MW/m^3)	**96**	**56**	**9**	**240**	**0.4**
Peak-to-Average Heat Flux Coolant (MW/m2)	2.8	2.6	12.8	1.43	50

Suggested Fusion Goals

- Neutron Wall Load > 10 MW/m^2
- Minimize Peak - to - Average Power Density

What is the Wall Load Capability of Current FW / Blanket Concepts?

Current Design Concepts

1) Ferritic / Solid Breeder / Helium (or Water)
   Ferritic / Li Pb / Water
2) Vanadium / Lithium / Lithium
3) SiC / Solid Breeder / Helium

Wall Load Capability

–Temperature and stress limits in the structure

–Temperature and other limits in breeder and coolant

	Ferritic	V alloy	SiC / SiC
Thermal Conductivity	26.5	28	8
Max. Temperature, C	550	650	1000
Design Stress limit, MPa	200	220	145*

*matrix cracking

Current Design Concepts and Materials for First Wall / Blanket

Do NOT Have the Capability to Meet the Fusion Challenge

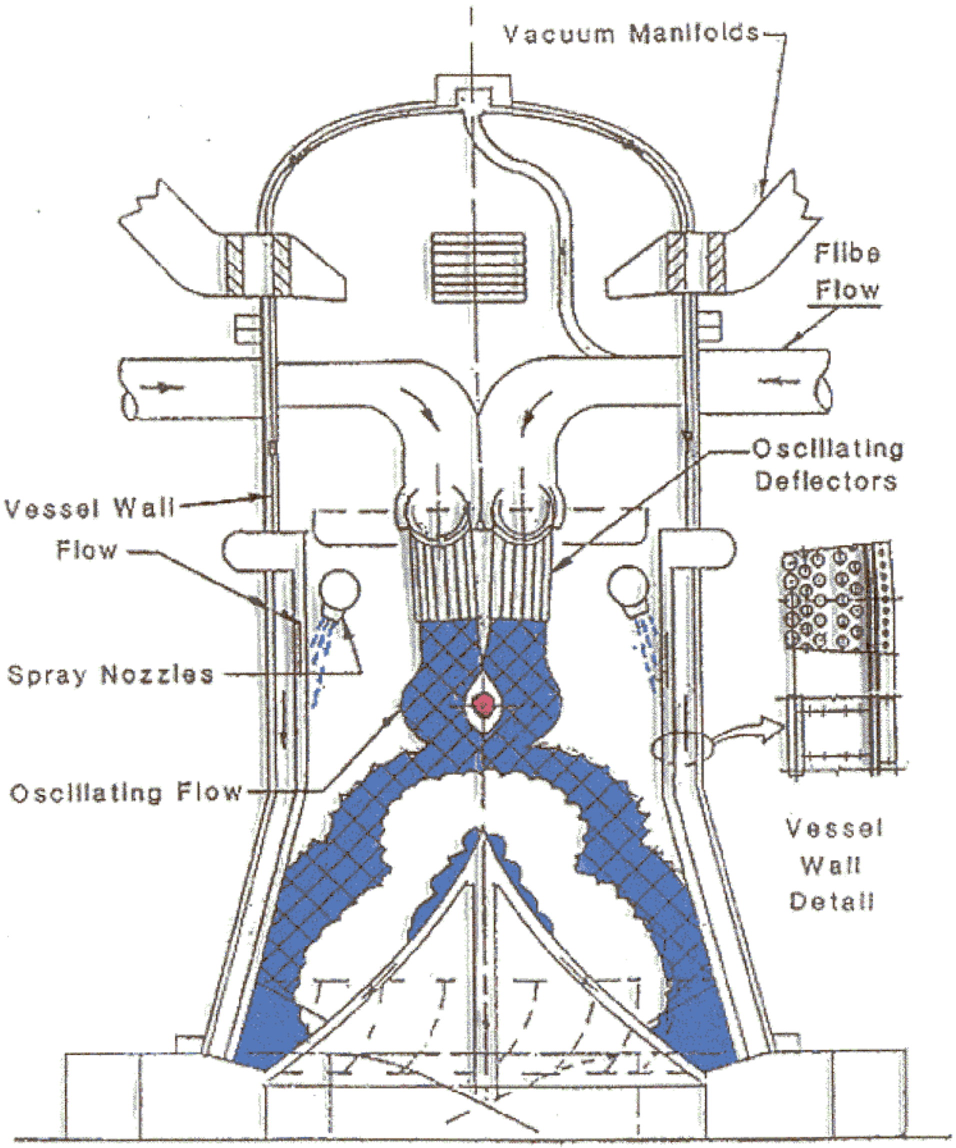
Concept	Wall Load Capability MW/m^2	Other Observations
Ferritic / He / Breeder **Ferritic / H_20 / Li Pb**	2	• Magnetic material • Fracture toughness
Vanadium Alloy / Lithium	2.5	• V works only with lithium • Is lithium acceptable? • Not feasible until a self healing coating is found
SiC / SiC / He / Breeder	1.5	• Serious feasibility issues • Do NOT know how to design • Poor thermal conductivity

Heat Extraction Issue
Suggested Future Directions

Aggressively Promote Creativity and Innovation to Stimulate NEW DESIGN CONCEPTS for First Wall / Blanket / Divertor / Shield (In-Vessel System) that Have

- ◊ **Less Constraints**
- ◊ **Higher Power Density Capability**
- ◊ **Larger Design Margin**
- ◊ **Better Breeding Capability**

Example of Innovation: IFE Liquid Wall Protection Schemes



<u>High Risk / High Payoff</u>

- Conventional stainless steel would become "low activation material" in IFE solid FW
- Much reduced loading conditions at FW; hence much higher core power density capability
- Radiation effects at the FW are eliminated as a serious issue

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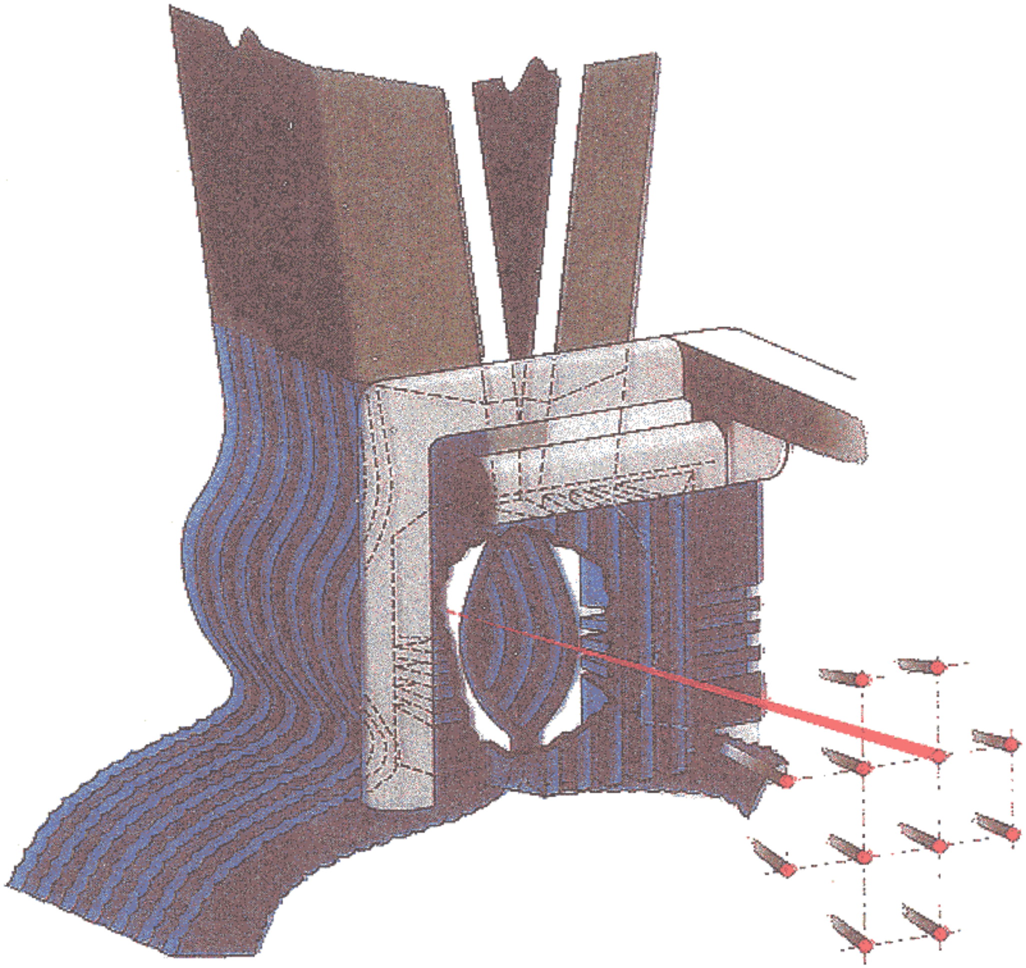

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Tritium Fuel Self Sufficiency

- Typical Example of Statements Frequently Made:
  "Fusion energy offers the long-term potential to provide an environmentally and economically attractive energy option with a virtually UNLIMITED and WIDELY AVAILABLE FUEL SUPPLY"

- We need to make sure this statement becomes true in the future

- Unfortunately, it is not true today:
  - ◊ A combination of more realistic designs, experiments and detailed evaluation show Serious Difficulties
  - ◊ Progress is hindered by lack of R&D
  - ◊ There is presently NO PLAN anywhere to demonstrate Tritium Self Sufficiency

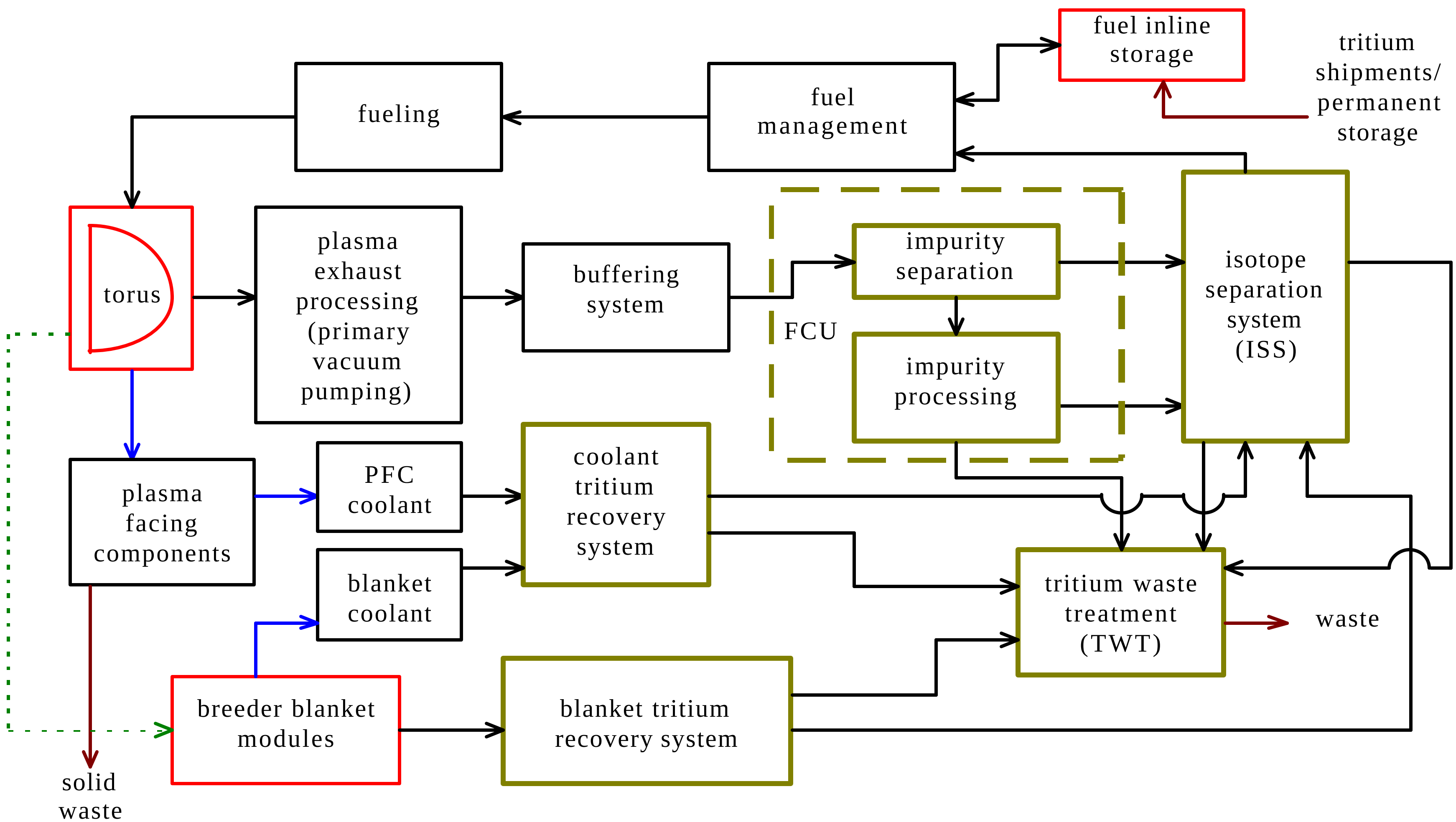
Tritium Self Sufficiency Condition

$$\wedge_a \geq \wedge_r$$

$\wedge_a$ = Achievable Tritium Breeding Ratio
(Based on accurate 3-D Modelling with Heterogeneity, geometry, and material details)

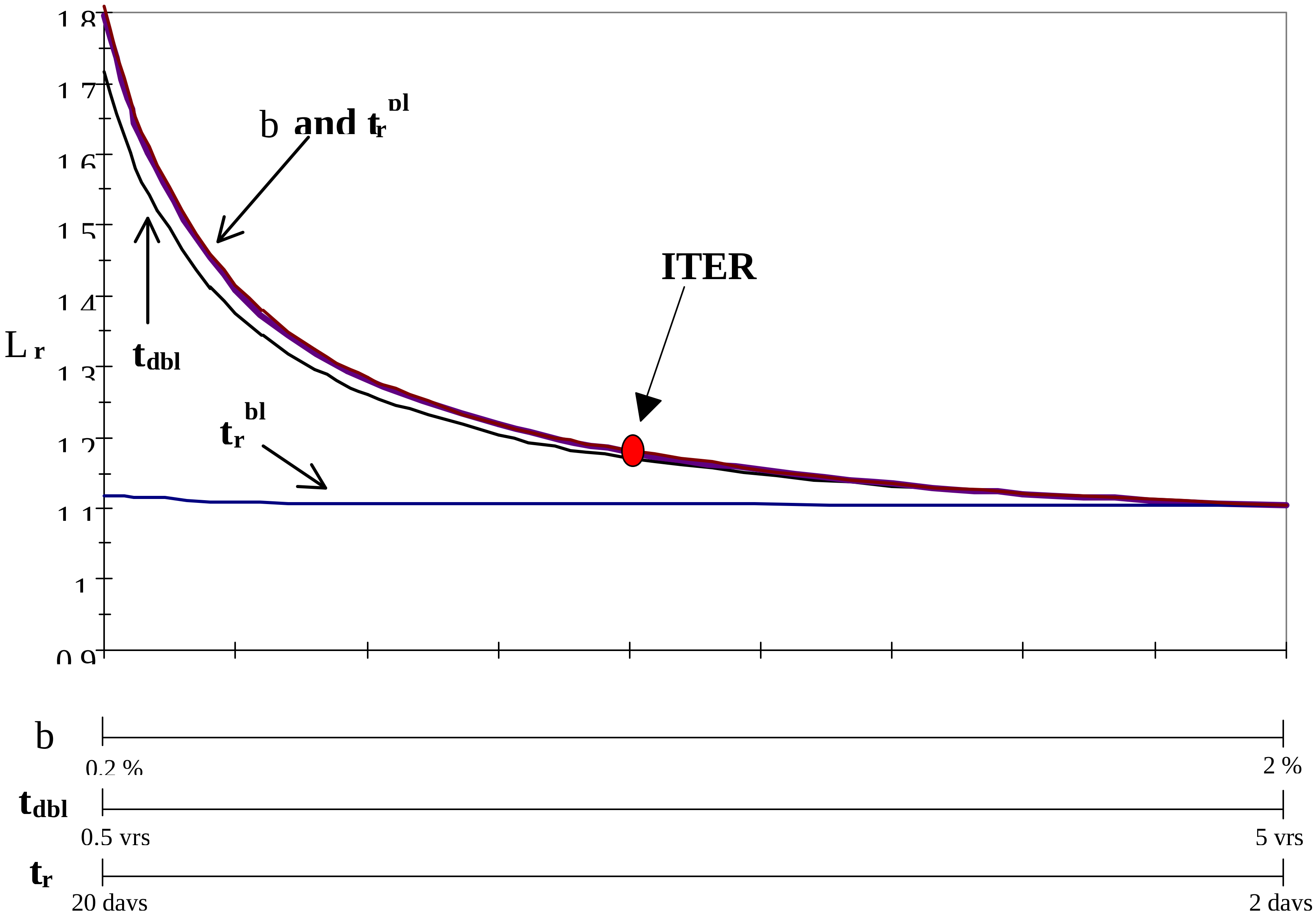
$\wedge_r$ = Required Tritium Breeding Ratio
(Accounting for time-dependent tritium decay, tritium inventories and flow rate, system start up)

Note:
- –Tritium is not available in nature
- –It is lost at a rate of 5.5% per year
- –Fusion Reactor needs start-up and saturation inventories



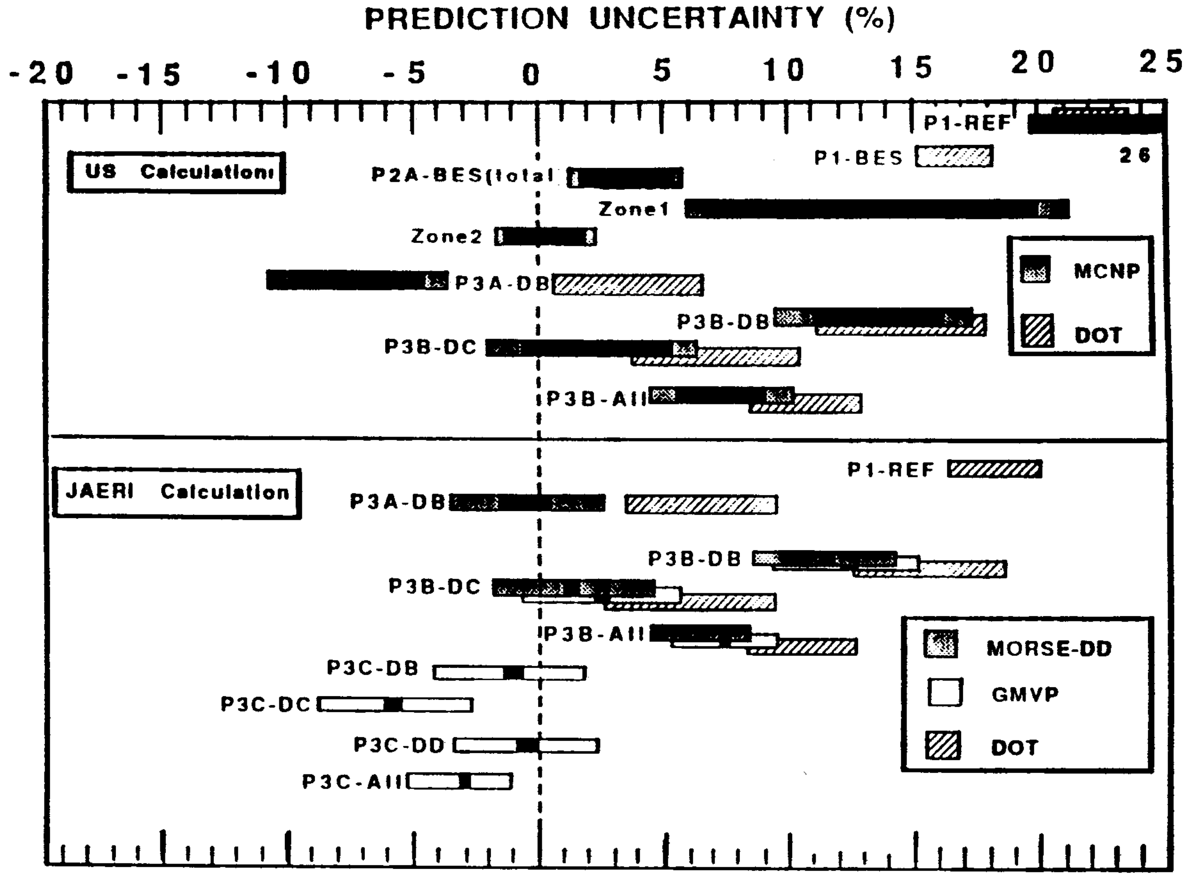
Tritium Fuel Cycle Modelling

Required TBR is > 1.1



Achievable Tritium Breeding Ratio

Ten Years of Experiments and Analysis in the Joint Japan - US Program Show Discrepancies Between Experiments and Calculations Leading to Uncertainties on the Order of 15%

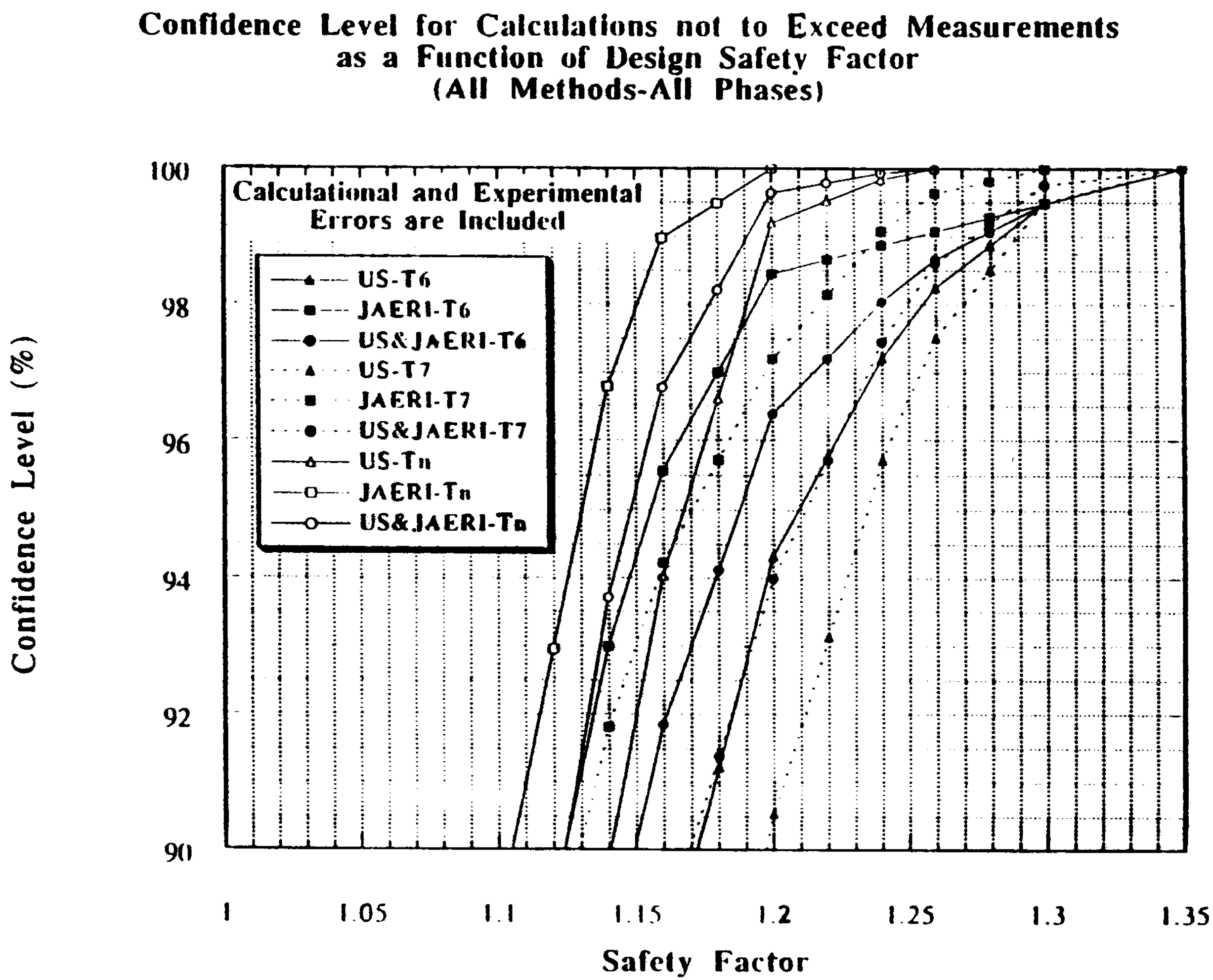


LINE-INTEGRATED TRITIUM PRODUCTION RATE FROM LI-6 (T-6)

MEASUREMENT: LI-Pellet

Achievable Tritium Breeding Ratio

Using Standard Engineering Science Approach, it is concluded that the "best calculated" TBR should be divided by a safety factor of ~ 1.15 to assure 95% confidence in the results



"Calculated" Tritium Breeding Ratio for Realistic Designs

- The most detailed first wall / blanket designs were developed by EU during the past several years. They include liquid and solid breeder blankets.
- Detailed 3-D Neutronics calculations accounting for structure and heterogeneity were performed by EU for DEMONET:

TBR Outboard	0.79	
TBR Inboard	0.25	
TBR Divertor Breeding	0.09	TBR ~ 1.04 to 1.07
Total TBR	1.13	
Penetration Effect	- 0.07	
Net TBR	1.06	

- US Calculations Confirm the EU calculations. In addition:
  - ◊ TBR is further reduced in ITER-type DEMO
  - ◊ ITER first wall is unacceptable in future devices
  - ◊ TBR will be further reduced by plasma heating / current drive front structure
  - ◊ Breeding in Divertor Region is Questionable

Why is the calculated TBR So Low Now?
(What happened to TBR = 1.5?)

1) Design

More detailed, mature , and realistic

- ◊ Thicker First Wall (2.5 cm)
- ◊ Larger Structure Volume Fraction (~ 15%)
- ◊ Thicker Module / Segment Side Walls (Box)

2) Calculations

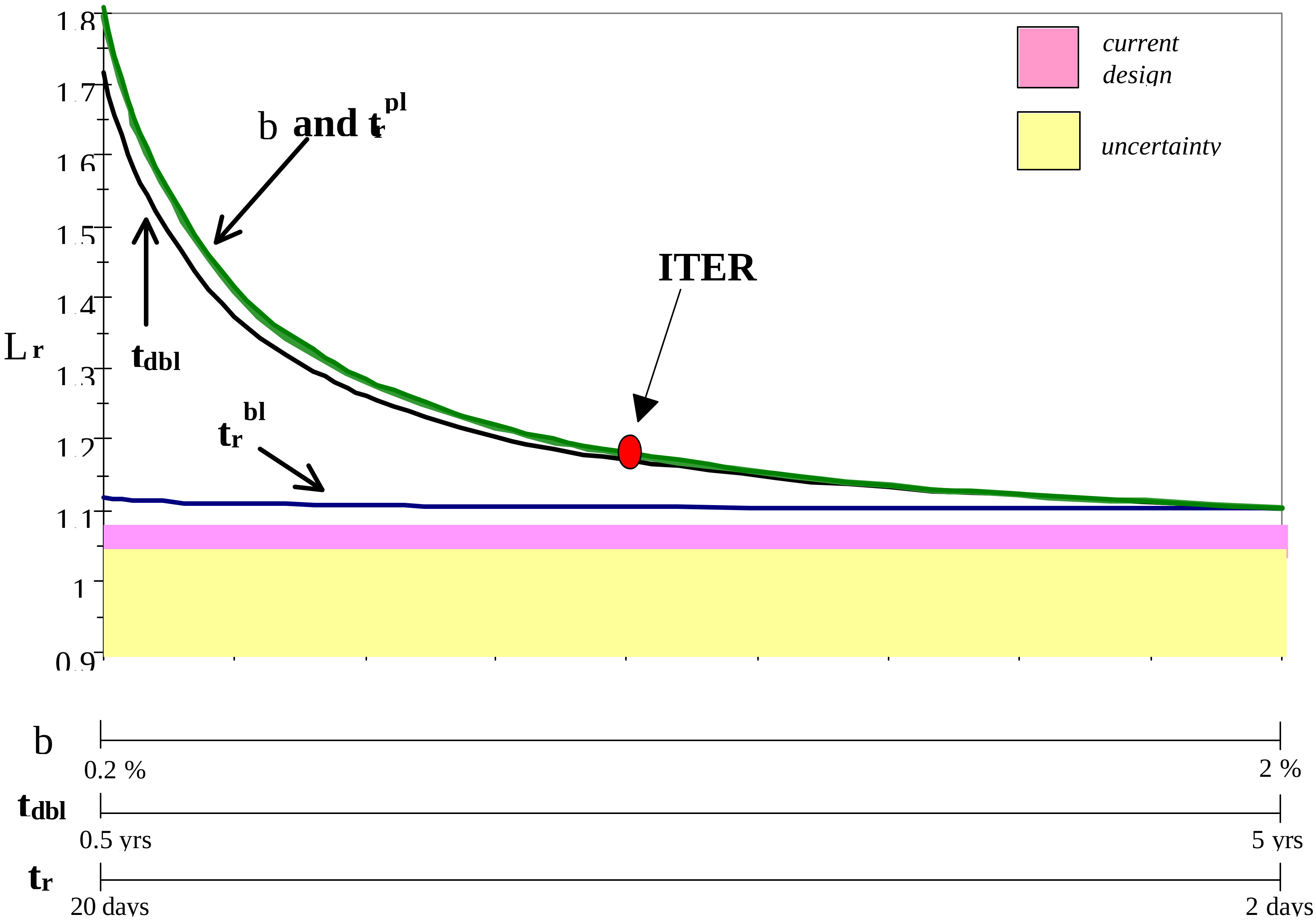
- ◊ Three - Dimensional
- ◊ Detailed HETEROGENOUS Modelling
- ◊ Detailed Geometrical Modelling

3) Nuclear Physics / Thermomechanics

- ◊ As more Beryllium is used, neutrons have much lower energy. Absorption in the structure increases
- ◊ Lower breeder thermal conductivity increases structure - to - breeder volume ratio

Note: For a given system, there is a maximum achievable TBR, i.e. further addition of beryllium will reduce TBR

Tritium Self Sufficiency is a Serious Issue



Tritium Self Sufficiency is a Serious Issue

Possible Directions to Meet the Challenge

1. Tritium Fractional Burnup in plasma > 5%
2. Do not plan on short doubling time!!
3. Seek FW / Blanket Concepts with Larger DESIGN MARGIN
   - ⇒Less Structure
   - ⇒Thin First Wall
   - ⇒Structural Materials with low parasitic neutron absorption
   - ⇒Improved Thermal Conductivity for breeding materials
4. Divertor Designs with Breeding Capability

AND

5. Find a way to demonstrate convincingly Tritium Self Sufficiency over the next 20 years (Requires a Full Breeding Sector test in ITER or another fusion device)

Two Highly Interrelated Challenging Issues:
A) Failure Rate   B) Maintainability

- A Practical Engineering System Must:
  A) Have Sufficient Reliability

  MTBF = Mean Time Between Failure

  B) Be Able to Recover From Failure in Short Time

  MTTR = Mean Time To Recover

- Two Key Questions Concerning MTBF & MTTR:
  1) What should be the goals for a practical fusion system?
  2) What values are achievable with current fusion designs?

Goals for MTBF & MTTR
Can be Easily Derived

<u>Availability = A</u>

A (Plant) = 75%

A (BOP) = 85%

A (Reactor) = 88%

<u>Reactor</u>

Assume 6 major components with equal outage risk

An example of such a component is FW / Blanket

A (Blanket) = 97.8 %

<u>A (FW / Blanket)</u>

$$A = \frac{MTBF}{MTBF + MTTR}$$

$$\boxed{\frac{MTBF}{MTTR} = 43.8}$$

<u>Note</u>: It is the Mean Time Between Failure which is the issue.
It is NOT lifetime

Failure is Different From Design Lifetime

Definition

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

Causes of Failures

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

Goals For MTBF & MTTR For First Wall/Blanket

MTBF = 43.8 MTTR

MTTR

- Estimated by many experts to be > 3 months
- By moving the vacuum vessel outside the blanket, we protect the vacuum vessel, but blanket removal takes longer and leaks represent failure

MTTR	**MTBF FW / B System**	**MTBF FW / B Module**
1 Month	**3.6** yr	**290** yr
3 Month	**11** yr	**877** yr

- First Wall/Blanket has typically 80 modules; each module is about 15 m^2 in surface area
- Such long MTBF requirement for such a large system is ALARMING

What MTBF Can Be Achieved?

Several Studies

- R. Bünde et al. (several articles, 1990-95)
- Abdou & Ying (1994)
- Detailed EU Blanket Evaluation (1994)

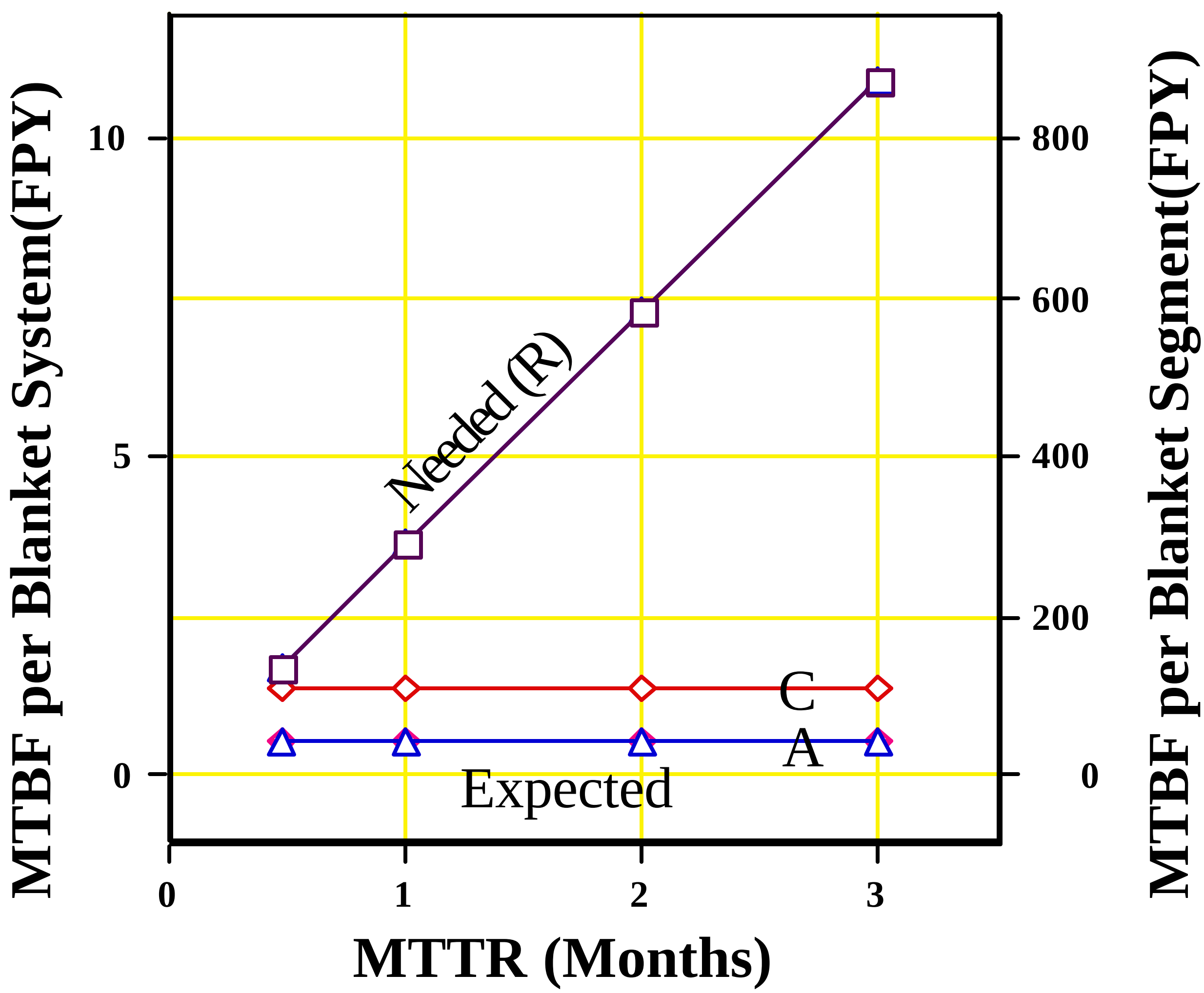
Methodology

- Compile Relevant Failure Rate from Mature Technologies (e.g. fission)
- Estimate Failure Frequency For the Best FW/Blanket Designs Available
    - ◊ Include Failures for Pipes and Welds
    - ◊ IGNORE (DO NOT Include) Fusion Specific Failure Modes

Failure Modes (FW)	**Failure Rate $hr^{-1}.m^{-1}$**	**Length**
Diffusion weld	1×10^{-9}	4.56 km
EB Weld	1×10^{-8}	2.93 km
Longitudinal weld	1×10^{-9}	19 km

Failure Modes (BLKT)	**Failure Rate $hr^{-1}.m^{-1}$**	**Length**
Longitudinal weld	1×10^{-9}	4.8 km
Butt weld	1×10^{-9}	2.58 km
Pipe bend (90°)	5×10^{-9}	1152 bends
Straight pipe	1×10^{-10}	2.9 km

R = Required
A = Expected with extensive R&D
(based on mature technology and no fusion-specific failure modes)
C = Potential improvements with aggressive R&D



Current FW / B Design Concepts are NOT Capable of Meeting the Challenging Reliability Requirements

Challenging Reliability and Maintainability Issues
(MTBF = 43.8 MTTR)

Possible Directions

1) Explore Revolutionary System Concepts (FW /Blanket / Divertor, VV, Magnets) that permit rapid replacement
   - ◊ If MTTR < 2 weeks can be realized, the goal MTBF can probably be realized with a serious R&D Program

2) Stimulate New and Innovative Concepts for which failure modes existing in fission, SG, and other current technologies are eliminated
   e.g. Free Flowing (or Magnetically formed) Thick Liquid Walls?

3) Higher Average Power Density with Peak - to - Average Near Unity

4) In general, failure rates can be reduced, for example, by:
   - ◊ Selecting concepts with Larger Design Margin
   - ◊ Minimizing Welds
   - ◊ Good Data Base
   - ◊ Extensive Testing

5) Need to obtain data on failure modes in first wall / blanket.
   Failure modes can be obtained only in VOLUME Tests (submodule)
   Large Volume, Modest Fluence Tests are much more Important than High Fluence, Specimen Tests

Concluding Remarks

The Region Immediately Surrounding the Plasma
Divertor / First Wall / Blanket / Vacuum Vessel / Shield:

- **Embodies a majority of the most challenging issues hampering the realization of fusion as an attractive energy source.**
- **Requires a serious re-examination of the current R&D path for FNT.**

Suggested Direction:

1. **Allocate REQUIRED resources.**
2. **Change approach to FNT R&D along two basic directions:**
   - **A) Continued EVOLUTION of current concepts by performing serious R&D designed to maximize performance and determine performance limits,**
   - **B) Stimulate the conception and development of REVOLUTIONARY ideas which utilize fundamentally different approaches and offer order of magnitude higher payoffs, even if the risks seem high.**