Perspective on Fusion Nuclear Science and Technology Issues and Development

Mohamed Abdou

Distinguished Professor of Engineering and Applied Science

Director, Center for Energy Science and Technology

Director, Fusion Science and Technology Center

University of California-Los Angeles (UCLA)

Keynote Presentation at ISFNT-9, Dalian, China, October 12, 2009

Binhai Road (Beach Road), Dalian

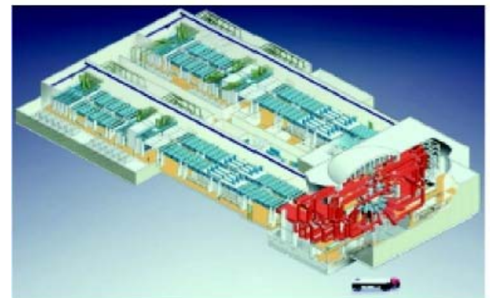
Perspective on Fusion Nuclear Science and Technology (FNST) Issues and Development

OUTLINE

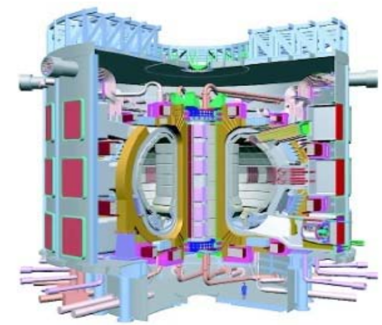
- Fusion Research Transition to Fusion Nuclear Science and Technology (FNST)
- Role and Technical Issues of FNST
- Science-Based Framework for FNST Development
- Stages and Facilities for FNST Development
- Role of ITER TBM
- Need for Fusion Nuclear Science Facility (FNSF/CTF/VNS)
- Development Issues: T Supply and RAMI
- Requirements on FNSF, examples of Designs and Testing Strategy
- Analysis and Implications of some FNST Technical Issues
- Summary

Fusion Research is about to transition from Plasma Physics to Fusion Science and Engineering

- **1950-2010**
  - **The Physics of Plasmas**
- **2010-2035**
  - **The Physics of Fusion**
  - **Fusion Plasmas-heated and sustained**
    - **$Q = (E_f / E_{input})$~10**
    - **ITER (MFE) and NIF (inertial fusion)**



National Ignition Facility



ITER

- **ITER is a major step forward for fusion research. It will demonstrate:**
  1. **Reactor-grade plasma**
  2. **Plasma-support systems (S.C. magnets, fueling, heating)**

But the most challenging phase of fusion development still lies ahead: The Development of Fusion Nuclear Science and Technology

The cost of R&D and the time to DEMO and commercialization of fusion energy will be determined largely by FNST. "Until blankets have been built, tested, and operated, predictions of the timescale of fusion entry into the energy market are necessarily imprecise." – Steve Cowley

Fusion Nuclear Science and Technology (FNST)
Fusion Power & Fuel Cycle Technology

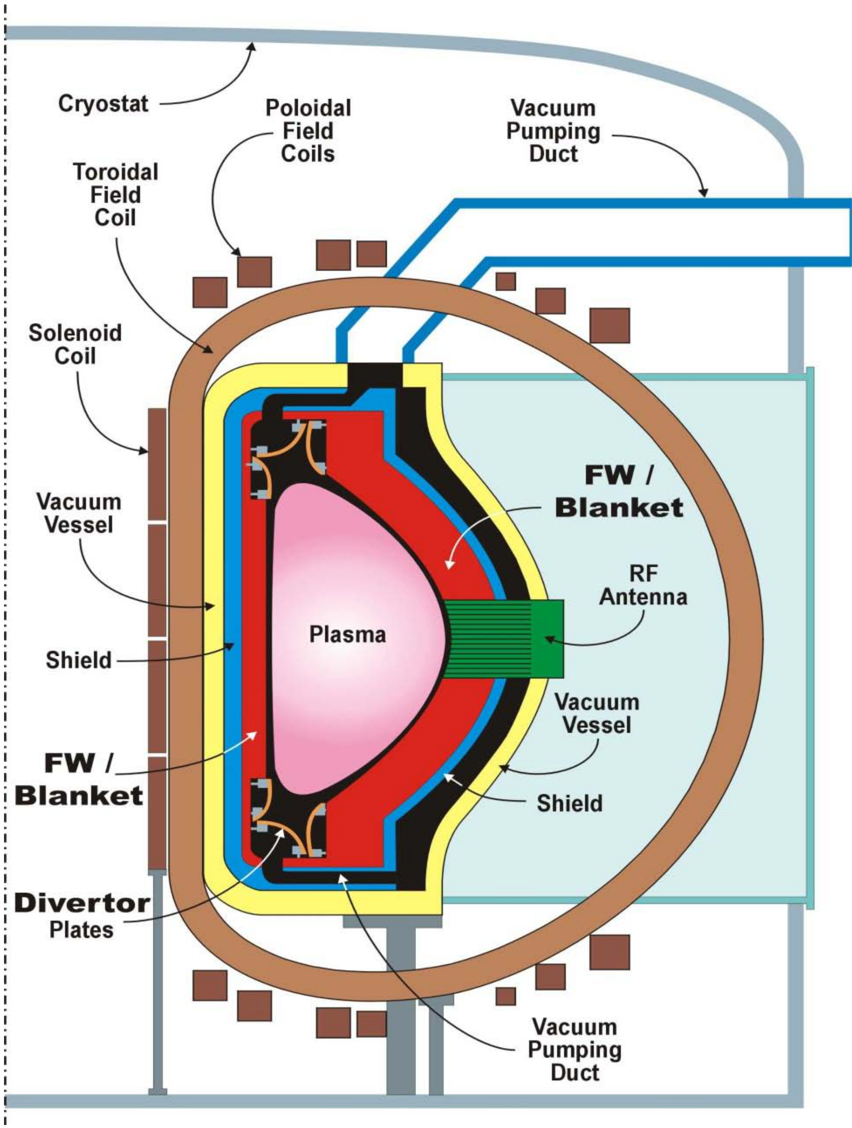
FNST includes the scientific issues and technical disciplines as well as materials, engineering and development of
fusion nuclear components:

From the edge of Plasma to TF Coils:

1. Blanket Components (includ. FW)
2. Plasma Interactive and High Heat Flux Components (divertor, limiter, rf/PFC elements)
3. Vacuum Vessel & Shield Components

Other Systems / Components affected by the Nuclear Environment:

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



Pillars of a Fusion Energy System

1. **Confined and Controlled Burning Plasma (feasibility)**
2. **Tritium Fuel Self-Sufficiency (feasibility)**
3. **Efficient Heat Extraction and Conversion (attractiveness)**
4. **Reliable System Operation (feasibility/attractiveness)**
5. **Safe and Environmentally Advantageous (feasibility/attractiveness)**

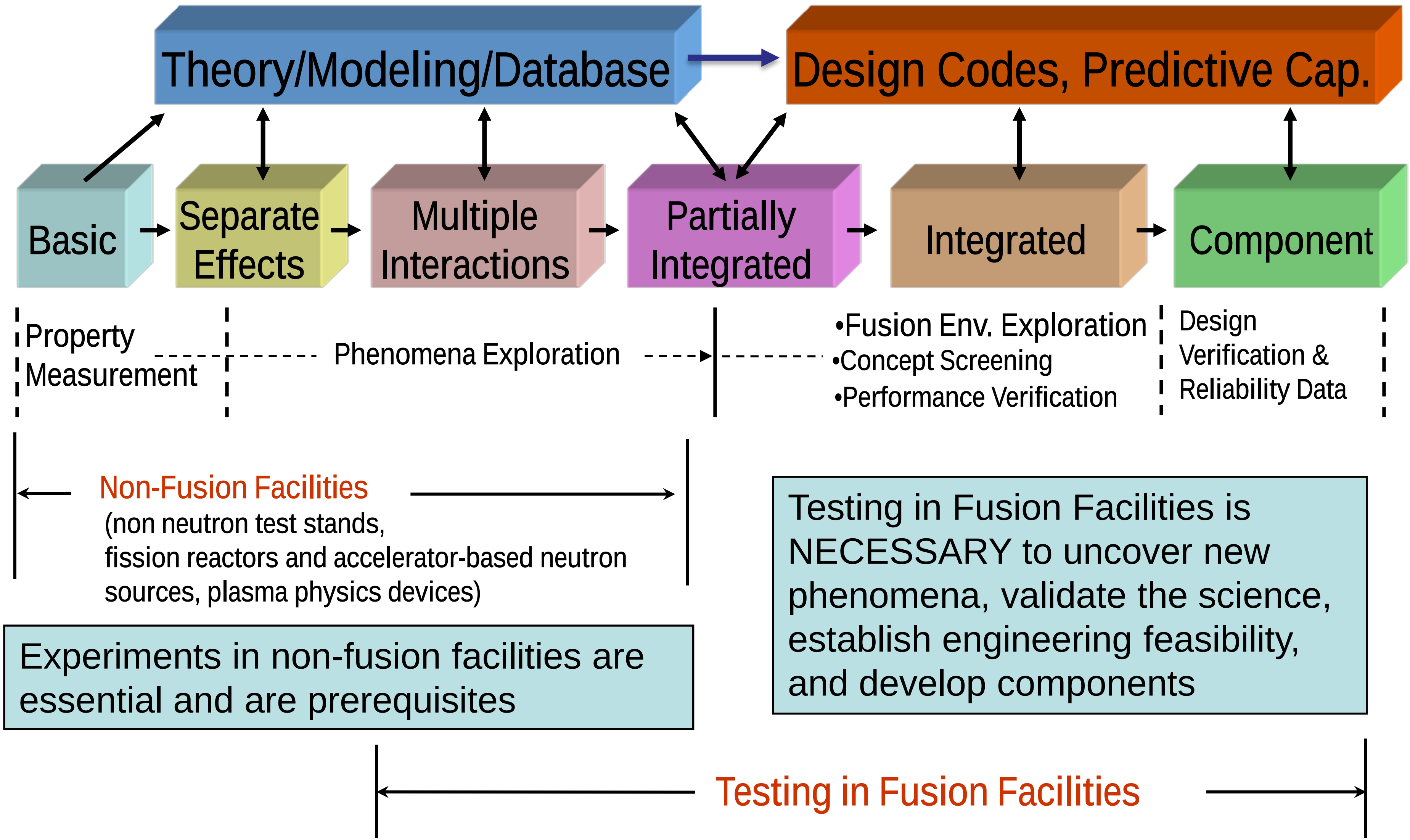
Fusion Nuclear Science and Technology plays the KEY role

Yet, Fusion Nuclear Science and Technology has not yet received the priority and resources needed in the world fusion program.

Summary of *Top- Level* Technical Issues for Fusion Nuclear Science and Technology (FNST)

1. D-T fuel cycle **tritium self-sufficiency** in a practical system
2. **Tritium extraction, inventory, and control** in solid/liquid breeders and blanket, PFC, fuel processing and heat extraction systems
3. **MHD Thermofluid** phenomena and impact on transport processes in electrically-conducting liquid coolants/breeders
4. Structural materials **performance and mechanical integrity under the effect of radiation and thermo-mechanical loadings** in blanket/PFC
5. Functional materials property changes and **performance under irradiation and high temperature and stress gradients** (including ceramic breeders, beryllium multipliers, flow channel inserts, electric and thermal insulators, tritium permeation and corrosion barriers, etc.)
6. **Fabrication and joining** of structural and functional materials
7. **Fluid-materials interactions** including interfacial phenomena, chemistry, compatibility, surface erosion and corrosion
8. Interactions between **plasma operation and blanket and PFC** materials systems, including PMI, electromagnetic coupling, and off-normal events
9. Identification and characterization of **synergistic phenomena** and **failure modes, effects, and rates** in blankets and PFC's in the fusion environment
10. System configuration and Remote maintenance with **acceptable machine down time**

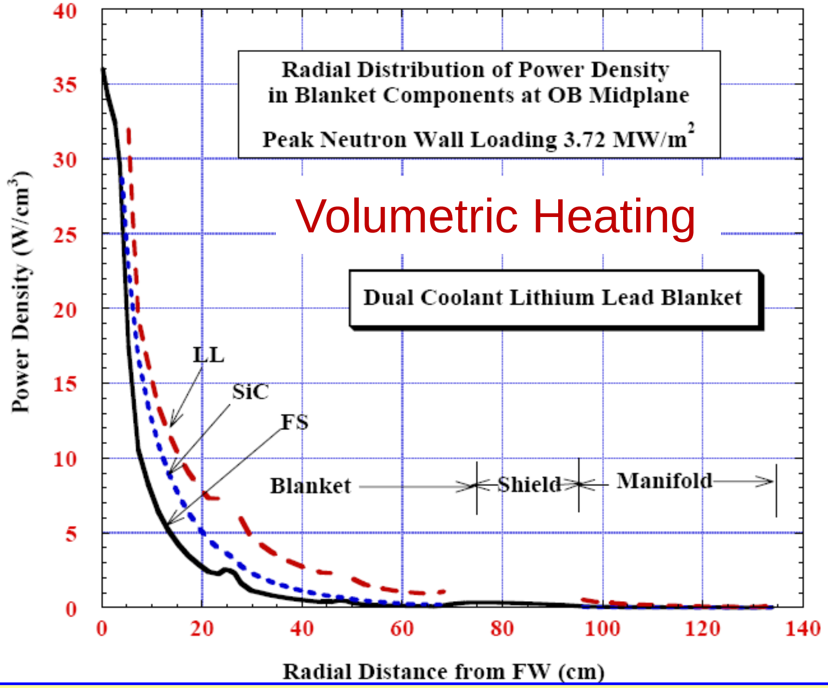
Science-Based Framework for FNST R&D involves modeling and experiments in non-fusion and fusion facilities

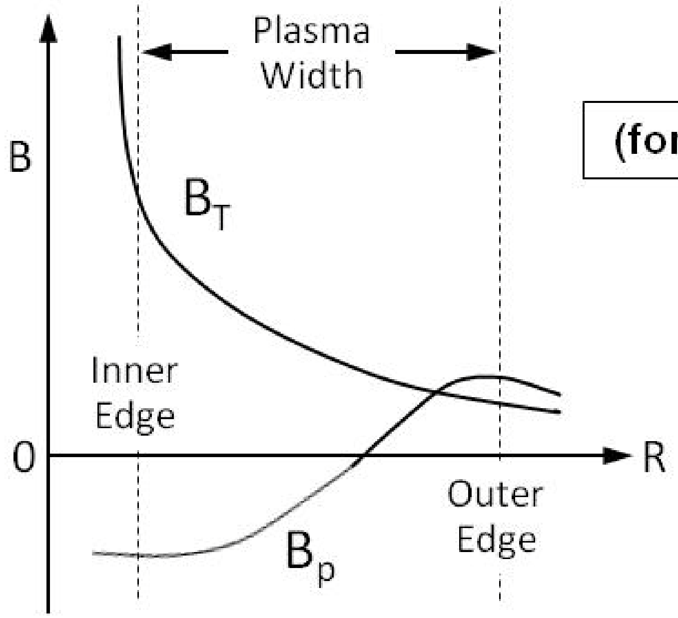


Fusion environment is unique and complex: multi-component fields with gradients

- Neutron and Gamma fluxes
- Particle fluxes
- Heat sources (magnitude and gradient)
  - Surface (from plasma radiation)
  - Bulk (from neutrons and gammas)

- Magnetic Field (3-component)
  - Steady field
  - Time varying field
- With gradients in magnitude and direction





Multi-function blanket in multi-component field environment leads to:

- *Multi-Physics, Multi-Scale Phenomena* ⇨ *Rich Science to Study*
- **Synergistic effects** that cannot be anticipated from simulations & separate effects tests. Modeling and Experiments are challenging
- Such unique fusion environment and synergistic effects can be reproduced only in plasma-based devices.

Three Stages of FNST Testing in Fusion Facilities Are Required Prior to DEMO

Stage I	Stage II	Stage III	
Fusion "Break-in" & Scientific Exploration	Engineering Feasibility & Performance Verification	Component Engineering Development & Reliability Growth	DEMO
0.1 - 0.3 MW-y/m²	**1 - 3 MW-y/m²**	**> 4 - 6 MW-y/m²**	
≥ 0.5 MW/m² ; burn > 200 s	**1-2 MW/m² steady state or long burn COT ~ 1-2 weeks**	**1-2 MW/m² steady state or long burn COT ~ 1-2 weeks**	
Sub-Modules/Modules	Modules	Modules/Sectors	

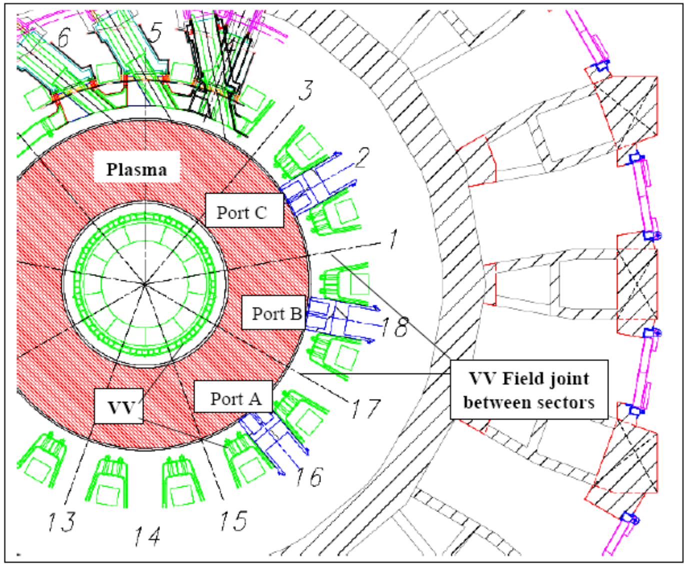
Stage I
- Initial exploration of coupled phenomena in fusion environment
- Screen and narrow blanket design concepts

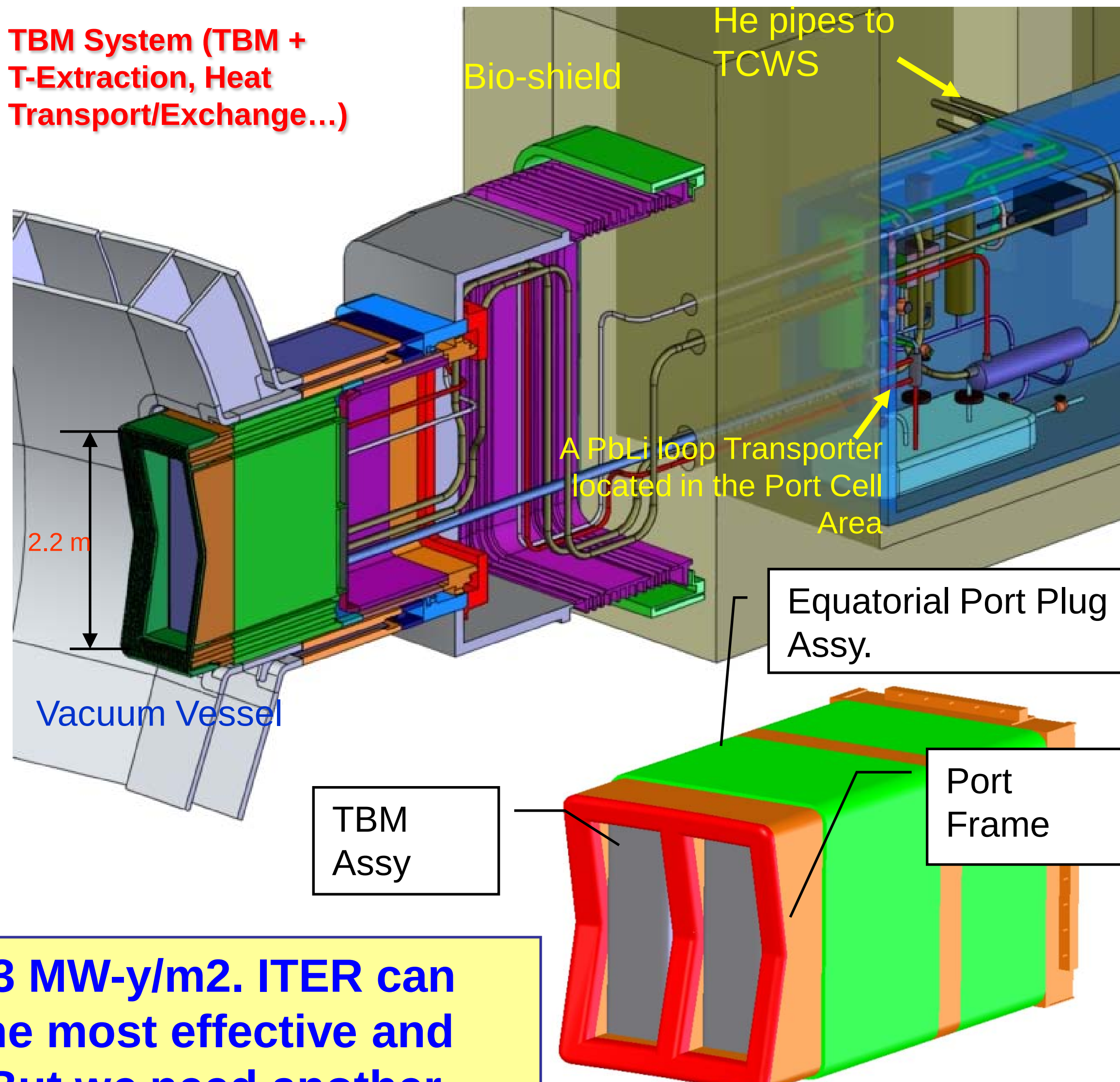
Stage II
- Establish engineering feasibility of blankets (satisfy basic functions & performance, up to 10 to 20 % of lifetime)
- Select 2 or 3 concepts for further development

Stage III
- Failure modes, effects, and rates and mean time to replace/fix components (for random failures and planned outage)
- Iterative design / test / fail / analyze / improve programs aimed at reliability growth and safety
- Verify design and predict availability of FNT components in DEMO

Where to do Stages I, II, and III?

ITER Provides Substantial Hardware Capabilities for Testing of Blanket Systems





- ITER has allocated 3 equatorial ports (1.75 x 2.2 m2) for TBM testing
- Each port can accommodate only 2 modules **(i.e. 6 TBMs max)**

Fluence in ITER is limited to 0.3 MW-y/m2. ITER can only do Stage I. ITER TBM is the most effective and least expensive to do Stage I. But we need another facility for Stages II & III.

Role of ITER TBM

- ITER will provide the first opportunity to test blankets in the real fusion environment
- Operating cost of ITER already paid for to test burning plasmas
  - Facility cost is free for TBM
  - Benefits of 7 parties collaborating to "screen" the many blanket options
- Most important recent step forward for ITER, FNST, and fusion:
  - **ITER Council decision in 2008 to undertake the TBM Program within the framework of the ITER agreement**
  - **Therefore, the Test Blanket Systems will now be part of the new ITER baseline**
- TBM is now serving as a driver to face engineering development challenges (e.g., fabrication and joining)
- **But a much larger worldwide research program is required for effective utilization of ITER TBM**
  - Research program is needed to investigate the FNST technical issues and how to realize in TBM the conditions that are necessary to simulate them
  - An extensive program should address what is to be measured in TBM and how to measure it (instrumentation)
- ITER TBM must be a serious project but it should be only one element of many in a much larger FNST research program

Fusion Nuclear Science Facility (FNSF)

- The idea of FNSF (also called VNS, CTF) is to build a small size, low fusion power DT plasma-based device in which Fusion Nuclear Science and Technology (FNST) experiments can be performed in the relevant fusion environment:

  1- at the smallest possible scale, cost, and risk, and

  2- with practical strategy for solving the tritium consumption and supply issues for FNST development.

  In MFE: small-size, low fusion power can be obtained in a low-Q (driven) plasma device, with normal conducting Cu magnets

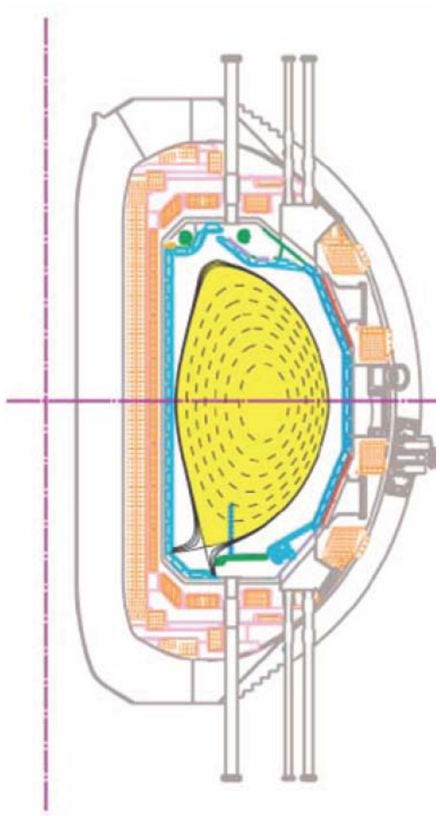
  – Equivalent in IFE: reduced target yield (and smaller chamber radius?)

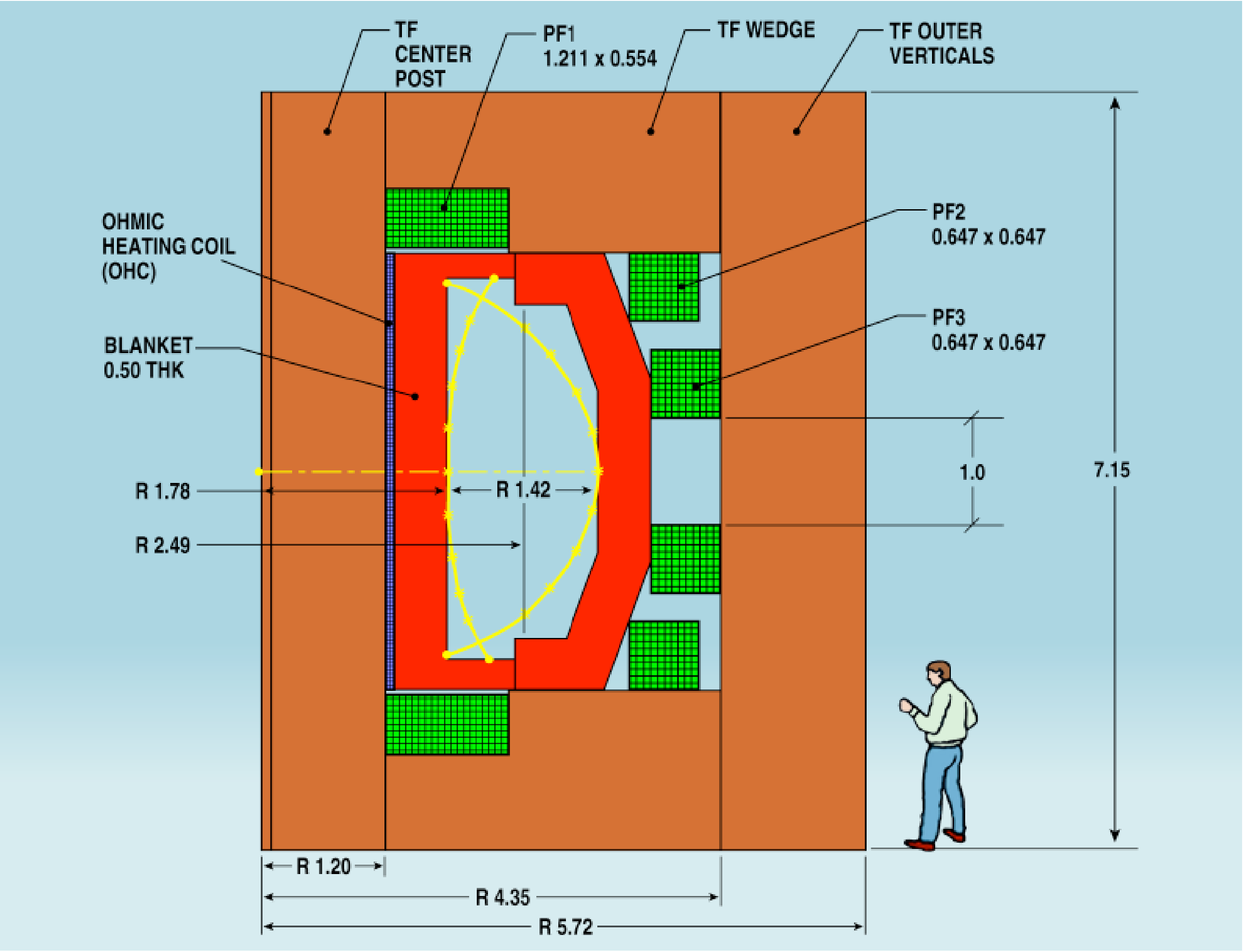
- There are at least TWO classes of Design Options for FNSF:

  – Tokamak with Standard Aspect Ratio, A ~ 2.8 – 4

  – ST with Small Aspect Ratio, A ~ 1.5

Example of Fusion Nuclear Science Facility (FNSF) Design Option: Standard Aspect Ratio (A=3.5) with demountable TF coils (GA design)





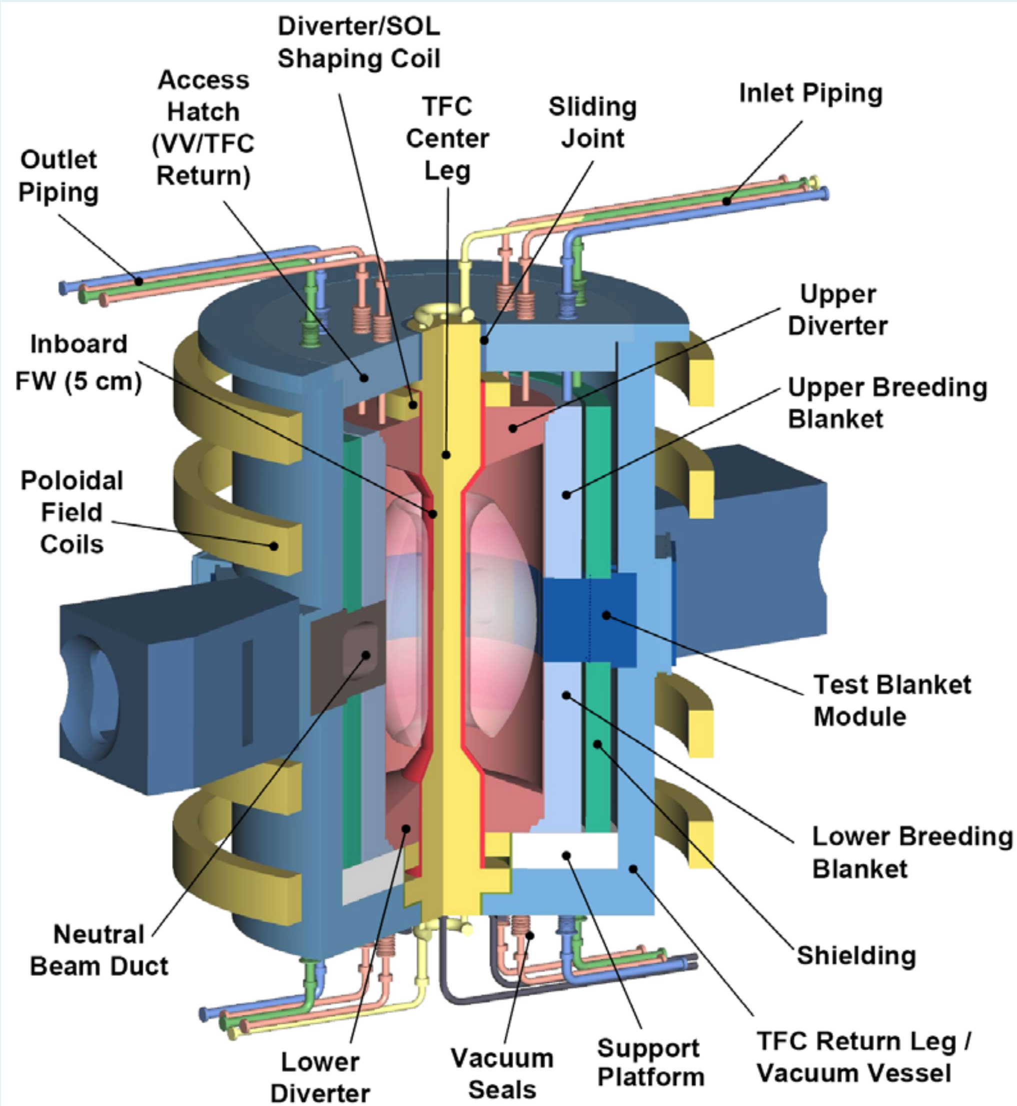
- High elongation, high triangularity double null plasma shape for high gain, steady-state plasma operation

Challenges for Material/Magnet Researchers:

- **Development of practical "demountable" joint in Normal Cu Magnets**
- **Development of inorganic insulators (to reduce inboard shield and size of device)**

Another Option for FNSF Design: Small Aspect Ratio (ST)
Smallest power and size, Cu TF magnet, Center Post

(Example from Peng et al, ORNL) R=1.2m, A=1.5, Kappa=3, Pfusion=75MW



W_L [MW/m^2]	0.1	1.0	2.0
R0 [m]	1.20		
A	1.50		
Kappa	3.07		
Qcyl	**4.6**	3.7	**3.0**
Bt [T]	**1.13**	2.18	
Ip [MA]	**3.4**	8.2	**10.1**
Beta_N	3.8		**5.9**
Beta_T	**0.14**	0.18	**0.28**
n_e [10^{20}/m^3]	**0.43**	1.05	**1.28**
f_{BS}	**0.58**	0.49	**0.50**
T_{avgi} [keV]	**5.4**	10.3	**13.3**
T_{avge} [keV]	**3.1**	6.8	**8.1**
HH98	1.5		
Q	**0.50**	2.5	**3.5**
P_{aux-CD} [MW]	**15**	31	**43**
E_{NB} [keV]	**100**	239	**294**
P_{Fusion} [MW]	**7.5**	75	**150**
T M height [m]	1.64		
T M area [m^2]	14		
Blanket A [m^2]	66		
$F_{n-capture}$	0.76		

Critical Factors that have Major Impact on Fusion Testing and Development Pathway for FNST:

1. Tritium Consumption / Supply Issue
2. Reliability / Maintainability / Availability Issue
3. Cost, Risk, Schedule

- The idea of a Fusion Nuclear Science Facility, FNSF (also called VNS, CTF, etc.) dedicated to FNST testing was born out of the analyses of these critical factors 20 years ago
- Today, these factors remain the key to defining details of FNSF mission, design, and testing strategy

The Issue of External Tritium Supply is Serious and has Major Implications on FNST (and Fusion) Development Pathway

Tritium Consumption in Fusion is HUGE! Unprecedented!

55.6 kg per 1000 MW fusion power per year

Production in fission is much smaller & Cost is very high:

Fission reactors: 2–3 kg/year

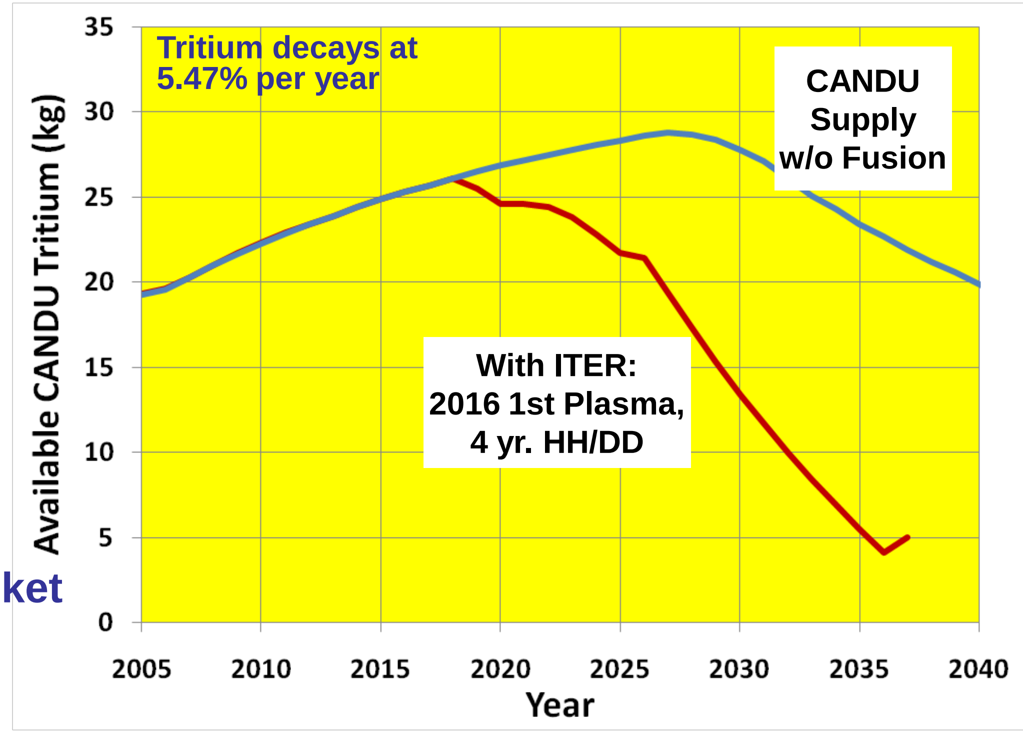
$84M-$130M/kg (per DOE Inspector General*)

*www.ig.energy.gov/documents/CalendarYear2003/ig-0632.pdf

CANDU Reactors: 27 kg from over 40 years, $30M/kg (current)

Tritium Decays at 5.47% per year

- **A Successful ITER will exhaust most of the world supply of tritium. Delays in ITER schedule makes it worse.**
- **No DT fusion devices with fusion power >50 MW, other than ITER, can be operated without a verified breeding blanket technology.**
- **Development of breeding blanket technology must be done in small fusion power devices.**



Two Issues In Building A DEMO:

1 – Need Initial (startup) inventory of >10 Kg per DEMO

(How many DEMOS will the world build? And where will startup tritium come from?)

2 – Need Verified Breeding Blanket Technology to install on DEMO

Reliability/Availability/Maintainability/Inspectability (RAMI)

- ❑ RAMI, particularly for nuclear components, is one of the most challenging issues for fusion DEMO and power plants.
- ❑ RAMI is a critical development issue that has major impact on the path to fusion development.

Device availability is reduced by two types of outages:

Scheduled Outage: (This you design for, manageable)

Unscheduled Outage: (Can kill your DEMO and your future)

Random failures do occur in any engineering system. Since they are random, they have the most serious impact on availability.

FNST R&D to realize acceptable availability (low failure rate, fast maintenance) will be the "time-controlling" step in fusion development.

A fusion device has MANY major components
Availability required for each component needs to be high

(Table based on information from J. Sheffield et al.)

Component	Num ber	Failure rate in hr^{-1}	MTBF in years	MTTR for Major failure, hr	MTTR for Minor failure, hr	Fraction of failures that are Major	Outage Risk	Component Availability
Toroidal Coils	16	5×10^{-6}	**23**	10^4	240	0.1	**0.098**	0.91
Poloidal Coils	8	5×10^{-6}	**23**	5×10^3	240	0.1	**0.025**	0.97
Magnet supplies	4	1×10^{-4}	**1.14**	72	10	0.1	**0.007**	0.99
Cryogenics	2	2×10^{-4}	**0.57**	300	24	0.1	**0.022**	0.978
Blanket	100	1×10^{-5}	**11.4**	800	100	0.05	**0.135**	0.881
Divertor	32	2×10^{-5}	**5.7**	500	200	0.1	**0.147**	0.871
Htg/CD	4	2×10^{-4}	**0.57**	500	20	0.3	**0.131**	0.884
Fueling	1	3×10^{-5}	**3.8**	72	--	1.0	**0.002**	0.998
Tritium System	1	1×10^{-4}	**1.14**	180	24	0.1	**0.005**	0.995
Vacuum	3	5×10^{-5}	**2.28**	72	6	0.1	**0.002**	0.998
Conventional equipment- instrumentation, cooling, turbines, electrical plant ---							**0.05**	0.952
TOTAL SYSTEM							**0.624**	0.615

DEMO availability of 50% requires: Divertor Availability ~ 87%
Blanket availability ~88% and blanket MTBF >11 years.

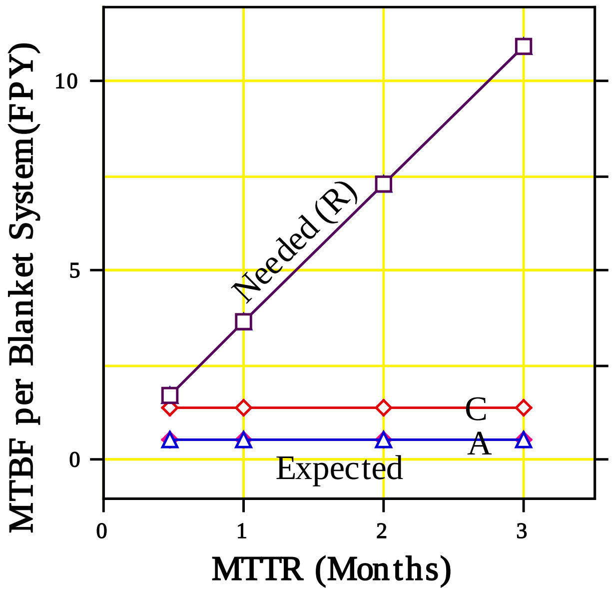
$$\textbf{Availability}_{(u,\,i)} = \frac{\textbf{MTBF}}{\textbf{MTBF + MTTR}}$$

MTBF = mean time between failures = 1/failure rate

MTTR = mean time to repair

- Current confinement concepts have long blanket MTTR > 1 month because of
a) complex configuration, and b) the blanket being INSIDE the vacuum vessel *(compared to replacement time of ~ 2 days of fuel in fission reactors)*.
This leads to reliability requirements on the Blanket/FW that are most challenging (blanket MTBF must be >11 years!).

- Failure rate is likely to be high because:
  - – large first wall area
  - – leaks inside the VV can not be tolerated
  - – harsh fusion environment

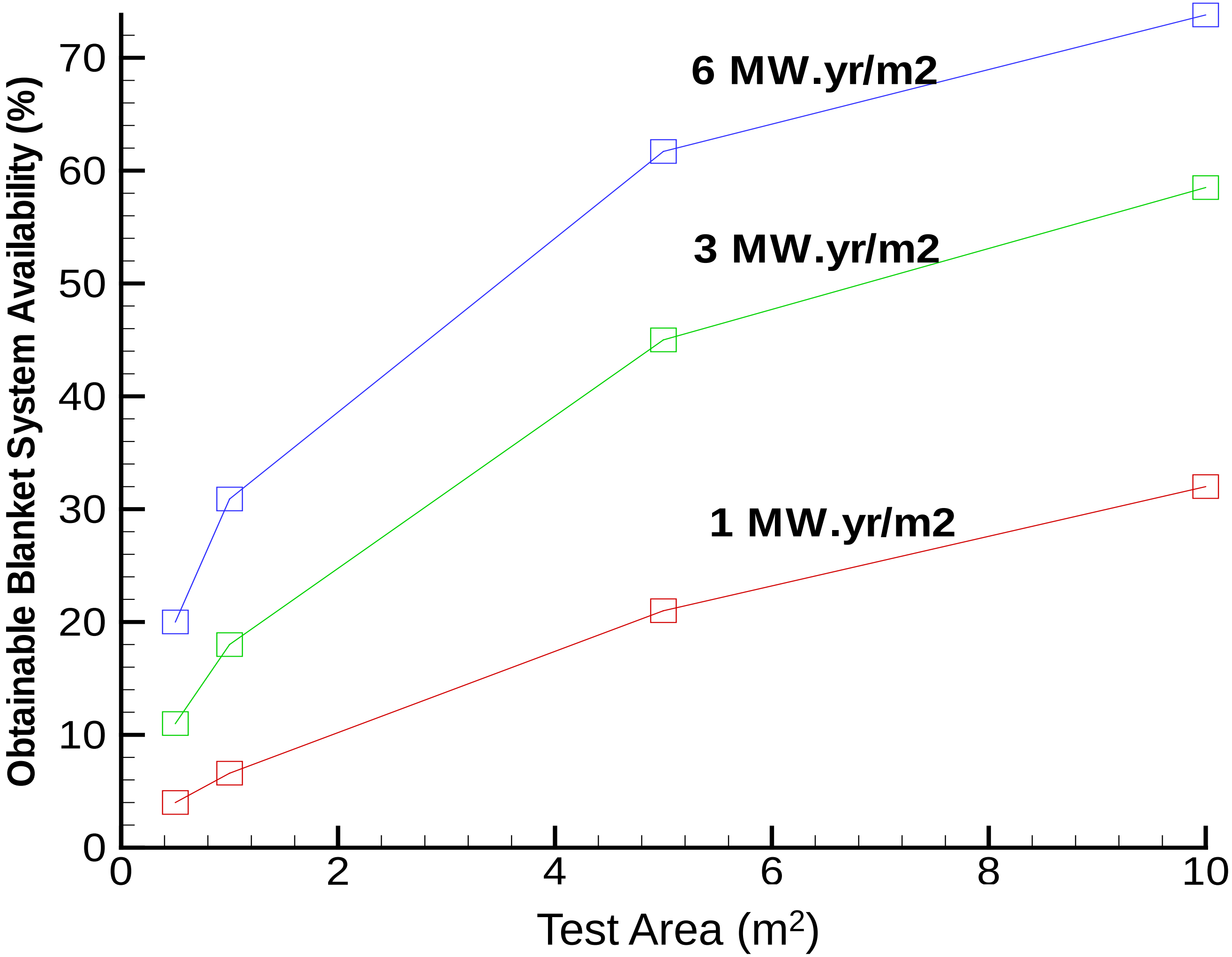


MTBF required >> achievable
Need MTTR < 2 weeks

Serious R&D on RAMI for FNST components

1 – Design for RAMI
2 – Obtain data on failure modes, rates and effects from testing in labs and fusion facilities
3 – Obtain data on maintenance/repair time (MTTR)
4 – Need very aggressive "reliability growth" testing program in fusion facilities

Using Standard "Reliability Growth" Methodology, We Can Estimate The Required Testing Time (fluence) and Test Area



MTTR = 1 month
1 failure during the test
80 blanket modules in blanket system
Experience factor = 0.8
Confidence Level = 50%
Test area per test article = 0.5 m^2
Neutron wall load = 2 MW/m^2

Level of Confidence based on Figure 15-2.2 in "FINESSE: A Study of the Issues, experiments and Facilities for Fusion Nuclear Technology Research & Development, Chapter 15 Reliability Development Testing Impact on Fusion Reactor Availability", Interim report, Vol. IV, PPG-821, UCLA, 1984.

It is a challenge to do enough "reliability growth" testing to ensure 88% Blanket Availability:

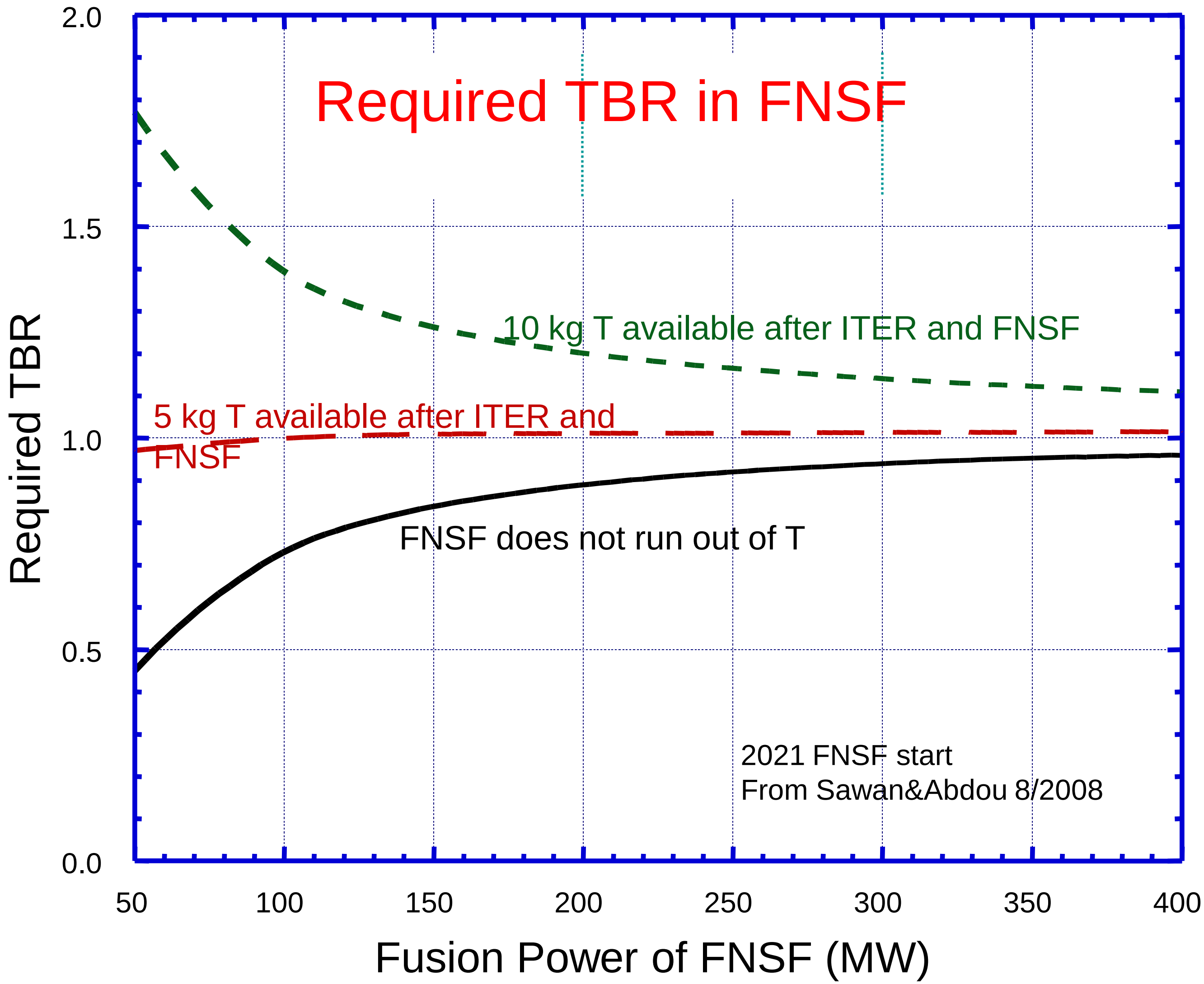
1- "Cumulative" testing fluence of > 6 $MW{\cdot}y/m^2$

2- Number of test modules per concept ~ 10-20 (two concepts require ~ 20 – 40 m^2)

FNSF has to breed tritium to:

a- supply most or all of its consumption

b- accumulate excess tritium sufficient to provide the tritium inventory required for startup of DEMO



Situation we are running into with breeding blankets: What we want to test (the breeding blanket) is by itself an ENABLING technology

Base Breeding Blanket and Testing Strategy in FNSF
(US Conclusions)

- **A Breeding Blanket should be installed as the "Base" Blanket on FNSF from the beginning**
  - Needed to breed tritium.
  - Switching from non-breeding to breeding blanket involves complexity and long downtime.There is no non-breeding blanket for which there is more confidence than a breeding blanket.
  - Using base breeding blanket will provide the large area essential to "reliability growth". This makes full utilization of the "expensive" neutrons.

- **The two primary concepts for DEMO (DCLL and HCCB in US case) are recommended for both "testing ports" and "Base" Breeding Blanket**

- **Both "port-based" and "base" blanket will have "testing missions"**
  - Base blanket operating in a more conservative mode (run initially at reduced parameters/performance)
  - Port-based blankets are more highly instrumented, specialized for experimental missions, and are operated near their high performance levels.

Structural Material for FNSF

- **Reduced activation Ferritic Steel (FS) is the only structural material option for DEMO. FS should be used in both base and testing breeding blankets on FNSF.**

- **FS irradiation data base from fission reactors extends to ~ 80 dpa, but it lacks He. There is confidence in He data up to 100 appm (~ 10 dpa).**

Structural Material Testing Strategy in FNSF

- **Strategy for developing structural material data base for design:**
  - Design initial breeding blanket for FNSF with FS for ~ 10 dpa.
  - Obtain real data on FS performance up to ~ 10 dpa in Stage I testing in FNSF.
  - Extrapolate by a factor of 2 (standard in fission and other development) to design next stage blanket in FNSF for 20 dpa.
  - Extrapolate using 20 dpa FNSF data to build Stage III blanket to operate up to 40 dpa.
- **FNSF will provide key information on structural material in 3 ways:**
  - From base breeding blanket – large surface area providing data on property changes, behavior, failure modes, effects and rates in materials, joints, and material interfaces.
  - From "test port-based" modules where the performance is pushed toward higher and lower limits (e.g. temperature) and more complete instrumentation to allow comprehensive data on material behavior and better diagnosis of what happened
  - Thousands of specimens at different operating conditions (e.g., temperatures) in a specifically designed "material test module".
- **Note results of testing structural materials in FNSF are conclusive.**
  - "Real" fusion environment – no uncertainty of spectrum or other environmental effects.
  - Testing of components with prototypical gradients, materials interactions, joints, and other fusion environmental conditions.

Summary of *Top- Level* Technical Issues for Fusion Nuclear Science and Technology (FNST)

1. D-T fuel cycle **tritium self-sufficiency** in a practical system
2. **Tritium extraction, i**... rs and blanket, PFC, fuel processing an...
3. **MHD Thermofluid** ph... in electrically-conducting liquid coolar...
4. Structural materials **pe**... **ler the effect of radiation and**
5. Functional materials pr... **adiation and high temperature an**... um multipliers, flow channel inserts, electric and therma...
6. **Fabrication and joini**...
7. **Fluid-materials inter**... emistry, compatibility, surface e...
8. Interactions between **p**... aterials systems, including PMI, ... ents
9. Identification and chara... **failure modes, effects, and rates** in blankets and PFC's in the fusion environment
10. System configuration and Remote maintenance with **acceptable machine down time**

Substantial progress has been made in many technical areas. But, challenging problems were also encountered.

The remainder of this talk will analyze only two broad issues (as examples):

1. **Tritium Issues**
2. **MHD Thermofluids and Fluid- Material Interactions (Interfacial Phenomena)**

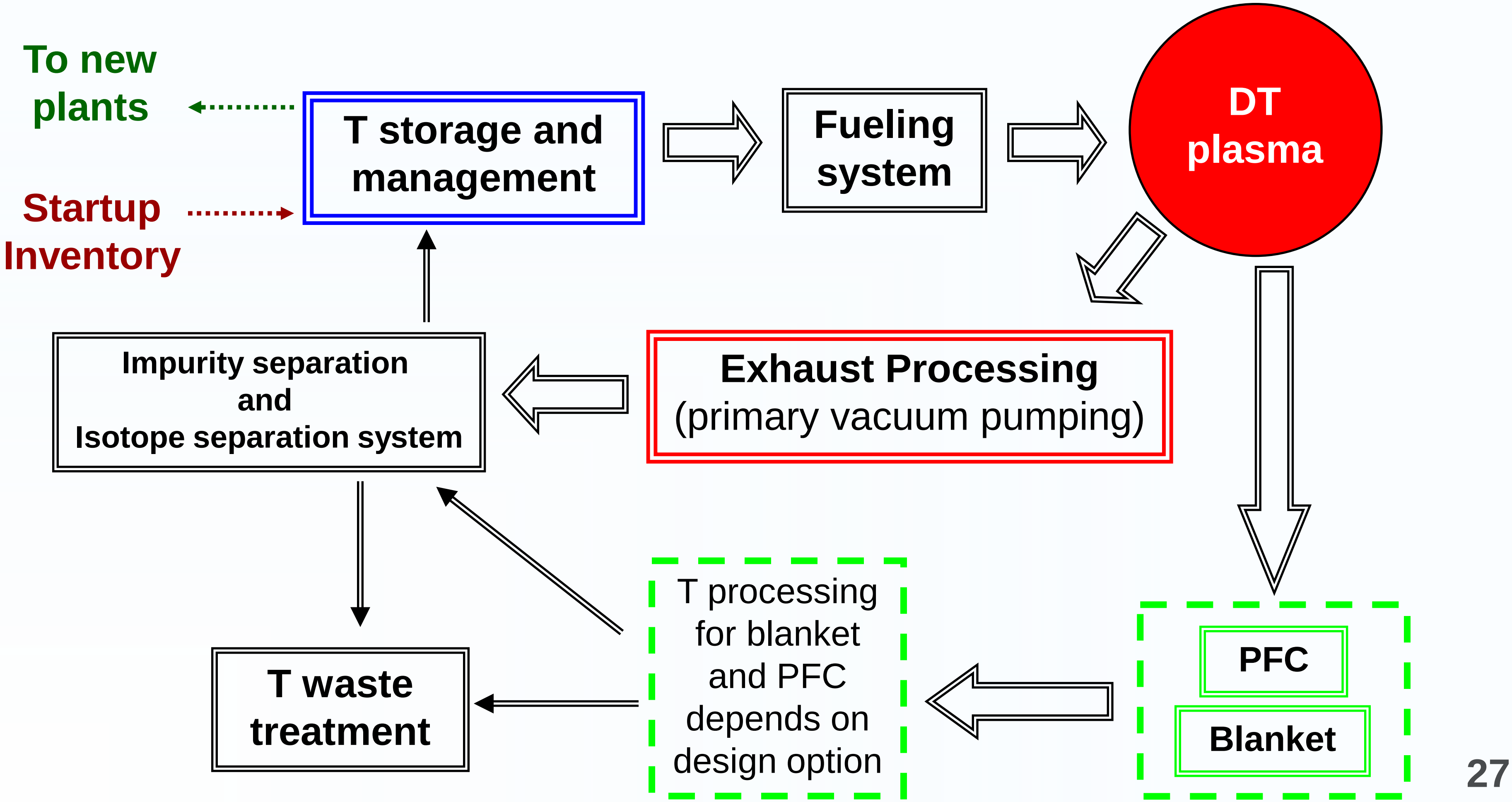
Tritium Issues

1. Available External Tritium Supply
2. Tritium burn-up Fraction
3. Tritium Inventory and Start-Up Requirements
4. Conditions for Attaining Tritium Self-Sufficiency
5. Tritium Permeation

Dynamic fuel cycle models were developed to calculate time-dependent tritium flow rates and inventories

(Dynamic Fuel Cycle Modelling: Abdou/Kuan et al. 1986, 1999)

Simplified Schematic of Fuel Cycle



Key Parameters Affecting Tritium Inventory (and amount of tritium loss by radioactive decay), and Hence, Required TBR

1) Doubling time for fusion power plants
2) Tritium burn-up fraction in the plasma (f_b)
3) Fueling efficiency
4) Time required for tritium processing of various tritium-containing streams (e.g. plasma exhaust, tritium-extraction fluids from the blanket), t_{tp}
5) "Reserve Time", i.e. days of tritium supply kept in "reserve" storage to keep plasma and plant operational in case of any malfunction in tritium processing system
6) Parameters and conditions that lead to large "trapped" inventories in reactor components (e.g. in divertor, FW, blanket)
7) Inefficiencies in various tritium processing schemes

Tritium Burn-up Fraction (f_b)

f_b = fusion reaction rate / tritium fueling rate

tritium injection rate = $\dfrac{\text{fueling rate}}{\text{fueling efficiency } (\eta_f)} = \dfrac{\text{fusion reaction rate}}{f_b\, \eta_f}$

Need to minimize tritium injection rate: Need high η_f and high f_b

•**Recent results: gas fueling is not efficient $\eta_f < 15\%$. Only pellet fueling can give η_f ~90%**

- An expression for f_b can be derived as $\boxed{f_b = 1/(1 + \dfrac{2}{n\tau^* < \sigma v >})}$

- $\tau^* = \tau / (1 - R)$ where R = recycling coefficient from the edge

- Previous reactor studies (STARFIRE, ARIES, EU, Japan) assumed very high R (> 90%) to obtain f_b > 35%. But recent results show that recycled DT from the edge do not penetrate into the plasma core and hence do not contribute to fusion reactions. Therefore $\tau^* \sim \tau$

- **ITER predicts f_b ~ 0.3%**

- ITER f_b does not extrapolate to a feasible fusion reactor

How can we increase f_b > 5% in fusion reactors?

The apparent dependence of f_b on only $n\,\tau$ is alarming!!

Plasma research and ITER must give this issue one of the highest priorities.

Impact of Tritium Burn-up Fraction on Tritium Inventory

$$I = I_{fe} + I_c$$

$I_{fe} \equiv$ Tritium inventory in systems associated with the plasma (fueling, exhaust, etc.)

$$I_{fe} \sim t_{tp} / f_b \eta_f$$

t_{tp} is the time for tritium processing (to go through the vacuum pumping, impurity separation, ISS, fuel fabrication and injection).

$I_c =$ Tritium inventory in other components, e.g. blanket (does not depend on f_b)

Implications of tritium burn-up fraction for ITER ~ 0.3%

A power reactor consumes ~ 0.5 kg per day, and if t_{tp} is ~ 24 hours like TSTA, then the tritium inventory in the fuel storage will be > 160 kg!! Totally unacceptable. If t_{tp} is reduced to 4 hours, I will be ~ 27 kg. Still too high!!

A power reactor with the same f_b as ITER would be unacceptable!

Why large tritium inventory is unacceptable

- Safety
- "Start-up" inventory from external sources not available
- Required tritium breeding ratio becomes much higher

Tritium self-sufficiency condition:
$\Lambda a \geq \Lambda r$

Λr = Required tritium breeding ratio

Λr is 1 + G, where G is the margin required to account for:

1) Supply tritium inventory for start-up of other reactors (for a specified doubling time).

2) Tritium inventory holdup in plant components (e.g. fueling system, plasma exhaust/vacuum pumping systems, etc.)

3) Losses via radioactive decay (5.47% per year)

Λr is dependent on many system physics and technology parameters.

Λa = Achievable tritium breeding ratio

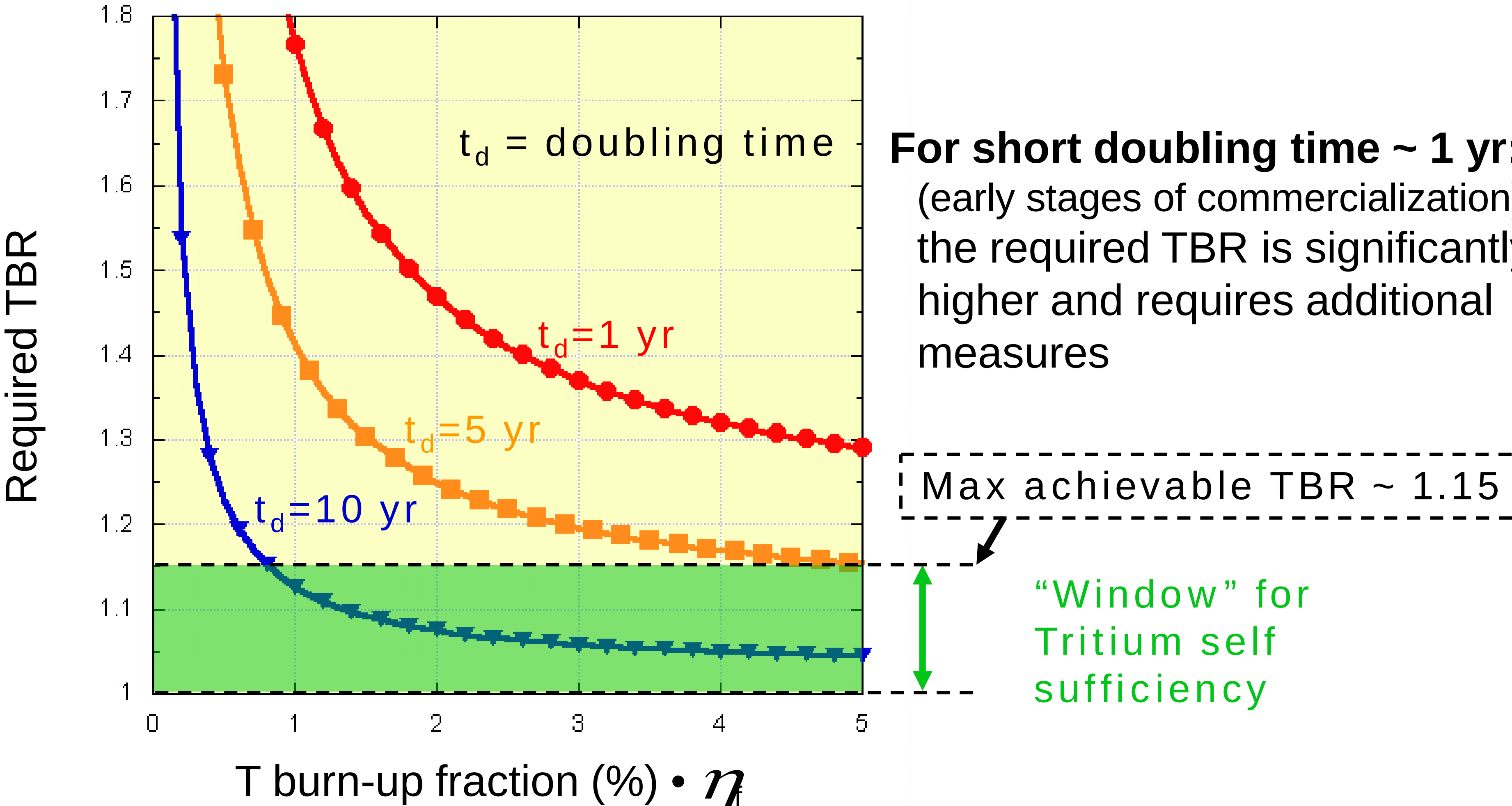
Λa is a function of technology, material and physics.

Tritium inventories associated with low f_b , η_f , *long* $\boldsymbol{t_{tp}}$ and short t_d are very large, leading to unrealistic requirements on TBR.

Attaining Tritium Self-Sufficiency in DT Fusion Imposes Key Requirements on Physics and Technology. For example: for doubling time > 5 years:

T burn-up fraction x fueling efficiency > 5%

Tritium processing time (in plasma exhaust processing) < 4 hours



For short doubling time ~ 1 yr:
(early stages of commercialization), the required TBR is significantly higher and requires additional measures

Role of ITER in Resolving Tritium Fuel Cycle Issues and Demonstrating the Principles of Tritium Self-Sufficiency

- We will learn from ITER what tritium burn-up fraction and fueling efficiency are achievable.
  - **ITER must explore methods to increase f_b η_f to > 5%.**
- Work on ITER fuel processing systems will help quantify inventories, flow rates, and processing times required in fusion at near reactor scale.
  - **At present ITER goal is to achieve tritium processing time of ~1 hour.**
    This is great! But it is for pulsed system with long-time between pulses and conditions for processing cryopanels that are not prototypical.
    Need to test prototypical conditions in the steady-state plasma operation phase.
- However, ITER in-vessel components will be less relevant due to low operating temperatures and non-prototypic materials and designs, and the absence of tritium breeding.
  - **ITER TBM will provide data on some aspects of tritium breeding and extraction, but will not enable accurate prediction of the "achievable TBR".**
- Demonstration of tritium self-sufficiency requires another fusion facility, in addition to ITER, in which full breeding blankets, or at least "complete sectors", and fully integrated tritium processing systems can be tested.

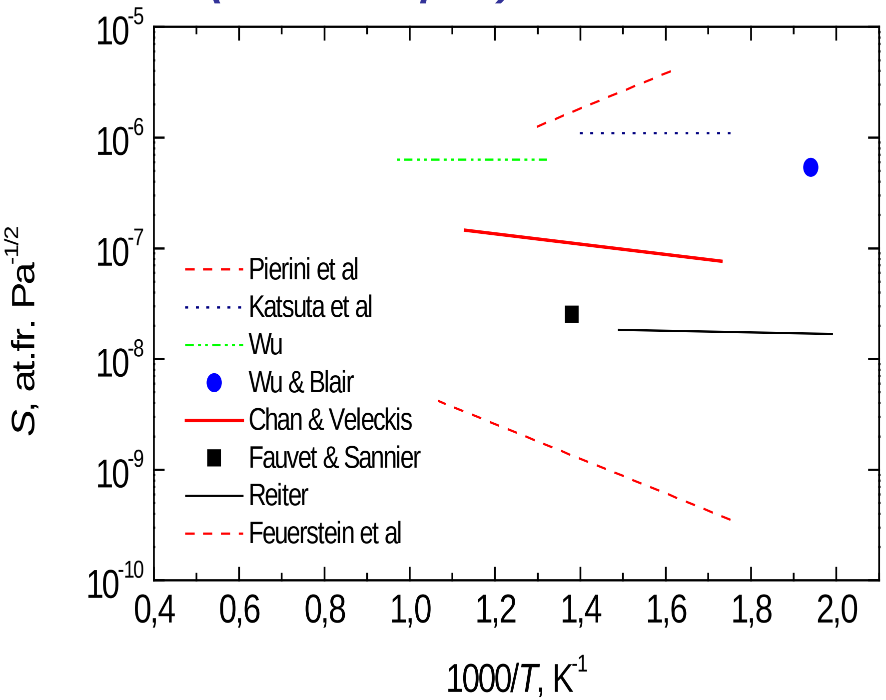
Tritium extraction, inventory, and control in fusion systems

Tritium technical issues for fusion:

- Tritium flow rates and inventories are large
- Most fusion blankets have high tritium **partial pressure**: (at blanket exit)
  DCLL~100 mPa, HCLL ~ 1000 Pa,
  DC Flibe ~ 380 Pa, He purge gas in solid breeders ~ 0.6 Pa
- The **temperature** of the blanket coolants and purges are high (500–700ºC)
- Surface area of heat exchanger is high, with thin walls
- Tritium is in **elementary form.**

These are perfect conditions for tritium permeation.

Scatter in T solubility measurements in PbLi (from Ricapito)



Source of variation is still not completely known (technique, surface effects, composition effects, impurity effects…)

Uncertainties are large

- Tritium fundamental behavior (solubility, diffusivity) in the many materials of blanket, coolants, processing systems not fully known
- Development and tests of tritium permeation barriers (in EU, up to 2003) have not yet been conclusive.
- The effects of multiple processes (transport, dissociation, diffusion, trapping, etc.); multiple materials, coolants and interfaces; and the synergistic effects of radiation are not completely characterized

MHD fluid Flow and Mass Transfer

Fluid-Material Interactions

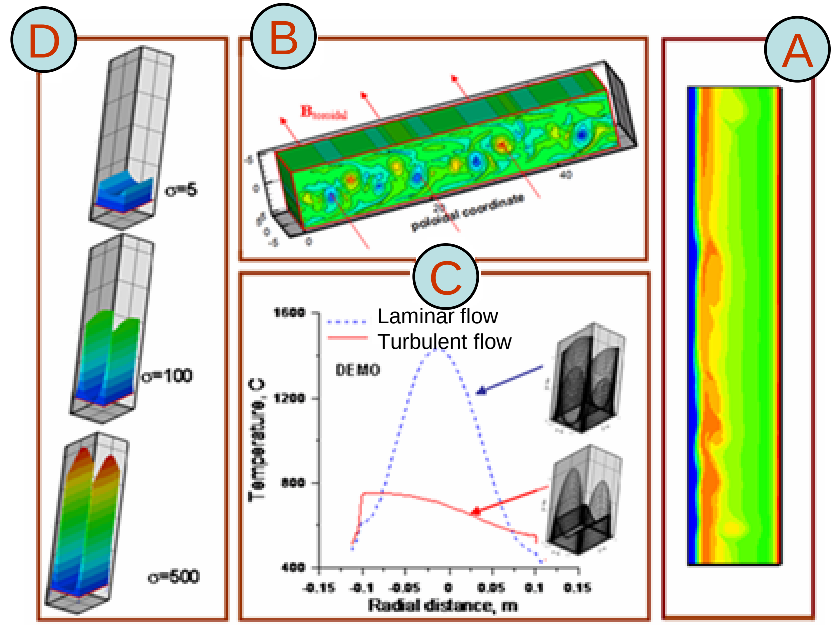
Interfacial Phenomena

Impressive Progress on MHD Fluid Flow

- Much better understanding and advances of phenomenological models for LM fluid flow in the fusion environment with magnetic field and nuclear heating.
- Major progress in developing computer codes for MHD fluid flow
  - 2-D codes Ha ~ 10^4 capability
  - **3-D codes for complex geometry:**

    Ha ~ 10^3

    (compared to Ha ~ 8 in 1988)
- Progress on MHD experiment: Good, but limited by relatively poor capabilities of existing facilities



A. Buoyancy forces associated with neutron heating cause intensive thermal convection.
B. MHD turbulence in blanket flows takes a special quasi-two-dimensional form.
C. Strong effect of turbulence on temperature in liquid and solid.
D. Typical MHD effect is formation of special "M-type" velocity profiles.

from S. Smolentsev (UCLA)

But, inadequate progress on modelling and experiments for mass transfer and the entire area of interfacial phenomena (fluid-material interactions)

Lessons learned: The most challenging problems in FNST are at the *INTERFACES*

- Examples:
  - **Corrosion** (liquid/structure interface temperature limit)
  - **Tritium permeation**
  - **MHD insulators**
  - **Thermal insulators**

- **This is where we had disappointments and our progress has been severely limited. The underlying physics is not well understood, hindering further progress towards higher performance blanket.**
- **We need *NEW APPROACH* for research on mass transfer, interfacial phenomena, and fluid-material interactions.**

Example: Corrosion – A serious issue for LM Blankets

- **At present, the interface temperature between PbLi and Ferritic steel is limited to < 470°C because of corrosion.**
- Such limits are derived from limited corrosion experiments with no magnetic field and very approximate modeling.
- Corrosion rate is highly dependent on temperature and velocity of LM.
- **Recent results from Riga show strong dependence of corrosion rate on magnetic field.**
- Corrosion deposition in the "cold section" is often the limiting criteria for determining the allowable interface temperature.
- **Corrosion includes many physical mechanisms that are currently not well understood** (dissolution of the metals in the liquid phase, chemical reactions of dissolved non-metallic impurities with solid material, transfer of corrosion products due to convection and thermal and concentration gradients, etc.).

- **We need new models and experiments that can predict corrosion rates and transport and deposition of corrosion products throughout the heat transport system.**
  - Need to account for MHD velocity profiles, complex geometry and temperature gradients in the "hot" and "cold" sections.

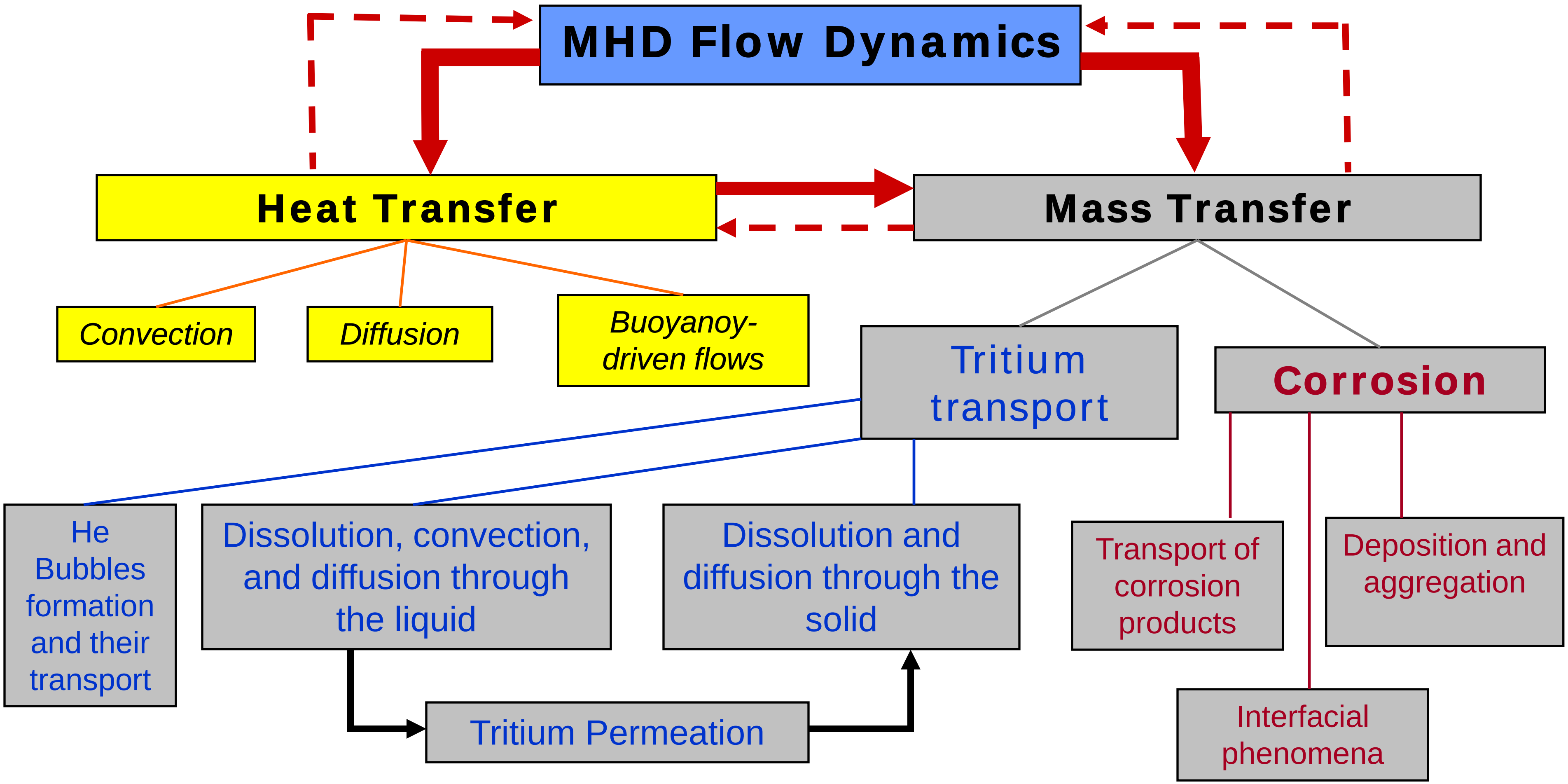
Corrosion rate for samples with and without a magnetic field

n	h_n , μm/year	
	$B_o = 0$	$B_o = 1.8$ T
1	523	967
2	458	877
3	381	694
4	293	846
5	388	726

Strong experimental evidence of significant effect of the applied magnetic field on corrosion rate.

From: F. Muktepavela et al. ***EXPERIMENTAL STUDIES OF THE STRONG MAGNETIC FIELD ACTION ON THE CORROSION OF RAFM STEELS IN Pb17Li MELT FLOWS*****, PAMIR 7, 2008**

Need More Substantial Effort on Modeling of *Interfacial Phenomena* (fluid-material interaction) Such effort must include fundamental phenomenological modeling as well as coupling/integration of MHD and heat and mass transfer, thermodynamics, and material properties



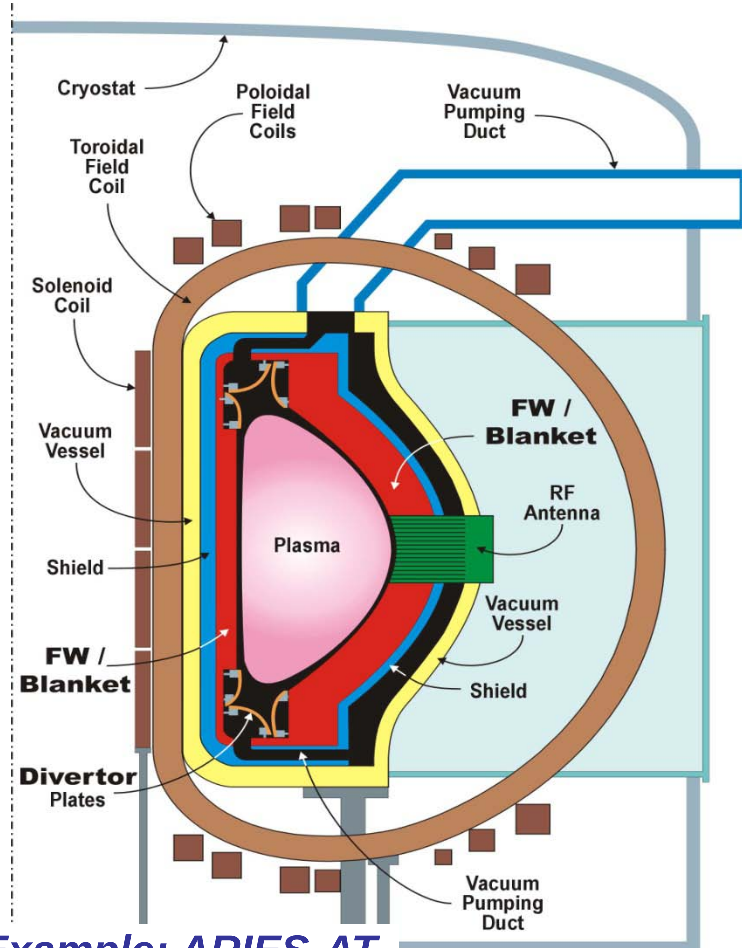
Also, ***experiments*** should progress from single effects to multiple effects in laboratory facilities and then to integrated tests in the fusion environment.

Interactions between plasma operation and blanket/PFC systems

Performance and requirements of both the Plasma and Blanket/PFC components are coupled in important ways

- Plasma / Surface Interactions – e.g. the plasma particle and energy incident on divertor / first wall surfaces modify the material, while impurities from and fuel retention in the surfaces strongly influence plasma operation
- Electromagnetic coupling – e.g. off-normal plasma events can generate large EM forces in blanket and PFC structures, while error fields generated from the use of ferritic steel structures can influence plasma confinement
- Spatial coupling and integration – e.g. space around the plasma must be shared by blankets and PFCs that capture energy and breed tritium, and plasma fueling & control systems, without impeding the function of either systems
- Tritium throughput and inventory – e.g. small T burn-up fraction leads to high tritium fueling rate and inventory, which increases T retention in PFC and the required TBR in the blanket

Blanket and PFC components are
- inside the vacuum vessel
- inside control coils, and in
- direct contact with the plasma



Example: ARIES-AT

ITER represents a large step forward in capability to investigate and understand Plasma/Blanket/PFC interactions

Issue/Parameter	Present Tokamaks	ITER	DEMO	Consequences
Energy exhaust (production) *GJ / day*	~ 10	3,000	60,000	- active cooling - max. tile thickness ~ 10 mm
Transient energy exhaust from plasma instabilities $\Delta T \sim \mathrm{MJ} / A_{\mathrm{wall}}\ (\mathrm{m}^2) / (1\ \mathrm{ms})^{1/2}$	~ 2	15	60	- require high $T_{\mathrm{melt/ablate}}$ - limit? ~ 40 for C and W - surface distortion
Yearly neutron damage in plasma-facing materials *displacements per atom*	~ 0	~ 0.5	20	- evolving material properties: thermal conductivity, swelling, traps for tritium
Max. gross material removal rate with 1% erosion yield *(mm / operational-year)*	< 1	300	3000	- must redeposit locally - limits lifetime - produces films
Tritium consumption *(g / day)*	< 0.02	20	500	- Tritium retention in materials and recovery

But even ITER uses blanket/FW/PFC designs, materials and temperatures that are not reactor relevant.

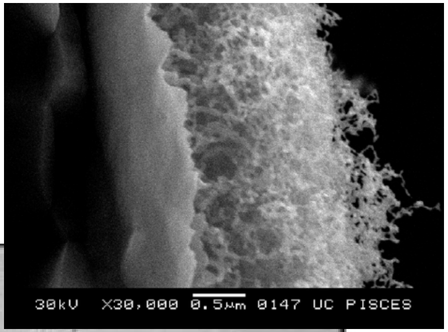
Table from Youchison, Nygren& Raffray (FNST Meeting , UCLA August 2009)

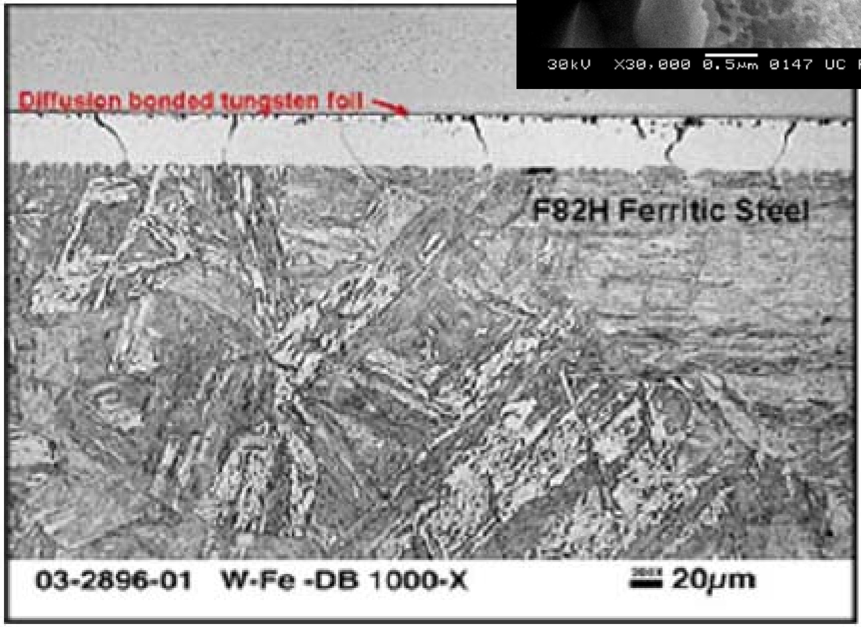
Developing practical systems and strategies that meet BOTH plasma & FNST requirements is a Challenge

- Ductile W, Armor joining
- Large scale low cost material production, fabrication, joining for RAFS and ODS RAFS
- Erosion, lifetime, W-fuzz, dust generation
- He flow control, instabilities, heat transfer enhancement, purity and tritium control
- Flaked and sputtered materials impacts on plasma, wall conditioning
- Extreme plasma transients and mitigation techniques
- Difficulty in simulating fusion conditions outside of a fusion device (thermal and EM loads)

Qualified materials do not exist for DEMO!

Examples of surface changes and layer cracking of W surfaces





Joint understanding of plasma and reactor relevant component behavior is necessary – e.g. evolving new concepts like Super-X Divertor

Summary

❑ Achieving high availability is a challenge for Magnetic Fusion Concepts

- Device has many components
- Blanket/PFC are located inside the vacuum vessel
- Maintenance time is too long and must be shortened
- Reliability requirements unprecedented, need aggressive “reliability growth” program

❑ Tritium available for fusion development other than ITER is rapidly diminishing

- Any DT fusion development facility other than ITER must breed its own tritium, making the Breeding Blanket an Enabling Technology
- Where will the initial inventory for the world DEMOs (~ 10 kg per DEMO) come from? How many DEMOs in the world?
- **Each country aspiring to build a DEMO will most likely need to build its own FNSF** — not only to have verified breeding blanket technology, but also to generate the initial tritium inventory required for the startup of DEMO.

❑ Achieving Tritium Self-Sufficiency in DT fusion systems imposes key requirements on Physics and Technology

- Tritium Burn-up fraction x fueling efficiency > 5%
- Tritium Processing time < 4 hours
- Practical breeding blanket with limited amount of structure, thin first wall, no significant neutron absorbers (e.g. no passive coils, etc), near full coverage

Concluding Remarks

- ITER is a major step forward. (So is NIF)
- **But, the most challenging phase of fusion development still lies ahead. It is the development of Fusion Nuclear Science and Technology (FNST).**
  - **FNST development will be the "time-controlling step" for fusion entry into the energy market.**
- **There has been substantial progress on understanding and resolving many FNST technical issues.** But there are critical issues for which there has been little or no progress because: 1- these issues represent major scientific and engineering challenges, and 2- the resources available for FNST R&D have been seriously limited.
- **The World Fusion Program must immediately launch an aggressive FNST R&D program if fusion energy is to be realized in the 21st century. It must include:**
  - **Fundamental modeling of important phenomena and multiple synergistic effects**
  - **Experiments in new and existing non-fusion facilities**
  - **TBM in ITER accompanied by both research and development programs.**
  - **A Fusion Nuclear Science Facility (FNSF) dedicated to FNST. FNSF is a small size, small power DT, driven-plasma device with Cu magnets**