

Fusion Nuclear Technology and Materials

R&D Challenges and Facilities Required for Fusion DEMO

Mohamed Abdou

Distinguished Professor of Engineering and Applied Science (UCLA)

Director, Center for Energy Science and Technology (UCLA)

Founding President, Council of Energy Research and Education Leaders, CEREL
(USA)

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R&D Challenges and Facilities Required for Fusion DEMO

Outline

- 1. DEMO Goal and Fusion Current Major Activities**
- 3. Fusion Nuclear Science and Technology (FNST) –
Introduction to functions, science and challenges**
 - Fusion environment and fusion nuclear components**
 - Blankets and Plasma-Facing components and Materials**
- 4. Fusion Materials Challenges**
- 5. FNST and Material Development Strategy**
- 6. Closing Remarks**

What is fusion?

- **Fusion powers the Sun and Stars.** Two light nuclei combine to form a heavier nuclei (the opposite of nuclear fission).

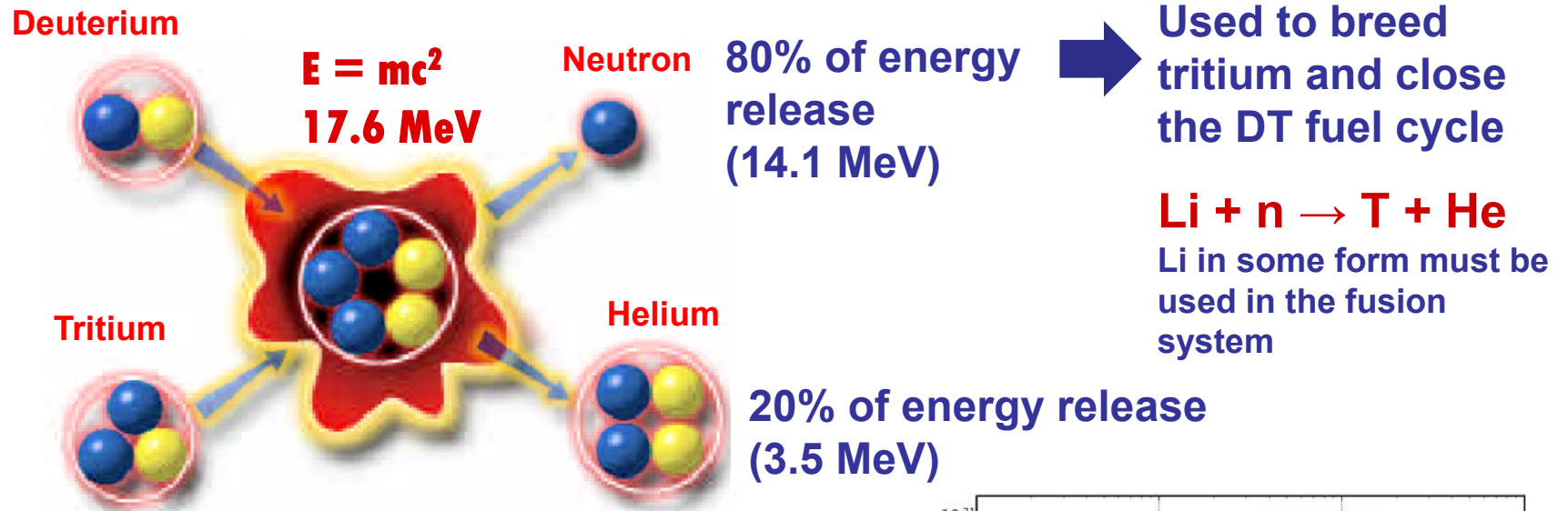
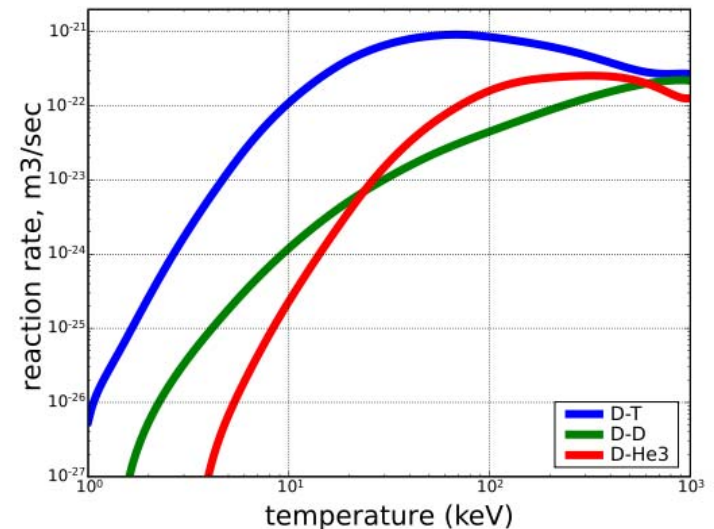


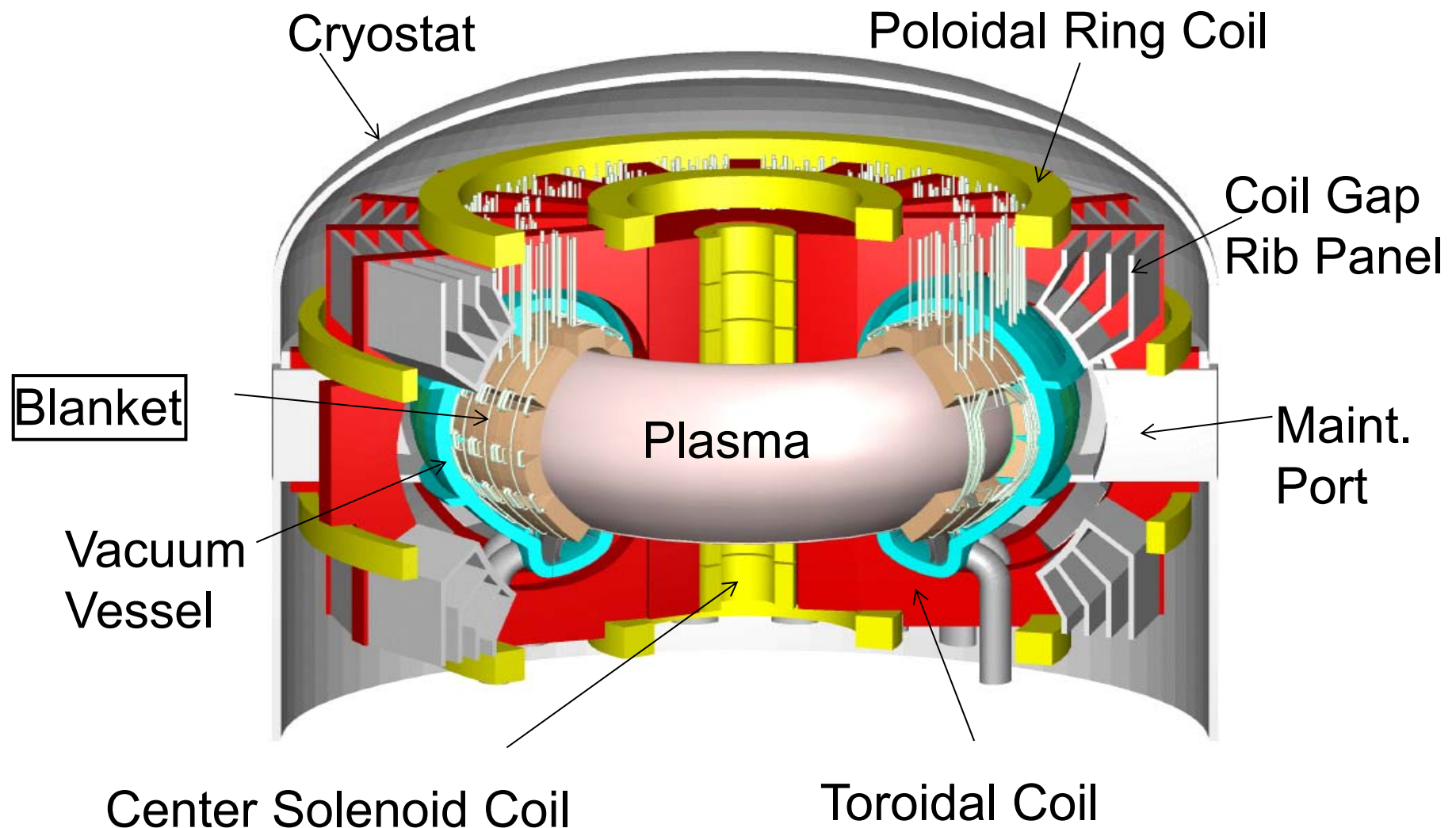
Illustration from DOE brochure

- Deuterium and tritium is the easiest, attainable at lower plasma temperature, because it has the largest reaction rate and high Q value.
- The World Program is focused on the D-T Cycle



The World Fusion Program has a Goal for a Demonstration Power Plant (DEMO) by ~2040(?)

Plans for DEMO are based on Tokamaks



(Illustration is from JAEA DEMO Design)

DEMO

A key goal of fusion plans in the world programs is the construction and operation of a demonstration power plant (Demo), which will enable the commercialization of fusion energy.

It is anticipated that several such fusion demonstration devices will be built around the world.

There are **variations** in Plans of World Fusion Programs as to:

- **WHEN** DEMO will be built
- Goals and Requirements for the **early phase** of DEMO operation

But there is agreement that DEMO must **ultimately** demonstrate the commercial practicality of fusion power.

The US addressed Goals and Requirements for DEMO in a “35-year plan” in 2003

Top-level goals for the fusion Demo (US)

Demonstrate a closed tritium fuel cycle

Safety and environmental impact:

- Not require an evacuation plan.
- Generate only low-level waste.
- Not disturb the public's day-to-day activities.
- Not expose workers to a higher risk than other power plants.

Economics:

- Demonstrate that the cost of electricity from a commercial fusion power plant will be competitive, and that other applications (e.g. hydrogen production, synthetic fuels, desalination) are also attractive.

Scalability:

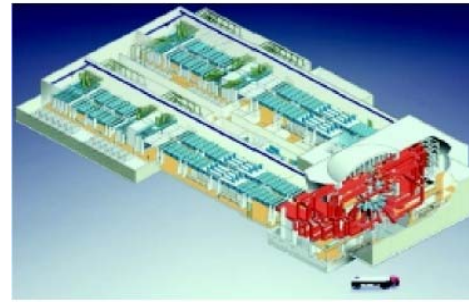
- Use the physics and technology anticipated for the first generation of commercial power plants.
- Be of sufficient size for confident scalability (>50%-75% of commercial).

Reliability:

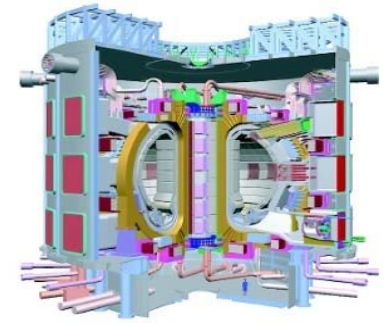
- Demonstrate remote maintenance of fusion core.
- Demonstrate routine operation with minimum number of unscheduled shutdowns per year.
- Ultimately achieve an availability > 50% and extrapolate to commercially practical levels.

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
 - $Q = (E_f / E_{\text{input}}) \sim 10$
 - ITER (MFE) and NIF (inertial fusion)
- 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)



National Ignition Facility



ITER

**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, prediction of the timescale of fusion entry into the energy market is difficult

Fusion Nuclear Science and Technology (FNST)

FNST is the science, engineering, technology and materials for the fusion nuclear components that generate, control and utilize neutrons, energetic particles & tritium.

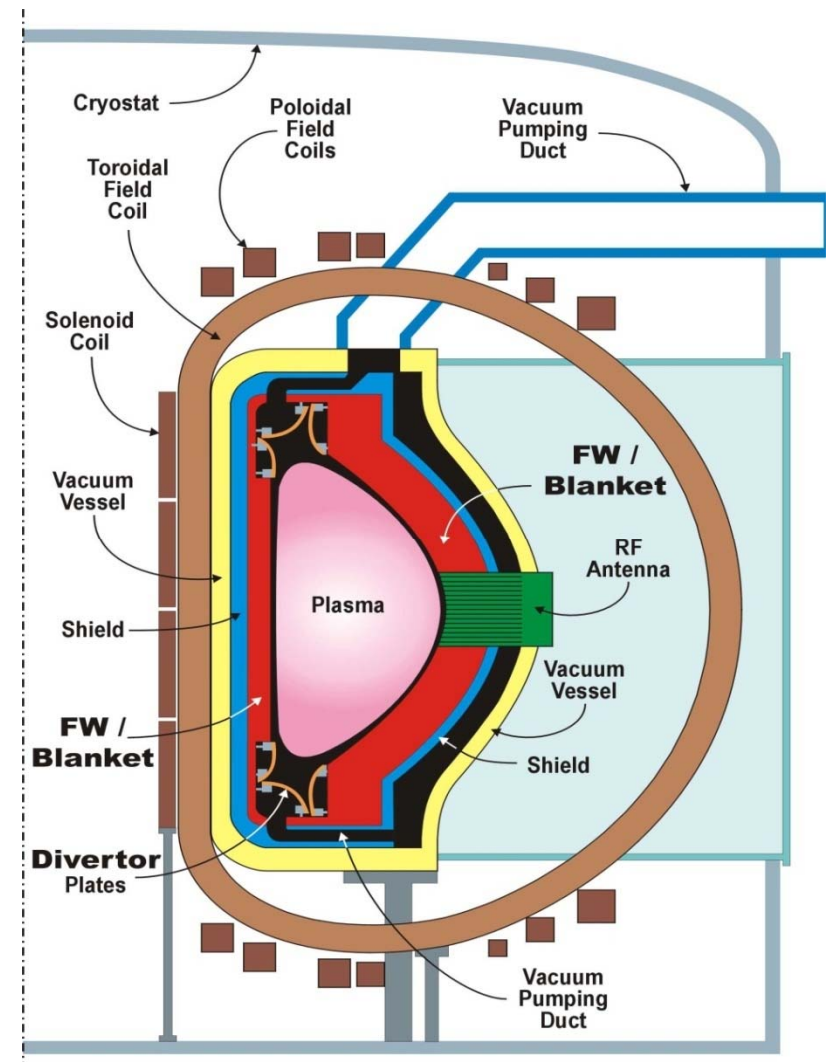
Inside the Vacuum Vessel

“Reactor Core”:

- **Plasma Facing Components**
divertor, limiter and nuclear aspects of plasma heating/fueling
- **Blanket (with first wall)**
- **Vacuum Vessel & Shield**

Other Systems / Components affected by the Nuclear Environment:

- Tritium Fuel Cycle
- Instrumentation & Control Systems
- Remote Maintenance Components
- Heat Transport & Power Conversion Systems



Fusion Nuclear Science and Technology (FNST)

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Inside the Vacuum Vessel “Reactor Core”:

- **Plasma Facing Components**
divertor, limiter and nuclear aspects of plasma heating/fueling
- **Blanket (with first wall)**
- **Vacuum Vessel & Shield**

Example of FNST challenge in the “core”

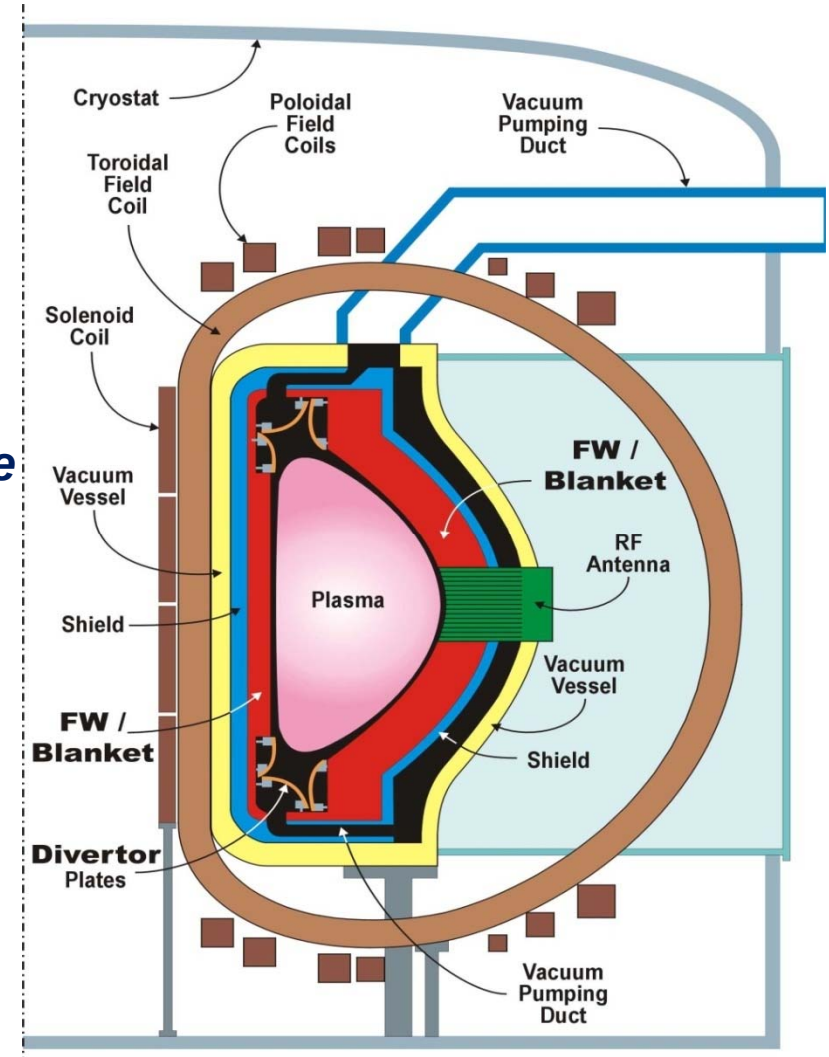
The location of the Blanket / Divertor inside the vacuum vessel is necessary but has major consequences:

a- many failures (e.g. coolant leak) require immediate shutdown

Low fault tolerance, short MTBF

b- repair/replacement take a long time

Attaining high Device “Availability” is a Challenge!!



Fusion Nuclear Environment is Complex & Unique

Neutrons (*flux, spectrum, gradients, pulses*)

- Radiation Effects
- Bulk Heating
- Tritium Production
- Activation and Decay Heat

Heat Sources (*thermal gradients, pulses*)

- Bulk (neutrons)
- Surface (particles, radiation)

Particle / Debris Fluxes (*energy, density, gradients*)

Magnetic Fields (*3-components, gradients*)

- Steady and Time-Varying Field

Mechanical Forces

- Normal (*steady, cyclic*) and Off-Normal (*pulsed*)

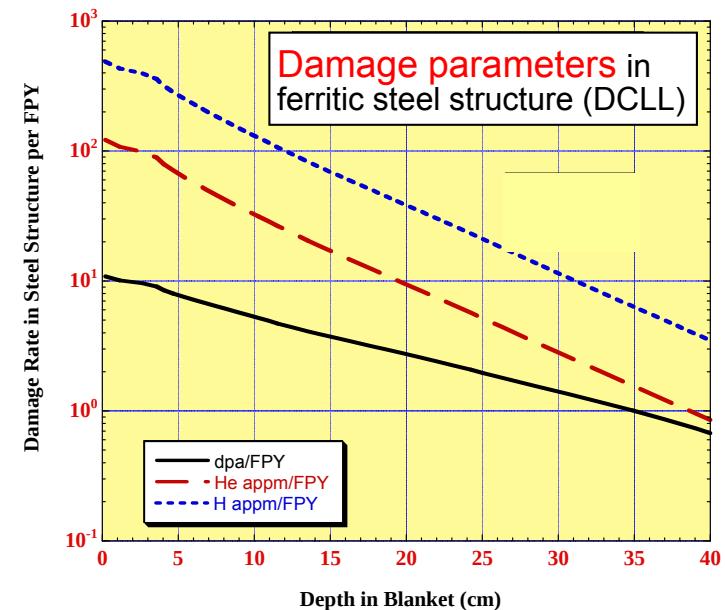
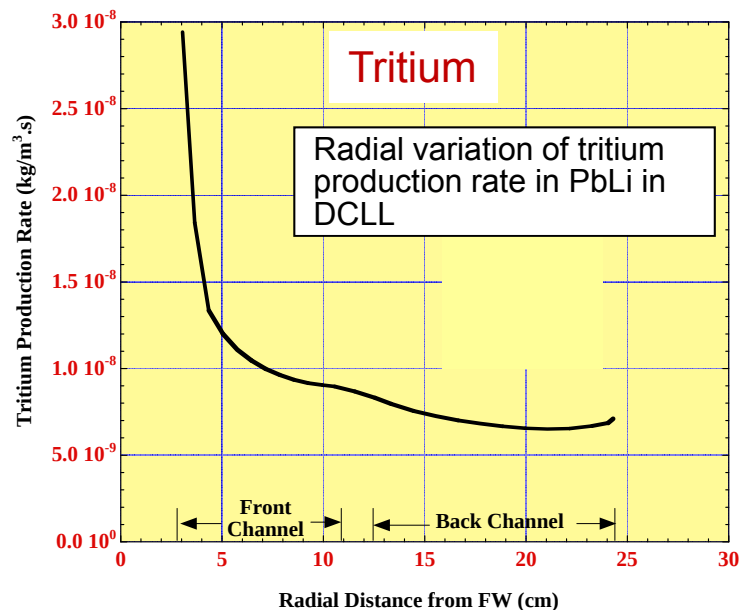
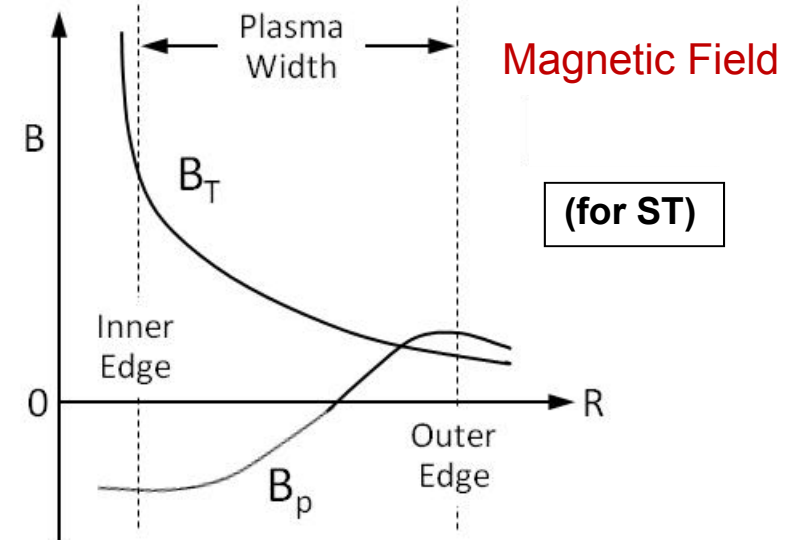
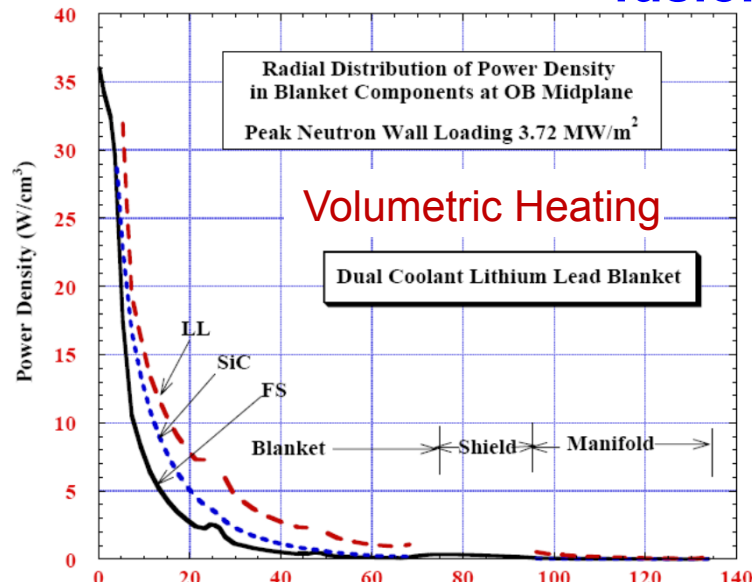
Multiple functions, materials,
and many interfaces in highly
constrained system

Combined Loads, Multiple Environmental Effects

- Thermal-chemical-mechanical-electrical-magnetic-nuclear interactions and synergistic effects
- Interactions among physical elements of components

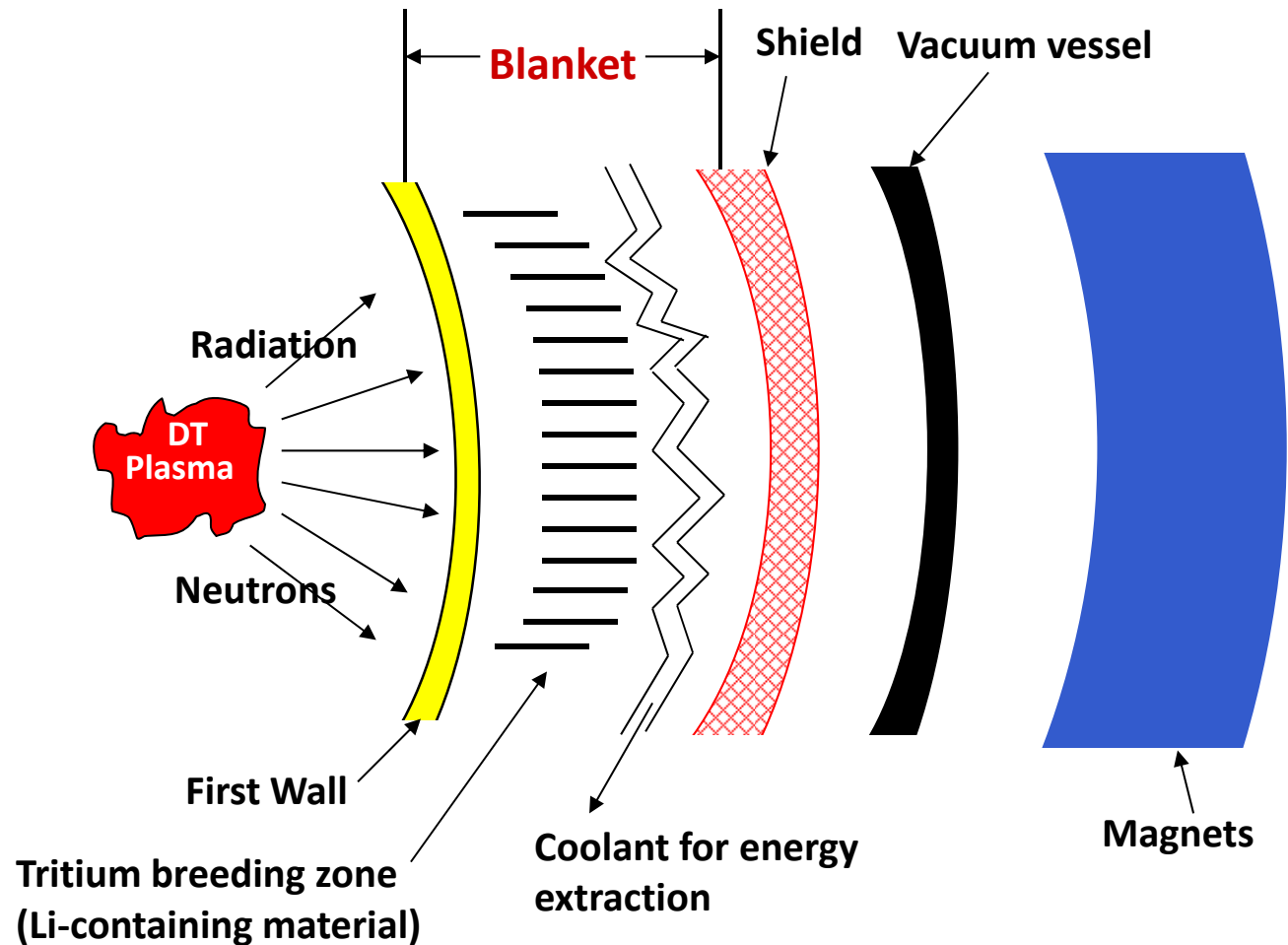
Non-fusion facilities (Laboratory experiments) need to be substantial to simulate multiple effects
Simulating nuclear **bulk heating in a large volume** is the most difficult and is most needed
Most phenomena are temperature (and neutron-spectrum) dependent– it needs DT fusion facility
The full fusion Nuclear Environment can be simulated only in DT plasma–based facility

There are strong GRADIENTS in the multi-component fields of the fusion environment



These gradients play a major role in the behavior of fusion nuclear components. They can be simulated only in DT plasma-based facility.

The primary functions of the blanket are to provide for: Power Extraction & Tritium Breeding



- Liquid metals (Li, PbLi) are strong candidates as breeder/coolant.
- Ceramic Breeders with He cooling are also strong candidates.

Classes of Blanket Concepts

(many concepts proposed worldwide)

A. Solid Breeder Concepts

- Solid Breeder: Lithium Ceramic (Li_2O , Li_4SiO_4 , Li_2TiO_3 , Li_2ZrO_3)
- Neutron Multiplier: Be or Be_{12}Ti
- Coolant: Helium or Water

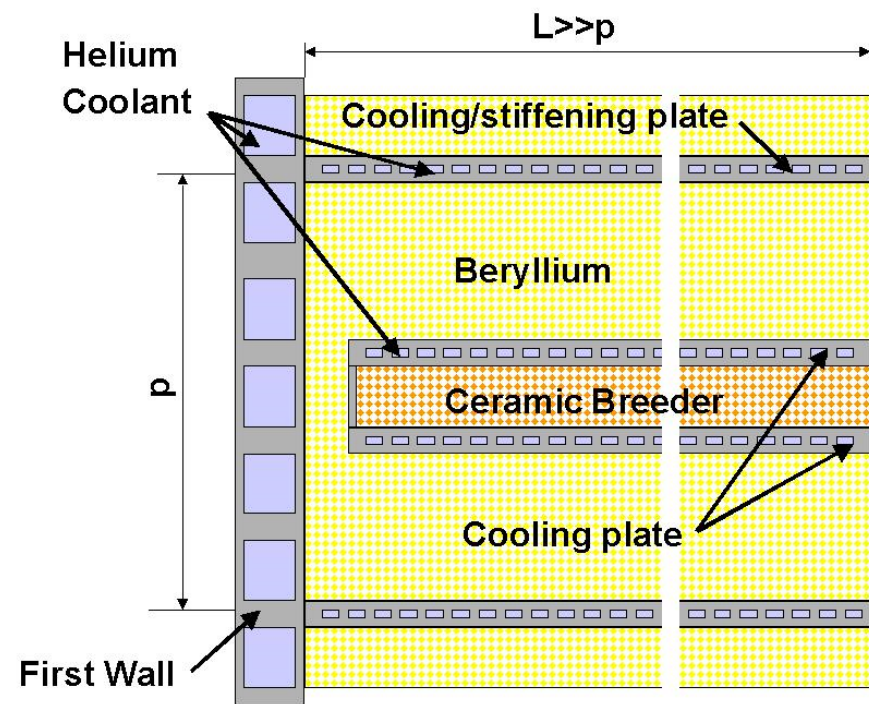
B. Liquid Breeder Concepts

Liquid breeder can be:

- a) **Liquid metal** (high electrical/thermal conductivity, low viscosity):
Li, or PbLi
- b) **Molten salt** (low electrical/thermal conductivity, high viscosity):
Flibe (LiF)_n · (BeF_2), Flinabe (LiF - BeF_2 - NaF)

A Helium-Cooled Li-Ceramic Breeder Concept : Example

- **High pressure Helium** cooling in structure (ferritic steel)
- **Ceramic breeder** (Li_4SiO_4 , Li_2TiO_3 , Li_2O , etc.) for tritium breeding
- **Beryllium** (pebble bed) for neutron multiplication
- **In-situ tritium removal*** with **Helium purge** (low pressure) to remove tritium through the “interconnected porosity” in ceramic breeder

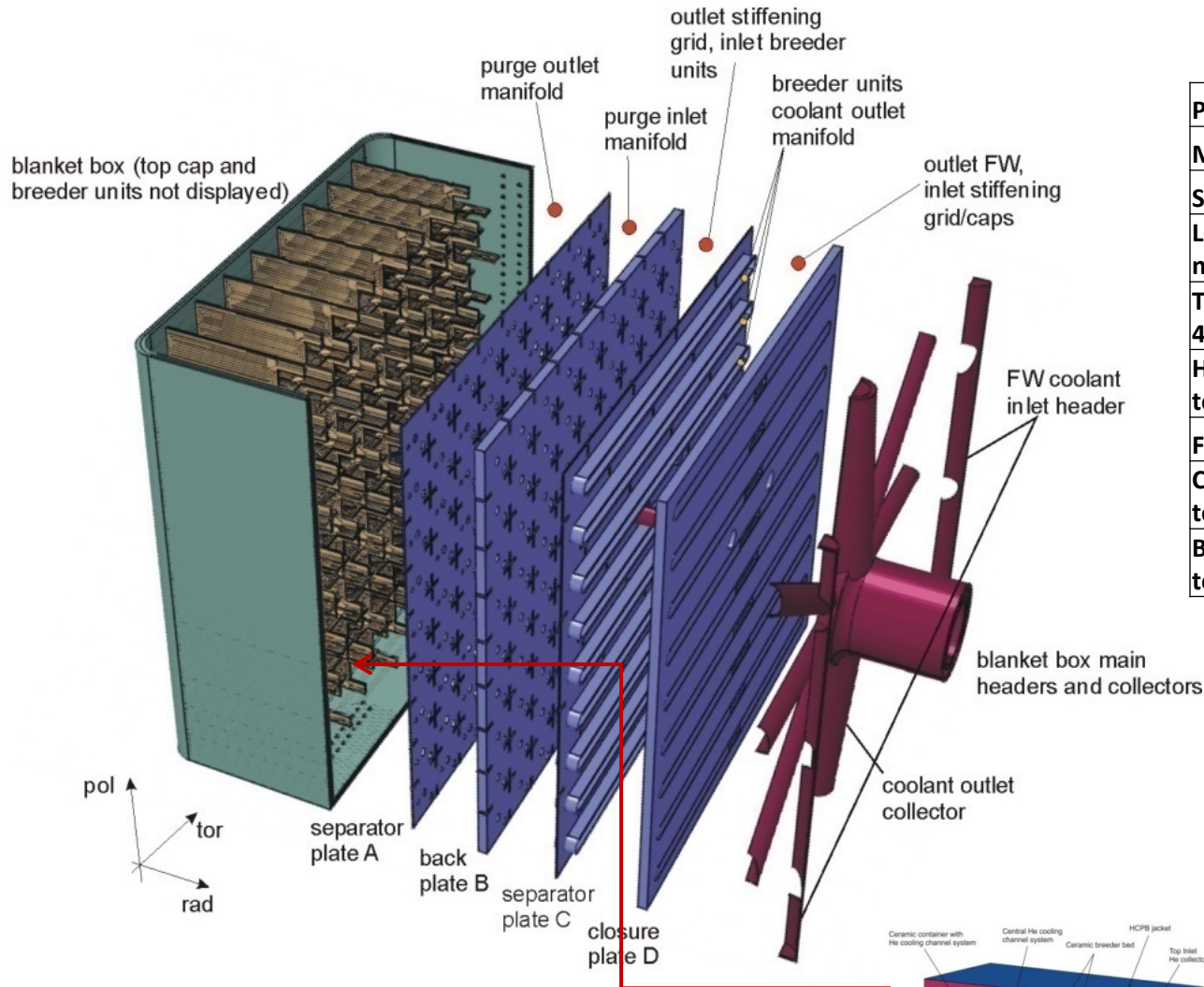


Several configurations exist (e.g. wall parallel or “head on” breeder/Be arrangements)

- * “In-situ” is necessary to keep tritium inventory in the system low.
“Batch” processing is not appropriate for fusion (>150 kg/yr 1000MWe fusion power plant).

Helium-Cooled Pebble Bed Module Structural Configuration

EU HCPB DEMO



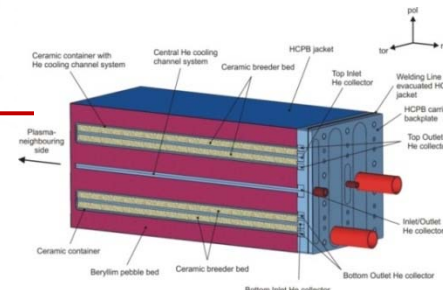
Breeder Unit to be inserted into the space between the grid plates

Plant fusion power	3300 MW
Mid-plane neutron wall load	2.24 MW/m ²
Surface heat flux	0.5 MW/m ²
Local blanket energy multiplication	1.25
Tritium Breeding Ratio (with 40% ⁶ Li enrichment and 46 cm)	1.14
Helium coolant inlet/outlet temperature	300 - 500°C
FW maximum temperature	550°C
Ceramic breeder pebble bed temperature	400-920°C
Beryllium pebble bed temperature	400-650°C

Tritium Inventory*

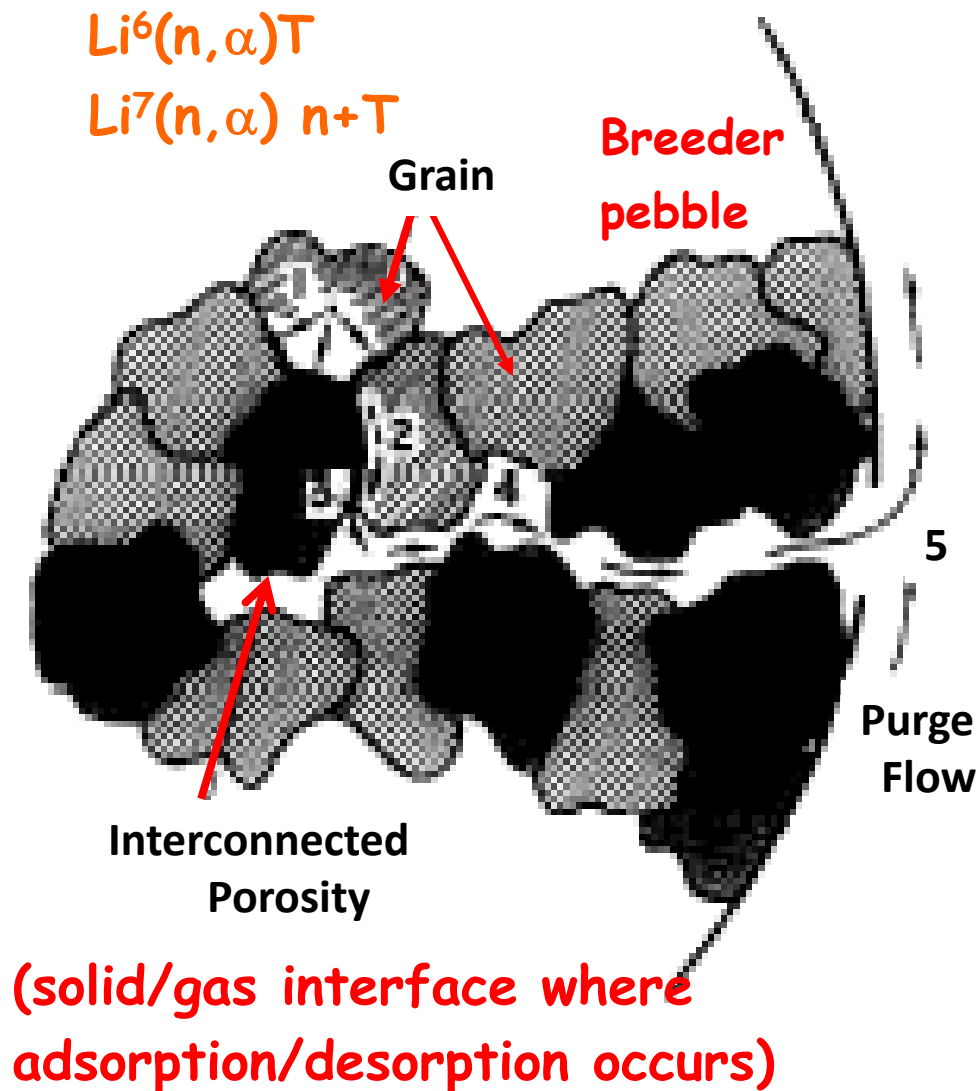
Ceramic: earlier estimation gave ~250 g in Li₄SiO₄

Beryllium: Low production of T, but high uncertainties in the effective release rate. It is still an open issue, R&D is ongoing in EU.



*L.V. Boccaccini, The concept of the breeding blanket for T-self sufficiency, comparison of different schemes, SOFT 25, Sep. 18, 2008

Mechanisms of tritium transport (for solid breeders)



Mechanisms of tritium transport

- 1) Intragranular diffusion
- 2) Grain boundary diffusion
- 3) Surface Adsorption/desorption
- 4) Pore diffusion
- 5) Purge flow convection

Purge gas composition:

$\text{He} + 0.1\% \text{H}_2$

Tritium release composition:

$\text{T}_2, \text{HT}, \text{T}_2\text{O}, \text{HTO}$

Reference: G. Federici, Ph.D. Dissertation, University of California at Los Angeles (October 1989); UCLA-FNT-30 Report (November 1989).

“Temperature Window” for Solid Breeders

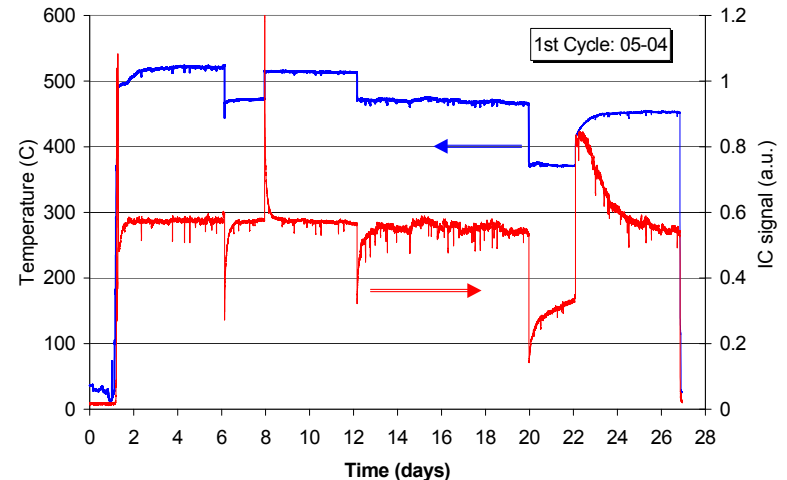
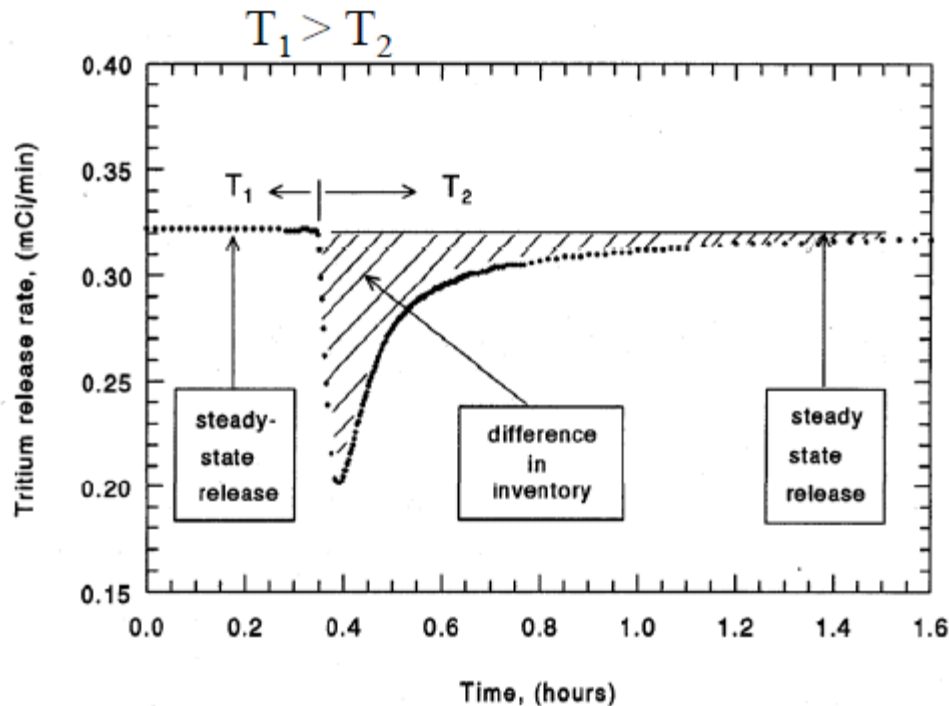
- The operating temperature of the solid breeder is limited to an acceptable “temperature window”: $T_{\min} - T_{\max}$
 - $T_{\min}$, lower temperature limit, is based on acceptable tritium transport characteristics (typically bulk diffusion). Tritium diffusion is slow at lower temperatures and leads to unacceptable tritium inventory retained in the solid breeder
 - $T_{\max}$, maximum temperature limit, to avoid sintering (thermal and radiation-induced sintering) which could inhibit tritium release; also to avoid phase change/mass transfer (e.g., LiOT vaporization)
- Low k (*thermal conductivity*), combined with the allowable operating “temperature window” for solid breeders, results in:
 - **Limitations on power density**, especially behind first wall and next to the neutron multiplier (limits on wall load and surface heat flux)
 - **Limits on achievable tritium breeding ratio** (beryllium must always be used; still TBR is limited) because of increase in structure-to-breeder ratio
 - Higher “effective” k is obtainable with a homogenous mixture of ceramic breeder (low k) and Be_{12}Ti (high k)

Many irradiation experiments were performed in fission reactors to quantify tritium release characteristics for various ceramic breeders

Recent experiment: EXOTIC 9/1 (EXtraction Of Tritium In Ceramics) in HFR-Petten with in-pile gas purge to quantify tritium release behavior. (The average total ^6Li burn-up is 3%. The total measured activity from tritium during irradiation is 220.42 Ci.)

Method (The **temperature step** technique is usually adopted to study in-pile tritium release kinetics)

In-pile tritium release data
Temperature varies between 340 and 580 °C

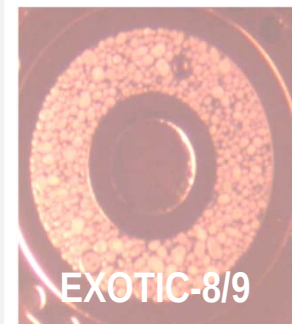
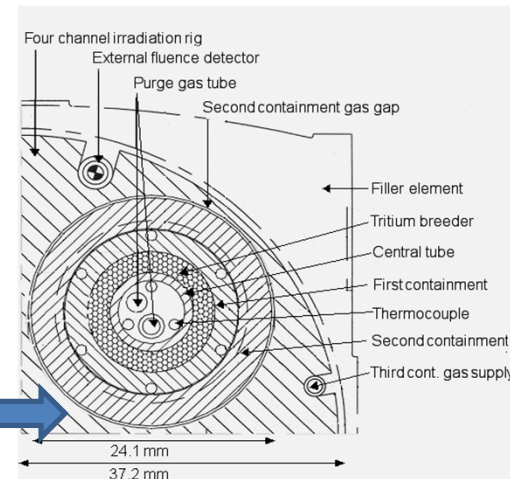


determine Tritium residence (τ):

$$\tau = \frac{I}{G}$$

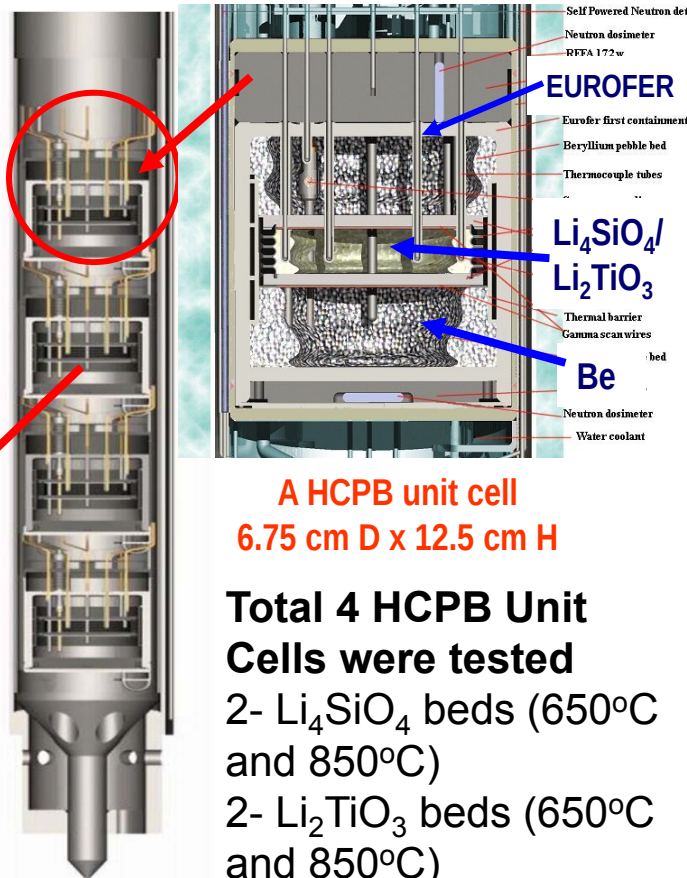
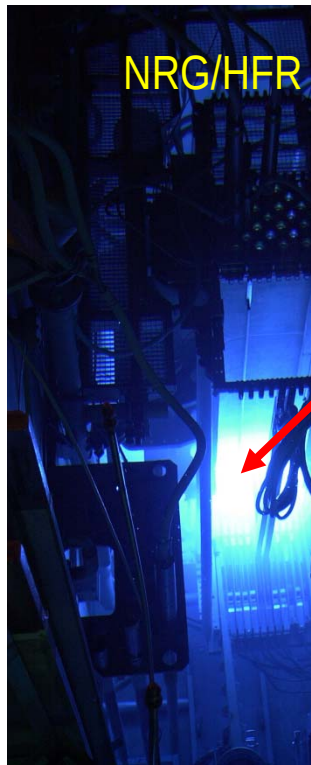
I = tritium inventory (mCi)
 G = tritium production rate (mCi/min)

Annular breeder pebble-bed, modest radial temperature gradient, 120 mm stack height



Neutron irradiation experiments in fission reactors were also performed to study thermal-mechanical behavior of EU HCPB unit cell at DEMO relevant temperatures and mechanical constraints

Example: Pebble bed assembly (PBA) test



A HCPB unit cell
6.75 cm D x 12.5 cm H

Total 4 HCPB Unit Cells were tested
2- Li_4SiO_4 beds (650°C and 850°C)
2- Li_2TiO_3 beds (650°C and 850°C)



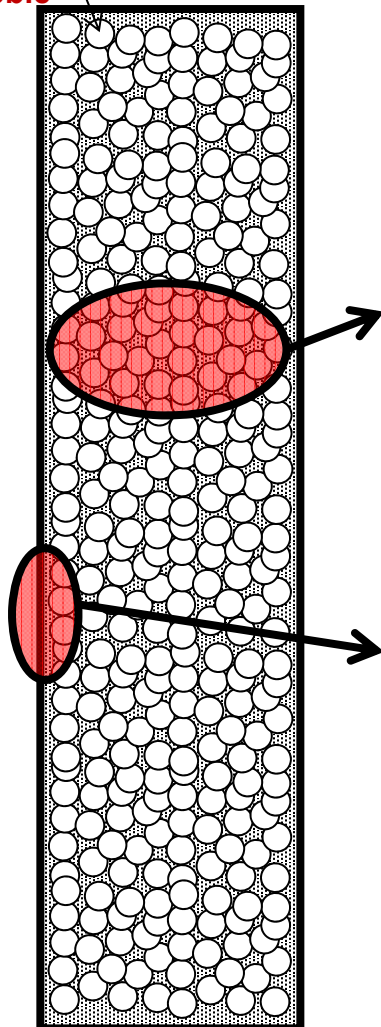
End of Irradiation of the PBA (ITER testing EOL)

- PBA has been operated in-pile for 12 irradiation cycles, 300 FPD
- Accumulate in 12 cycles, or 7200 hours:
 - 8×10^{22} at T production
 - Lithium burn ups 2 to 3%
 - ~2 dpa in Eurofer

- Experimental results with Li_4SiO_4 pebble bed qualitatively benchmarks FEM predicted stress/strain gradients.

Material Database for Solid Breeder Blanket Pebble Bed Thermo-mechanics

Ceramic breeder or Be pebble



Pebble bed schematics

Pebble bed thermo-physical and mechanical data

- (1) Effective thermal conductivity
- (2) Effective modulus
- (3) Thermal creep correlation
- (4) Effective thermal expansion rate
- (5) Pebble failure data
- (6) Increase of effective thermal conductivity with compressive and creep strain
- (7) criteria of pebble surface roughness and sphericity

Pebble bed – wall interface thermo-mechanical data

- (1) Heat conductance
- (2) Friction coefficient

Modeling and analysis method

- (1) Modification of **continuous model** for large scale analysis
- (2) Discrete Element Method (**DEM**) for investigation of contact characteristics

Liquid Breeder Blanket Concepts

1. Self-Cooled

- Liquid breeder circulated at high speed to serve as coolant
- Concepts: Li/V, Flibe/advanced ferritic, flinabe/FS

2. Separately Cooled

- A separate coolant, typically helium, is used. The breeder is circulated at low speed for tritium extraction.
- Concepts: LiPb/He/FS, Li/He/FS

3. Dual Coolant

- First Wall (highest heat flux region) and structure are cooled with a separate coolant (helium). The idea is to keep the temperature of the structure (ferritic steel) below 550°C, and the interface temperature below 480°C.
- The liquid breeder is self-cooled; i.e., in the breeder region, the liquid serves as breeder and coolant. The temperature of the breeder can be kept higher than the structure temperature through design, leading to higher thermal efficiency.

Flows of electrically conducting coolants will experience complicated **MHD** effects in the magnetic fusion environment 3-component magnetic field and complex geometry

- Motion of a conductor in a magnetic field produces an EMF that can **induce current** in the liquid. This must be added to Ohm's law:

$$\mathbf{j} = \sigma(\mathbf{E} + \mathbf{V} \times \mathbf{B})$$

- Any induced current in the liquid results in an additional **body force** in the liquid that usually opposes the motion. This body force must be included in the Navier-Stokes equation of motion:

$$\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \nabla) \mathbf{V} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{V} + \mathbf{g} + \frac{1}{\rho} \mathbf{j} \times \mathbf{B}$$

- For **liquid metal coolant**, this body force can have dramatic impact on the flow: e.g. **enormous MHD drag**, highly distorted velocity profiles, non-uniform flow distribution, modified or suppressed turbulent fluctuations.

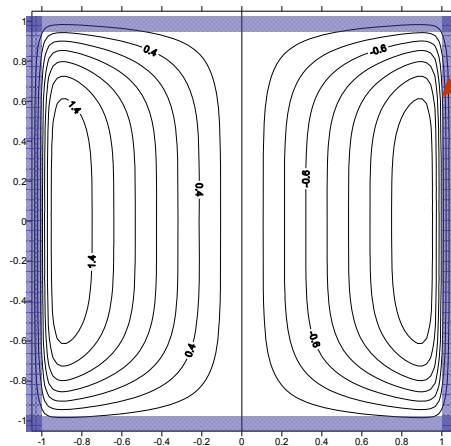
Dominant impact on LM design.

Challenging Numerical/Computational/Experimental Issues

**Self-Cooled liquid Metal
Blankets are NOT feasible now
because of MHD Pressure Drop.**

**A perfectly insulated “WALL”
can solve the problem, but is it
practical?**

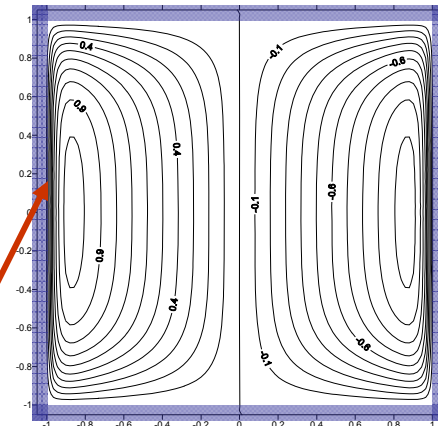
Conducting walls



Lines of current enter the low resistance wall – leads to very high induced current and high pressure drop

All current must close in the liquid near the wall – net drag from $j \times B$ force is zero

Insulated walls



- Net $J \times B$ body force

$$\nabla p = VB^2 t_w \sigma_w / a$$
- For high magnetic field and high speed (self-cooled LM concepts in inboard region) the pressure drop is large
- The resulting stresses on the wall exceed the allowable stress for candidate structural materials

- Perfect insulators make the net MHD body force zero
- But insulator coating crack tolerance is very low ($\sim 10^{-7}$).
 - It appears impossible to develop practical insulators under fusion environment conditions with large temperature, stress, and radiation gradients
- Self-healing coatings have been proposed but none has yet been found (research is on-going)

Impact of MHD and no practical Insulators: No self-cooled blanket option

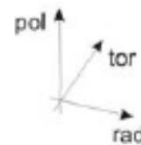
Separately-cooled LM Blanket

Example: PbLi Breeder / Helium Coolant with RAFM

- EU mainline blanket design
- **All energy removed by separate Helium coolant**
- *The idea is to avoid MHD issues*
But, PbLi must still be circulated to extract tritium
- **ISSUES:**
 - Low velocity of PbLi leads to high tritium partial pressure, which leads to tritium permeation (Serious Problem)
 - T_{out} limited by PbLi compatibility with RAFM steel structure ~ 470 C (and also by limit on Ferritic, ~ 550 C)
- **Possible MHD Issues :**
 - MHD pressure drop in the inlet manifolds
 - B- Effect of MHD buoyancy-driven flows on tritium transport

Module box
(container & surface
heat flux extraction)

**Breeder cooling
unit** (heat extraction
from PbLi)



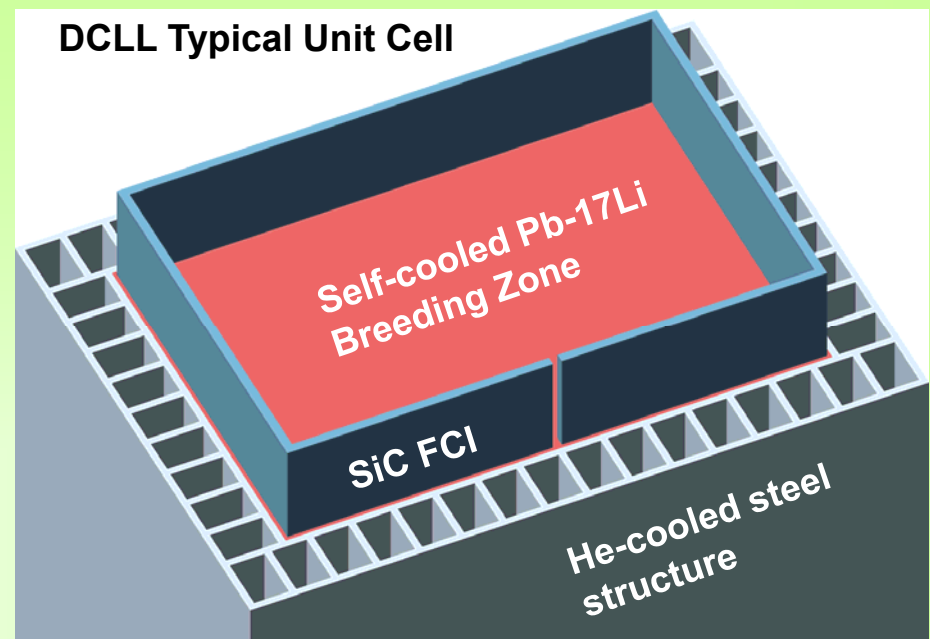
Stiffening structure
(resistance to accidental in-box
pressurization i.e., He leakage)

He collector system
(back)

**Drawbacks: Tritium
Permeation and limited
thermal efficiency**

Pathway Toward Higher Temperature Through Innovative Designs with Current Structural Material (Ferritic Steel): *Dual Coolant Lead-Lithium (DCLL) FW/Blanket Concept*

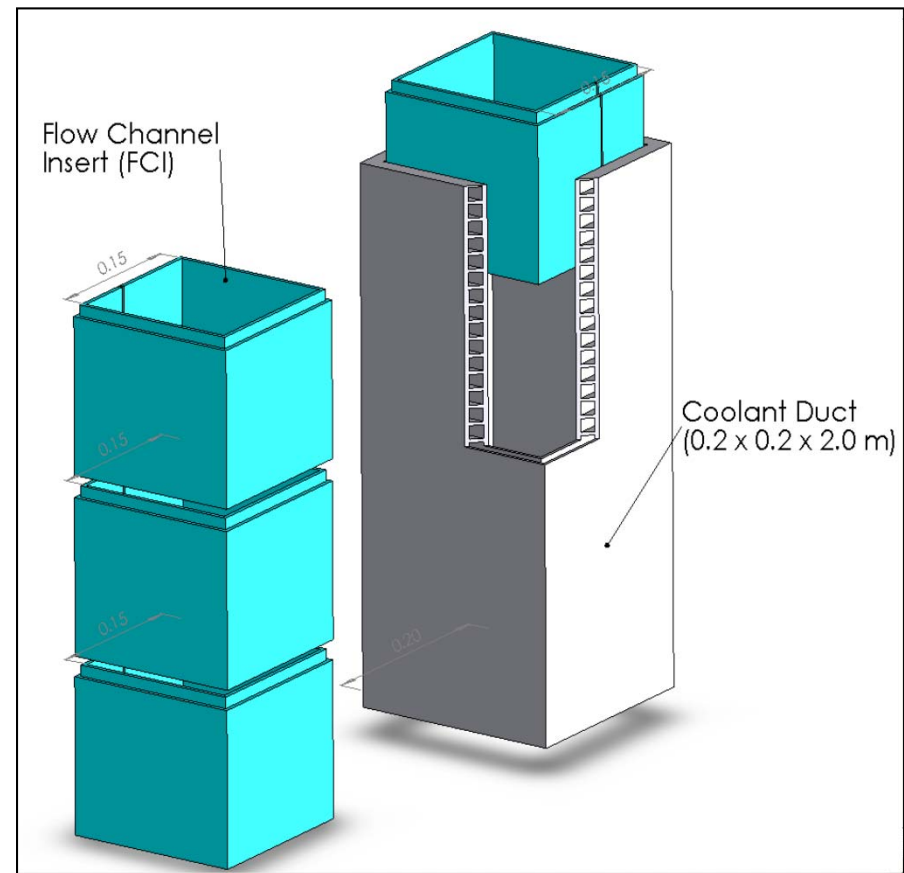
- ❑ First wall and ferritic steel structure cooled with helium
- ❑ Breeding zone is self-cooled
- ❑ Structure and Breeding zone are separated by SiCf/SiC composite *flow channel inserts (FCIs)* that
 - ❖ Provide thermal insulation to decouple PbLi bulk flow temperature from ferritic steel wall
 - ❖ Provide electrical insulation to reduce MHD pressure drop in the flowing breeding zone



Pb-17Li exit temperature can be significantly higher than the operating temperature of the steel structure ⇒ High Efficiency

Flow Channel Inserts are a critical element of the high outlet temperature DCLL

- FCIs are roughly box channel shapes made from some material with low electrical and thermal conductivity
 - SiC/SiC composites and SiC foams are primary candidate materials
- They will *slip* inside the He Cooled RAFS structure, but not be rigidly attached
- They will slip fit over each other, but not be rigidly attached or sealed
- FCIs may have a thin slot or holes in one wall to allow better pressure equalization between the PbLi in the main flow and in the gap region
- FCIs in front channels, back channels, and access pipes will be subjected to different thermal and pressure conditions; and will likely have different designs and thermal and electrical property optimization



R&D ISSUES of PbLi BLANKETS

- MHD pressure drop and flow distribution / balancing
- T permeation
- SiC FCI related issues (e.g., insulation, thermal stress, degradation of thermophysical properties under neutron irradiation)
- Compatibility between PbLi and structural and functional materials in the presence of a strong magnetic field
- Limits on operating temperature, re-deposition of radioactive corrosion products in the transport/HX system; clogging of the LM tract with corrosion products

Experiments in Riga (funded by Euratom)

Show Strong Effect of the Magnetic Field on Corrosion (Results for Ferritic Steel in PbLi)

Macrostructure of the washed samples
after contact with the PbLi flow



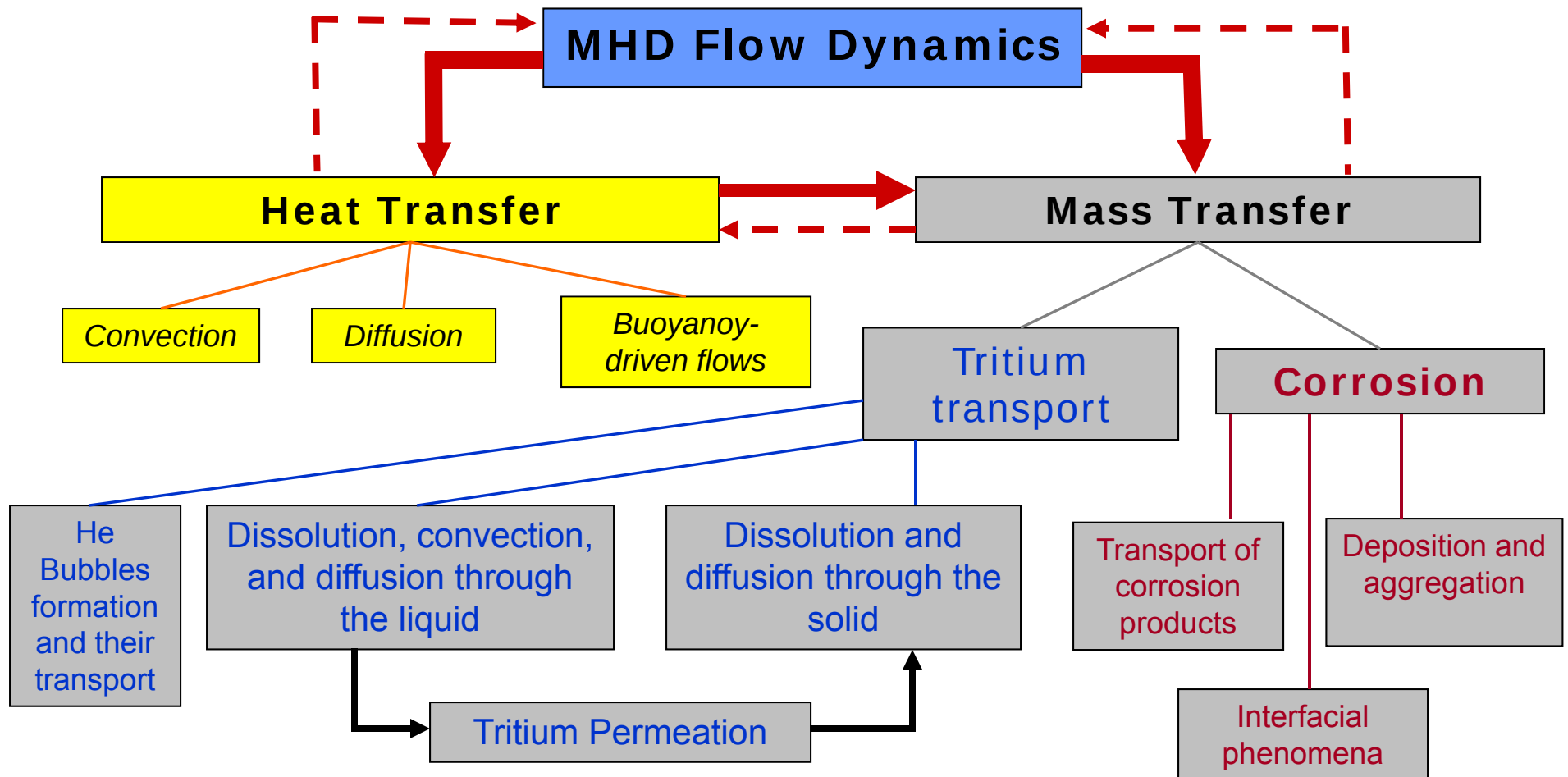
From: F. Muktepavela et al. *EXPERIMENTAL STUDIES OF THE STRONG MAGNETIC FIELD ACTION ON THE CORROSION OF RAFM STEELS IN Pb17Li MELT FLOWS*, PAMIR 7, 2008

Corrosion rate h_n for samples
without and with magnetic field

n	h_n , $\mu\text{m/year}$	
	$B_0 = 0$	$B_0 = 1.8 \text{ T}$
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. The underlying physical mechanism has not been fully understood yet.

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.

Lessons learned:

The most challenging problems in FNST are at the *INTERFACES*

- Examples:
 - **MHD insulators**
 - **Thermal insulators**
 - **Corrosion** (liquid/structure interface temperature limit)
 - **Tritium permeation**
- Research on these interfaces **must integrate the many technical disciplines of fluid dynamics, heat transfer, mass transfer, thermodynamics and material properties in the presence of the multi-component fusion environment** (must be done jointly by blanket and materials researchers)

Top-Level Technical Issues for FNST (set 1 of 2)

(Details of these issues published in many papers, Last update: December 2009)

Tritium

1. “Phase Space” of practical plasma, nuclear, material, and technological conditions in which tritium self sufficiency can be achieved
2. Tritium extraction, inventory, and control in solid/liquid breeders and blanket, PFC, fuel injection and processing, and heat extraction systems

Fluid-Material Interactions

3. MHD Thermofluid phenomena and impact on transport processes in electrically-conducting liquid coolants/breeders
4. Interfacial phenomena, chemistry, compatibility, surface erosion and corrosion

Materials Interactions and Response

5. Structural materials performance and mechanical integrity under the effect of radiation and thermo-mechanical loadings in blanket/PFC
6. Functional materials property changes and performance under irradiation and high temperature and stress gradients (including HHF armor, ceramic breeders, beryllium multipliers, flow channel inserts, electric and thermal insulators, tritium permeation and corrosion barriers, etc.)
7. Fabrication and joining of structural and functional materials

Top-Level Technical Issues for FNST (set 2 of 2)

Plasma-Material Interactions

- 8. Plasma-surface interactions, recycling, erosion/redeposition, vacuum pumping**
- 9. Bulk interactions between plasma operation and blanket and PFC systems, electromagnetic coupling, and off-normal events**

Reliability, Availability, Maintainability (RAMI)

- 10. Failure modes, effects, and rates in blankets and PFC's in the integrated fusion environment**
- 11. System configuration and remote maintenance with acceptable machine down time**

All issues are strongly interconnected:

- they span requirements**
- they span components**
- they span many technical disciplines of science & engineering**

Reliability/Availability/Maintainability/Inspectability (RAMI) is a Serious Issue for Fusion Development (table from Sheffield et al)

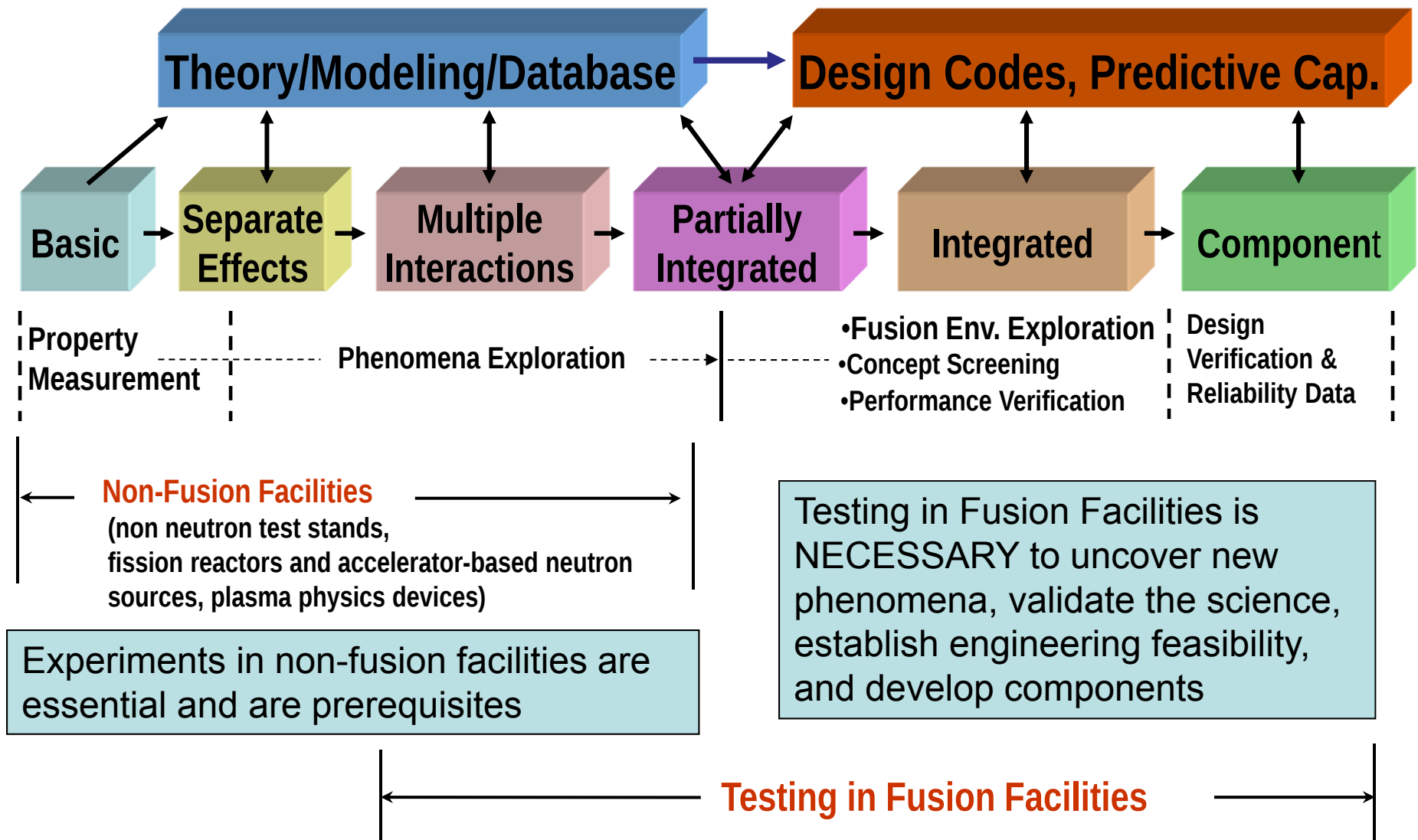
Availability required for each component needs to be high								
Component	#	failure rate (1/hr)	MTBF (yrs)	MTTR/type		Fraction Failures Major	Outage Risk	Component Availability
				Major (hrs)	Minor (hrs)			
Toroidal	16	5×10^{-6}	23	10^4	240	0.1	0.098	0.91
Two key parameters: MTBF – Mean time between failures MTTR – Mean time to repair								
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							0.884
Fueling	1							0.998
Tritium System	1							0.995
Vacuum	3							0.998
Conventional equipment								0.952
TOTAL SYSTEM (Due to unscheduled maintenances)							0.624	0.615

DEMO availability of 50% requires:

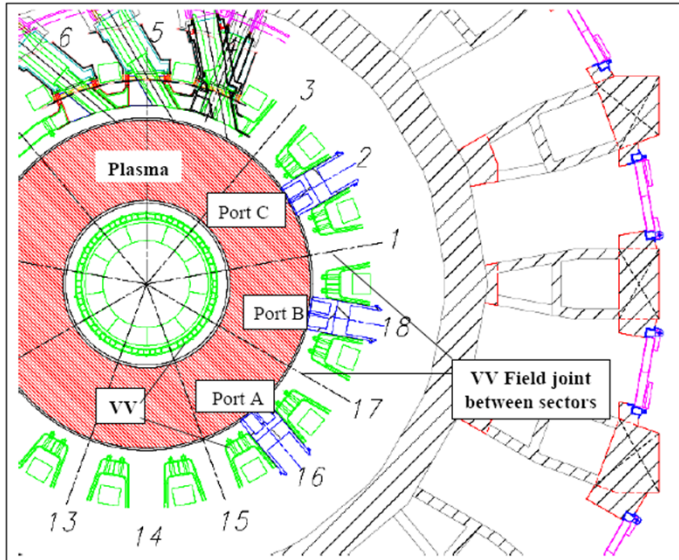
- Blanket/Divertor Availability ~ 87%
- Blanket **MTBF > 11 years**
- MTTR < 2 weeks

Extrapolation from other technologies shows expected MTBF for fusion blankets/divertor is as short as ~hours/days, and MTTR ~months
GRAND Challenge: Huge difference between Required and Expected!!

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

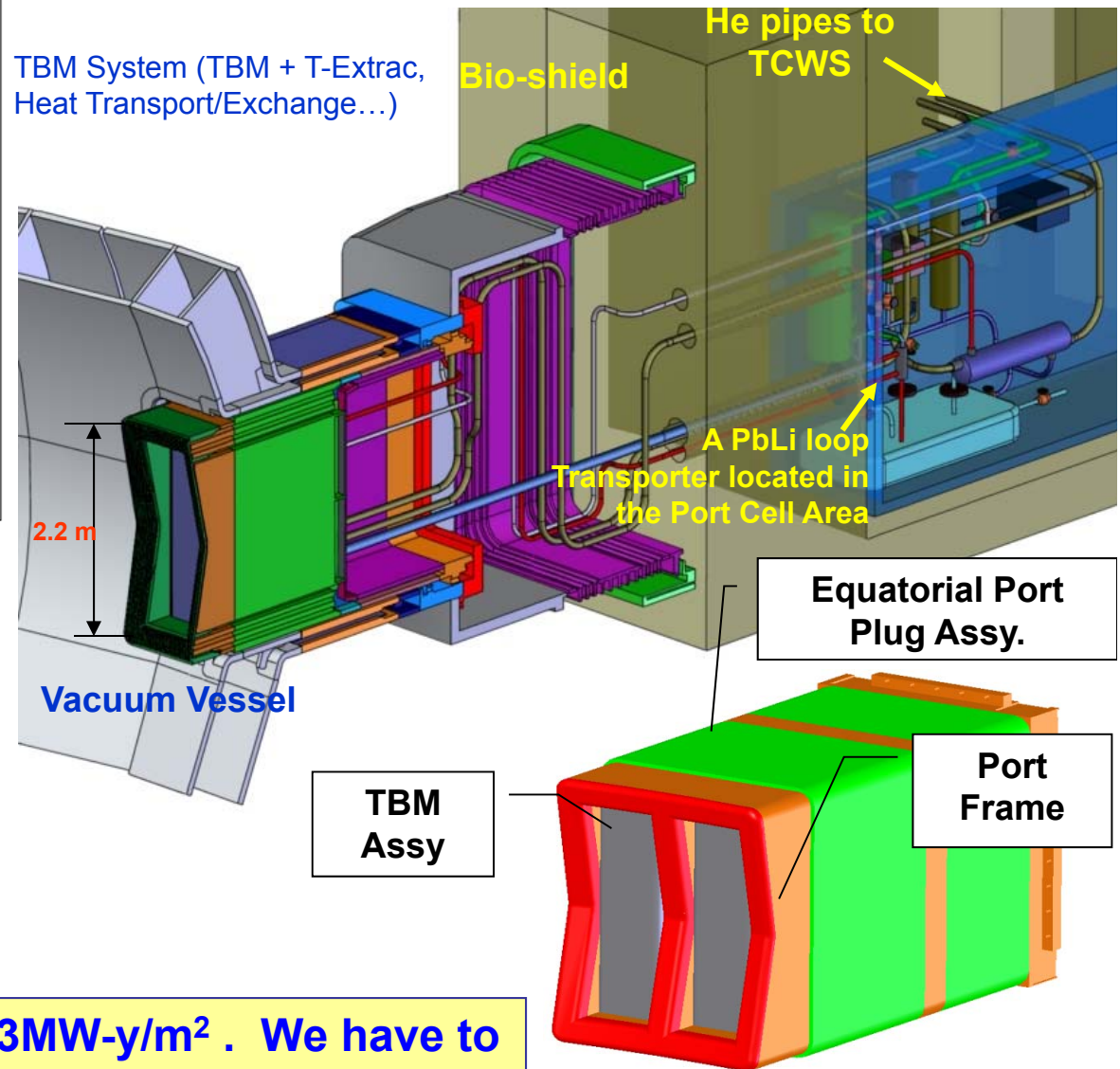


ITER Provides Substantial Hardware Capabilities for Testing of Blanket System

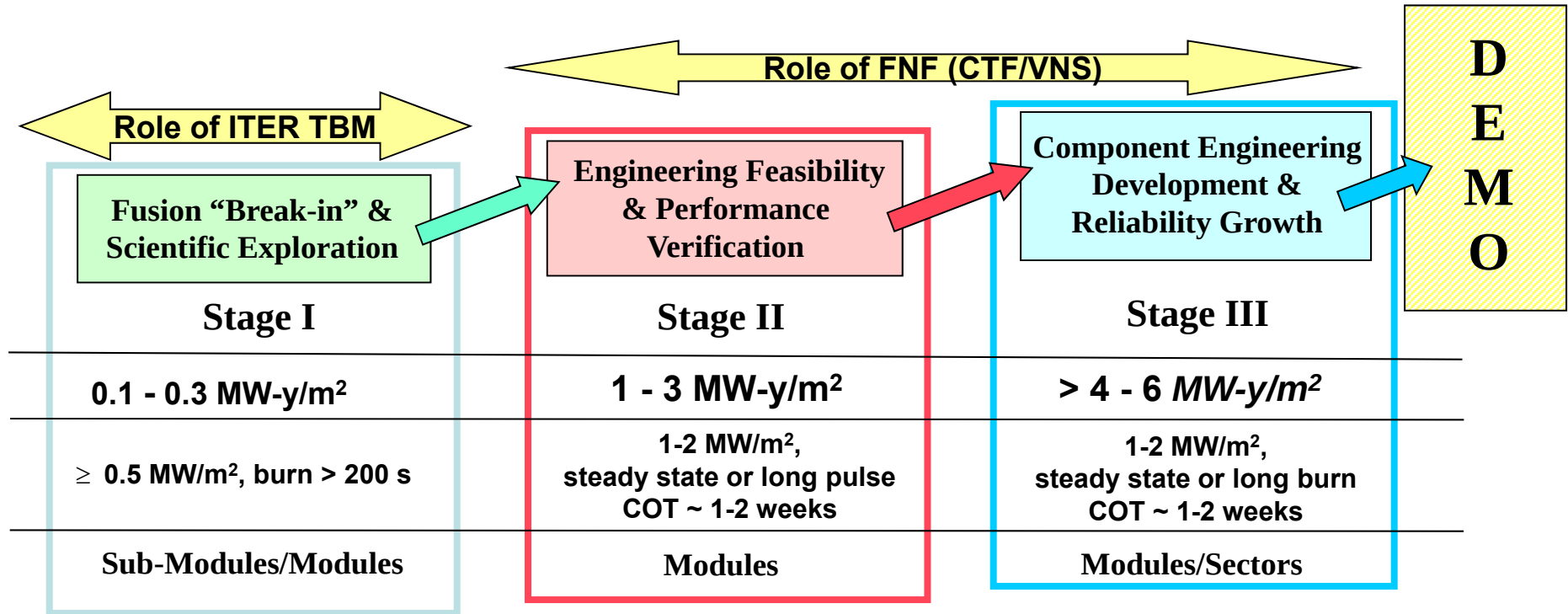


- ❑ ITER has allocated 3 **ITER equatorial ports** ($1.75 \times 2.2 \text{ m}^2$) for TBM testing
- ❑ Each port can accommodate only 2 modules (**i.e. 6 TBMs max**)

Fluence in ITER is limited to 0.3 MW-y/m^2 . We have to build another facility, for FNST development



THREE Stages of FNST Testing in Fusion Facilities are Required Prior to DEMO



- ITER is designed to fluence < 0.3MW-y/m². ITER can do only Stage I
- A Fusion Nuclear Facility, FNSF is needed, in addition to ITER, to do Stages II (Engineering Feasibility) and III (Reliability Growth)
 - FNSF must be small-size, low fusion power (< 150 MW), hence, a driven plasma with Cu magnets.

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** and tritium self sufficiency can be demonstrated 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.*

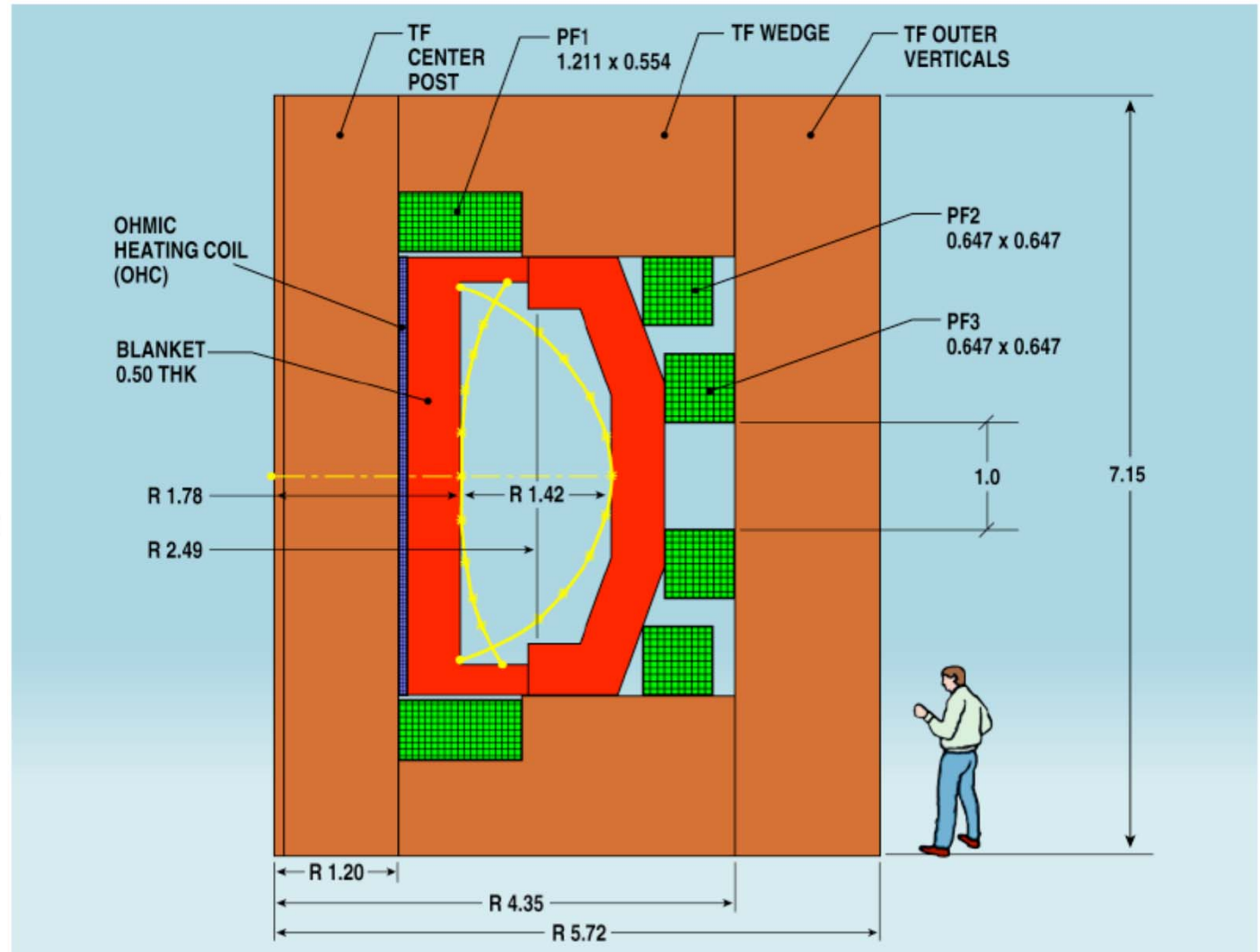
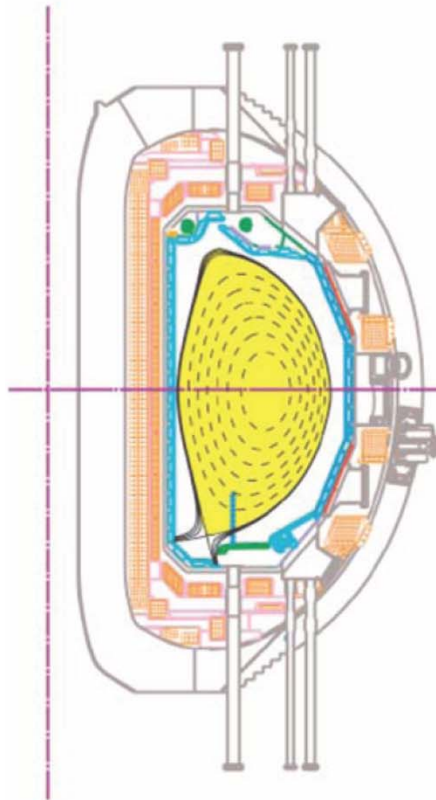
In MFE: small-size, low fusion power can be obtained in a low-Q (driven) plasma device, with normal conducting Cu magnets.

The DD Phase of FNSF also has a key role in providing integrated testing without neutrons prior to the DT Phase.

Why FNSF should be low fusion power, small size

- To reduce risks associated with external T supply and internal breeding shortfall
- Reduce cost (note Blanket/FW/ Divertor will fail and get replaced many times)
- FNST key requirement 1-2 MW/m² on 10-30 m² test area
- Cost/risk/benefit analysis lead to the conclusion that FNSF fusion power <150 MW
- For Tokamak (standard A & ST) this led to recommendation of:
 - Low Q plasma (2-3) - and encourage minimum extrapolation in physics
 - Normal conducting TF coil (to reduce inboard B/S thickness, also increase maintainability e.g. demountable coils).

Example of Fusion Nuclear Facility (FNF) Device 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)

Reduced activation Ferritic/Martensitic Steel (FS) is the reference structural material option for DEMO

- FS is used for TBMs in ITER and for mockup tests prior to ITER
- FS should be the structural materials for both base and testing breeding blankets on FNSF.
- FS irradiation data base from fission reactors extends to ~80 dpa, but it generally lacks He (only limited simulation of He in some experiments).
 - ✓ There is confidence in He data in fusion typical neutron energy spectrum up to at least 100 appm He (~10 dpa).
 - Note: Many material experts state confidence that FS will work fine up to at least 300 appm He at irradiation temperature > 350°C.

FNSF Strategy/Design for Breeding Blankets, Structural Materials, PFC & Vacuum Vessel

- DD phase role : All in-vessel components, e.g. divertor, FW/Blanket performance verification without neutrons before proceeding to the DT Phase

Day 1 Design

- Vacuum vessel – low dose environment, proven materials and technology
- Inside the VV – **all is “experimental.”** Understanding failure modes, rates, effects and component maintainability is a crucial FNSF mission.
- Structural material - reduced activation ferritic steel for in-vessel components
- Base breeding blankets - conservative operating parameters, ferritic steel, 10 dpa design life (acceptable projection, obtain confirming data ~10 dpa & 100 ppm He)
- Testing ports - **well instrumented, higher performance blanket experiments (also special test module for testing of materials specimens)**

Upgrade Blanket (and PFC) Design, Bootstrap approach

- Extrapolate a factor of 2 (standard in fission, other development), 20 dpa, 200 appm He. Then extrapolate next stage of 40 dpa...
- Conclusive results from FNSF (real environment) for testing structural materials,
 - no uncertainty in spectrum or other environmental effects
 - prototypical response, e.g., gradients, materials interactions, joints, ...

Key Summary Points (1 of 3)

- The fusion nuclear environment is complex and unique with multiple fields and strong gradients. The nuclear components exposed to this environment have multiple functions, materials, and interfaces.
 - New Phenomena, important multiple and synergetic effects
- Simulating **nuclear bulk heating in a large volume with gradients** is **essential** to observe key phenomena.
 - But this simulation can be achieved only in DT-plasma-based facility.
 - Therefore, the goal of the first phase of FNSF operation is to provide the environment for fusion nuclear science experiments – Discovery and Exploration of new phenomena.
- There are **3 stages** for FNST development in DT fusion facility(ies):
 1. Scientific Feasibility and Discovery
 2. Engineering Feasibility and Validation
 3. Engineering Development and Reliability Growth

These **3** stages may be fulfilled in one FNSF **OR** may require one or more parallel and consecutive FNSFs. **We will not know until we build one.**

Key Summary Points (2 of 3)

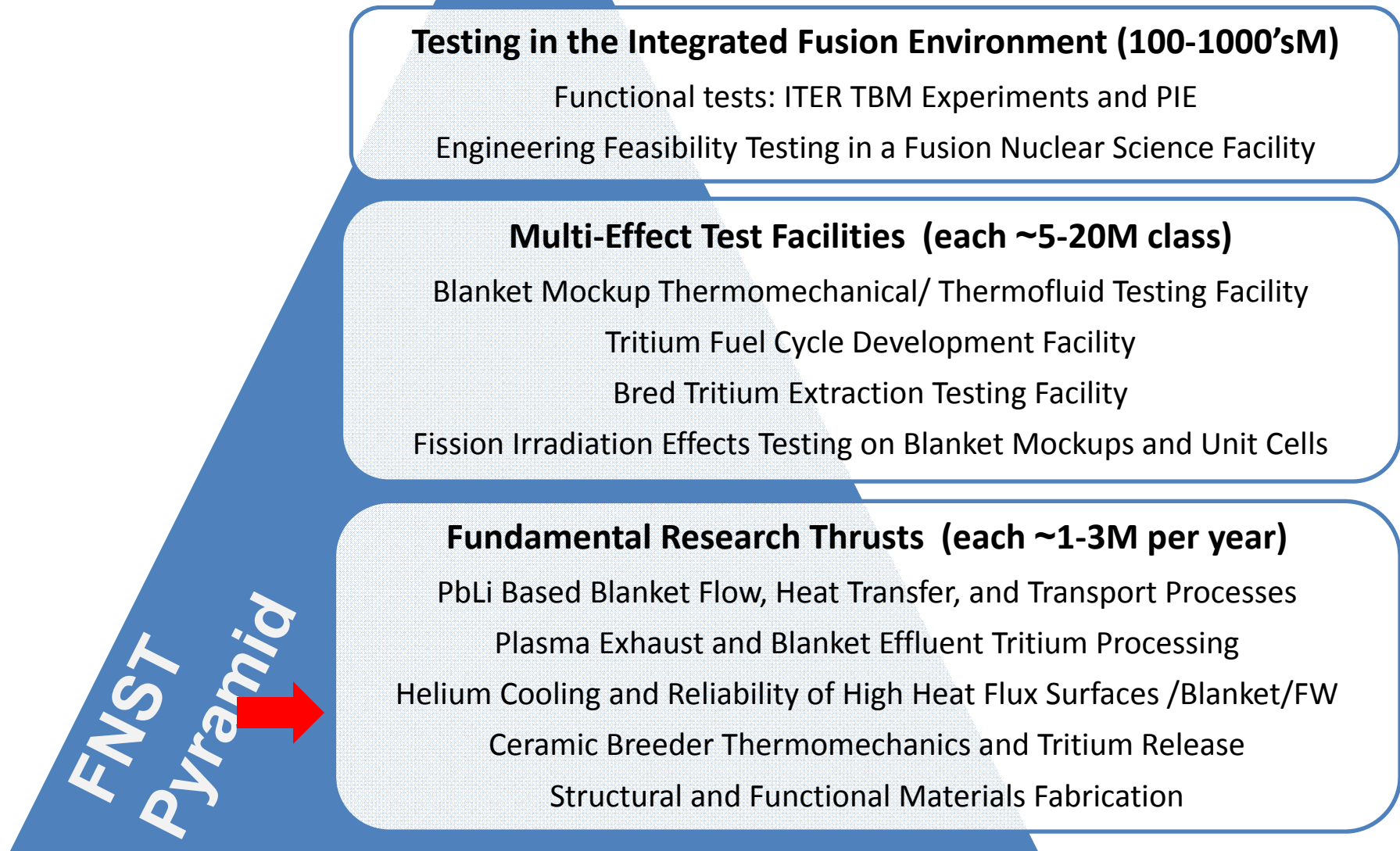
- There are serious Reliability/Availability/Maintainability (RAMI) issues. For the nuclear components, the difference between “expected” and “required” is huge for both MTBF, MTTR.
 - RAMI must be explicitly addressed in the strategy for FNSF design and operation.
 - RAMI can be a Deciding Factor in evaluating different options for FNSF mission and designs. Note : first phase of first FNSF will experience “infant mortality”.
 - “Reliability growth”, increasing MTBF, and decreasing MTTR must be part of the FNSF mission.
 - Fusion programs must find a way to engage experts in RAMI.
 - RAMI can be the “Achilles Heel” for fusion.
- Most of the external tritium supply will be exhausted by ITER.
 - FNSF and other DT facilities must breed their own tritium.
- We identified a “phase space” of physics and technology conditions in which tritium self sufficiency can be attained. This “phase space” provides clear goals for design and performance of plasma, blanket, PFC, tritium processing, and other subsystems.

Validation of achievable and required TBR, and ultimately T self-sufficiency can be realized only from experiments and operation of DT fusion facility(ies).

Key Summary Points (3 of 3)

- Material development must be “component-based”, **not** an “abstract stand-alone” objective. Many performance parameters of FW/Blanket/Divertor determine the objectives and strategy of material development. If we must refer to “dpa” for DEMO, the goal is ≤ 50 dpa
- At least in the first phase of FNSF, all components inside the vacuum vessel are “experimental”.
- **Blanket Development Strategy in FNSF**
 - A “Base” breeding blanket from the beginning operating initially at reduced parameters/performance
 - “Port-based” blankets – highly instrumented, operated near their high performance levels, more readily replaceableBoth have “testing missions”.
- **Material Development Strategy in FNSF**
 - Initial first wall / blanket / divertor for 10 dpa, 100 appm He in FS
 - Extrapolate a factor of 2 to 20 dpa, 200 appm He, etc. (Bootstrap approach)
 - Conclusive results from FNSF with “real” environment, “real” components

Establish the base of the pyramid **Before** proceeding to the top
We need substantial NEW Laboratory-scale facilities NOW



Concluding Remarks

- **Launching an aggressive FNST R&D program now is essential to defining “informed” vision and “credible” pathway to fusion energy.**

Most Important Steps To Do Now

1. Substantially expand exploratory R&D

- Experiments and modeling that begin to use real materials, fluids, and explore multiple effects and synergistic phenomena
 - Major upgrade and new substantial laboratory-scale facilities
 - Theory and “FNST Simulation” project (parallel and eventually linked to “plasma simulation” project).

➤ This is essential prior to any “integrated” tests (TBM, FNSF, etc.)

2. Move as fast as possible to “integrated tests” of fusion nuclear components – these can be performed only in DT plasma-based facility.

a) TBM in ITER

b) FNSF: Initiate studies to confront challenges with FNSF (think of “0+1” not “DEMO-1”).

- Address practical issues of building FNSF “in-vessel” components of the same materials and technologies that are to be tested.

➤ Evaluate issues of facility configuration, maintenance, failure modes and rates, physics readiness (Quasi-steady state? $Q \sim 2-3$?). These issues are critical - some are generic while others vary with proposed FNSF facility.

3. Utilize international collaboration (only when it is “effective”).

FNST research requires advancing the state-of-the-art, and developing highly integrated **predictive capabilities for many cross-cutting scientific and engineering disciplines**

- neutron/photon transport
- neutron-material interactions
- plasma-surface interactions
- heat/mass transfer
- MHD thermofluid physics
- thermal hydraulics
- tritium release, extraction, inventory and control
- tritium processing
- gas/radiation hydrodynamics
- phase change/free surface flow
- structural mechanics
- radiation effects
- thermomechanics
- chemistry
- radioactivity/decay heat
- safety analysis methods and codes
- engineering scaling
- failure modes/effects and RAMI analysis methods
- design codes

FNST research requires the talents of many scientists and engineers in many disciplines.

Need to attract and train bright young students and researchers.

Thank You for Your Attention!

Backup Slides

Scientific & Technical Challenges for Fusion Materials

- ❑ Fusion materials are exposed to a hostile environment that includes combinations of high temperatures, reactive chemicals, large time-dependent thermal-mechanical stresses, and intense damaging radiation.
- ❑ Key issues include thermal stress capacity, coolant compatibility, waste disposal, and radiation damage effects.
- ❑ The 3 leading structural materials candidates are ferritic/martensitic steel, V alloys and SiC composites (based on safety, waste disposal, and performance considerations).

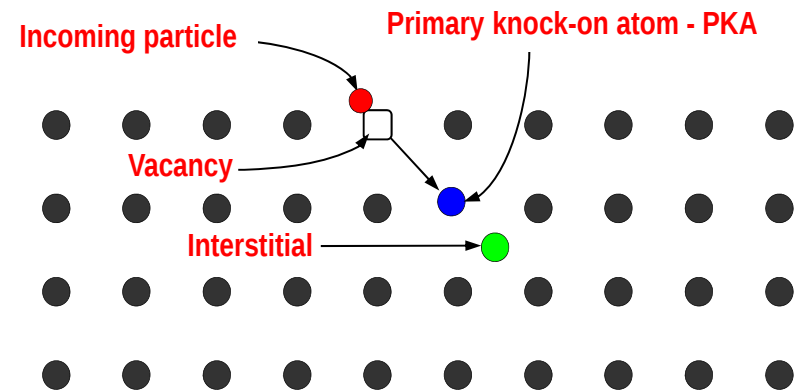
➤ **The ferritic/martensitic steel is the reference structural material for DEMO**

– (Commercial alloys (Ti alloys, Ni base superalloys, refractory alloys, etc.) have been shown to be unacceptable for fusion for various technical reasons).

- ❑ *Structural materials are most challenging, but many other materials (e.g. breeding, insulating, superconducting, plasma facing and diagnostic) must be successfully developed.*

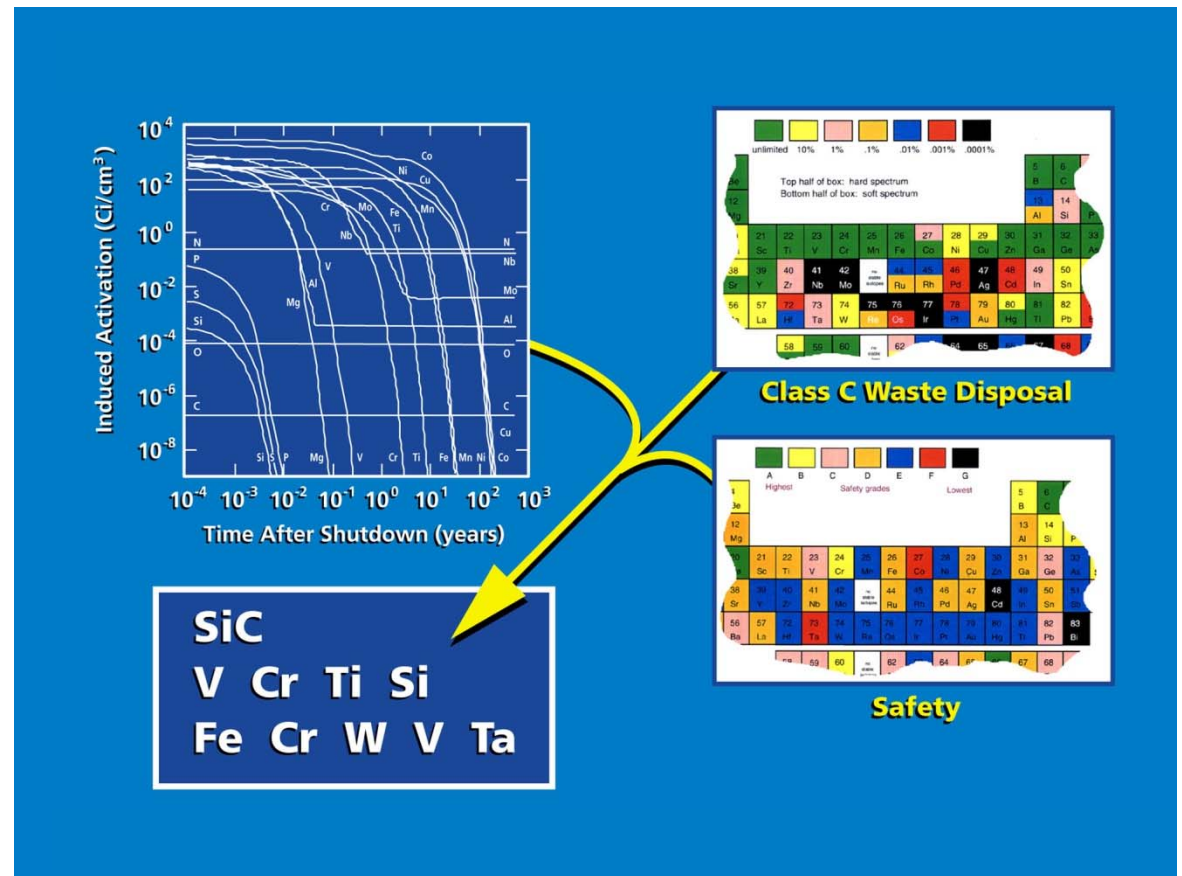
Radiation Damage Fundamentals

- ❑ Material properties are determined by microstructure.
 - Grain size, other internal interfaces
 - Dislocation structures
 - Size and density of second phases
- ❑ Irradiation with energetic particles leads to atomic displacements:
 - Neutron exposure can be expressed in terms of the number of atomic displacements per atom – dpa
 - Lifetime exposures range from ~0.01 to >100 dpa (0.001 – 10 MW-y/m²).
 - Atomic displacements lead to microstructural evolution, which results in substantial property degradation.
- ❑ One key to achieving highly radiation resistant materials is to enhance vacancy-interstitial recombination or self-healing.

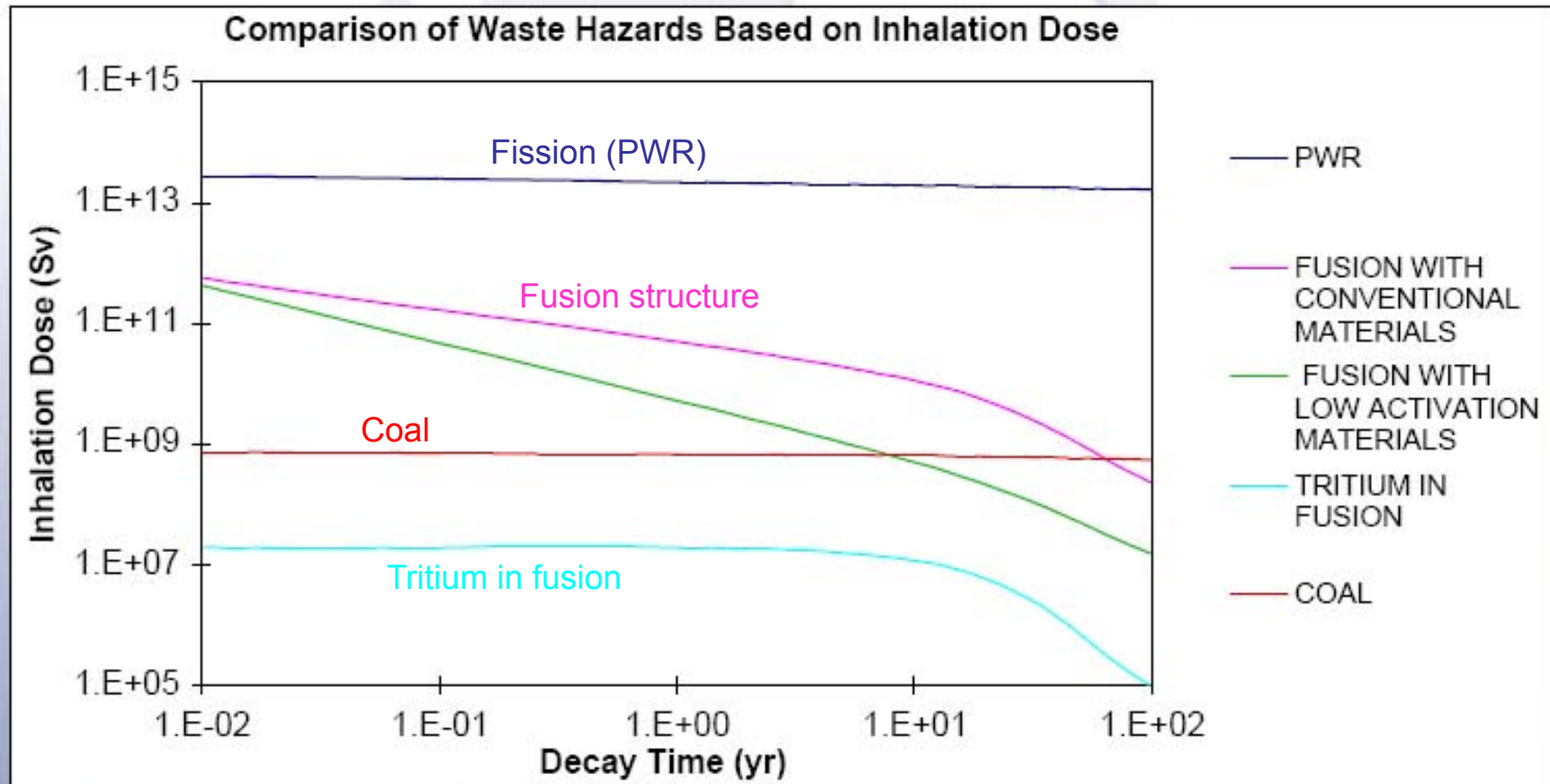


In fusion, the fusion process does not produce radioactive products. Long-term radioactivity and waste disposal issues can be minimized by careful **SELECTION of MATERIALS**

- This is in contrast to fission, where long term radioactivity and waste disposal issues are “intrinsic” because the products of fission are radioactive.
- Based on safety, waste disposal, and performance considerations, the three leading candidates are:
 - RAF/M and NFA steels
 - SiC composites
 - Tungsten alloys (for PFC)



Radiotoxicity (inhalation) of waste from fusion is less than fission and similar to that from coal at 100 years.

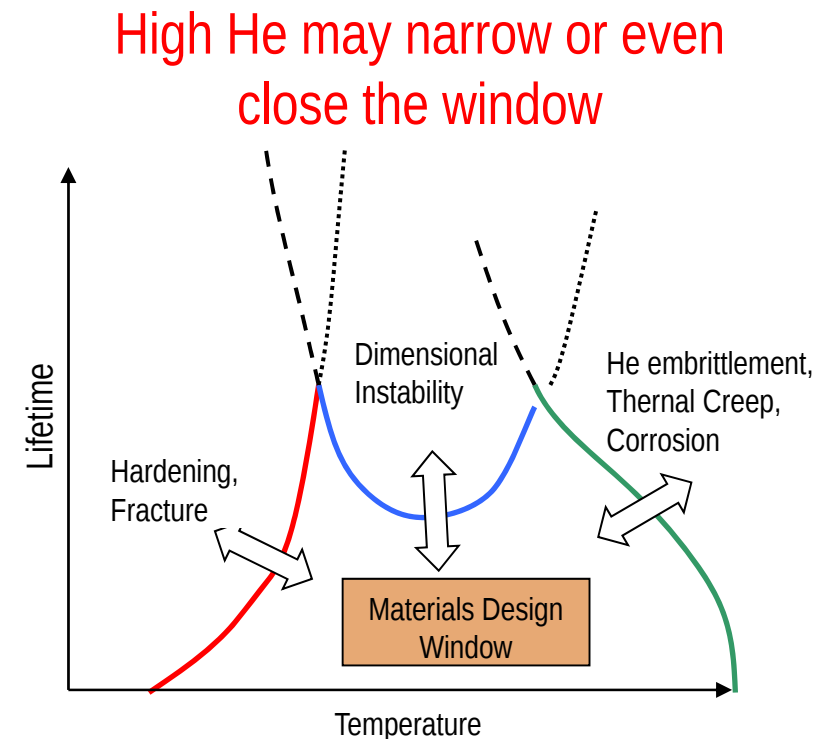


- From "A Study of the Environmental Impact of Fusion" (AERE R 13708).
- Coal radiotoxicity is based on Radon, Uranium, Thorium, and Polonium in coal ash
- Inhalation represents major pathways for uptake of material by the human body
- Dose hazard used here is a relative measure of radiotoxicity of material

Effects of Fusion Environment on Bulk Material Properties

High dpa and He (unique to fusion) coupled with high stresses result in:

- Microstructure and property changes over long time.
 - Voids, bubbles, dislocations and phase instabilities.
 - Dimensional instabilities (swelling and irradiation-thermal creep).
 - Loss of strain hardening capability.
 - He embrittlement at low and high temperatures.
 - Fatigue, creep-fatigue, crack growth.
 - Enhanced corrosion, oxidation and impurity embrittlement (refractories).
 - Transient and permanent changes in electrical and thermal properties.



N. Ghoniem & B.D. Wirth, 2002

Common interest of fission and fusion structural materials: operating temperature and radiation dose (dpa)

(There are many other areas of synergy between fission and fusion technologies)

Notes:

- Fusion values presented here are the maximum at front of the FW/B.
- Dose in fusion structural material has steep radial gradients. Deeper in the blanket:
 - Damage decreases by ~an order of magnitude
 - Spectrum is softer and helium production is smaller, similar to fission

GEN IV

VHTR: Very High temperature reactor

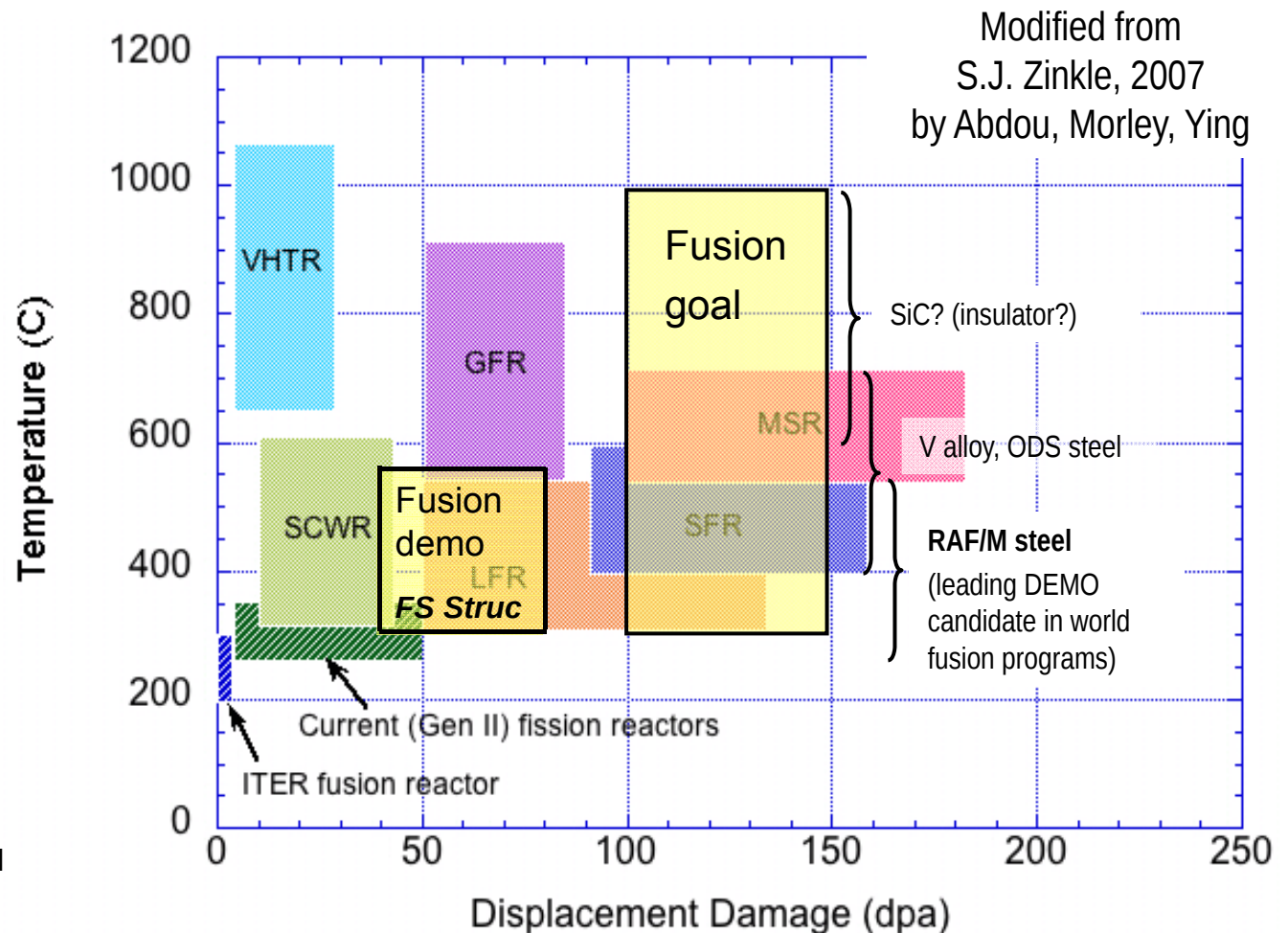
SCWR: Super-critical water cooled reactor

GFR: Gas cooled fast reactor

LFR: Lead cooled fast reactor

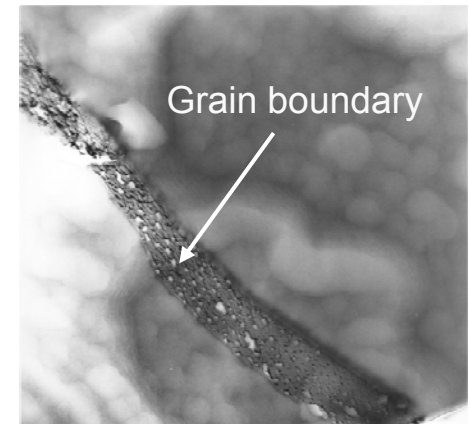
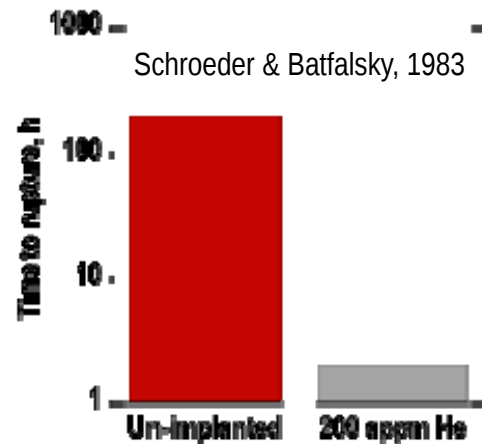
SFR: Sodium cooled fast reactor

MSR: Molten salt cooled reactor

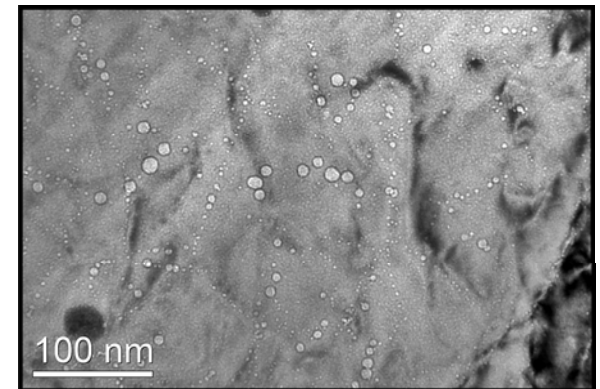
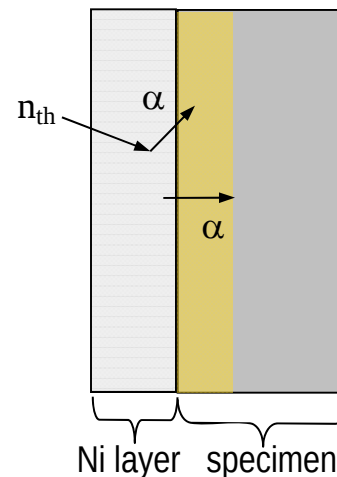


Impact of He-Rich Environment on Neutron Irradiated Materials

- A unique aspect of the DT fusion environment is **large** production of gaseous transmutant He and H.
- Accumulation of He can have major consequences for the integrity of fusion structures such as:
 - Loss of high-temperature creep strength.
 - Increased swelling and irradiation creep at intermediate temperatures.
 - Loss of ductility and fracture toughness at low temperatures.
- *In situ* He injection technique developed to inform models of He transport, fate and consequences.



In situ He injector
micro-IFMIF
technique



Yamamoto, et al., 2009

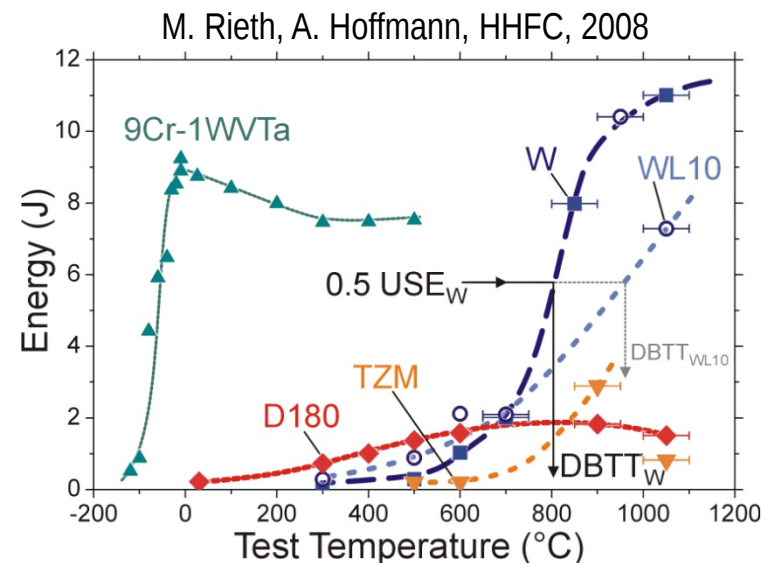
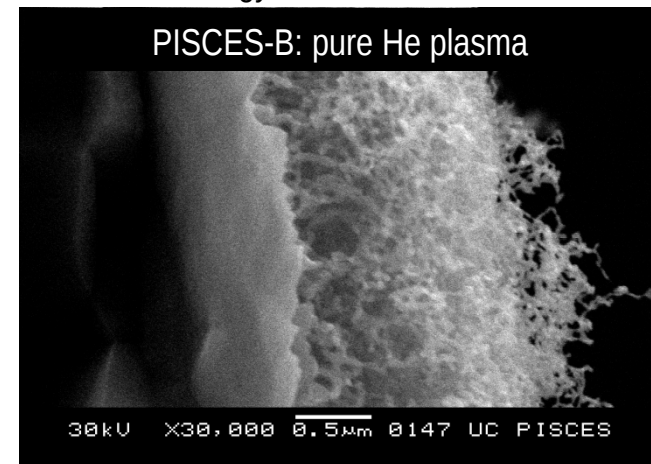
Role of Irradiation Sources in Fusion Materials Science

- Overcoming *neutron-induced* radiation damage degradation is a key step in fusion materials development. Other Important Issues: fabrication and joining, corrosion and compatibility, and thermophysical properties , etc
- Evaluation of fusion radiation effects requires simultaneous displacement damage and He generation, with He /dpa ratio ~ 10-12
- Ion irradiations – effects of dpa and gas generation can be studied to high levels, but cannot simulate neutron damage because charged particle damage rates are ~1000 times larger than for fusion conditions. In addition, ions produce damage over micron length scales thereby preventing measurement of bulk material properties.
- **Ferritic Steel irradiation data base from fission reactors extends to ~80 dpa, but it generally lacks He (only limited simulation of He in some experiments).**
 - ✓ **There is confidence in He data in fusion typical neutron energy spectrum up to at least 100 appm He (~10 dpa).**

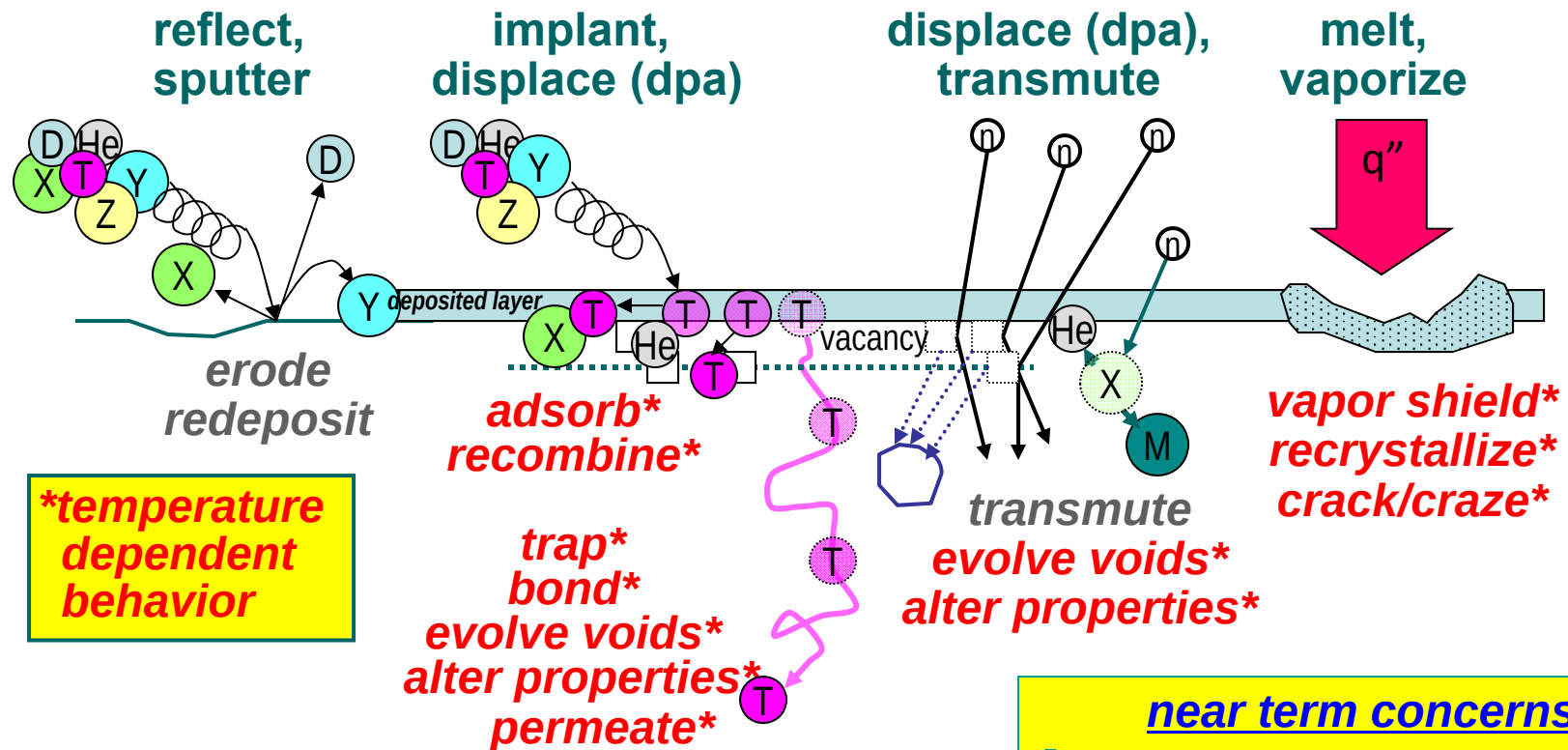
Plasma Facing Materials Must Tolerate Extreme Heat, Neutron & Particle Fluxes

- ❑ Typical materials considered for PFC (e.g. Divertor) include graphite, beryllium and tungsten.
- ❑ Tungsten alloys (or other refractory alloys) are the only possible structural materials for divertor applications ($q'' > 10 \text{ MW/m}^2$) due to their excellent thermo-physical properties.
- ❑ However, critical issues need to be addressed:
 - Creep strength
 - Fracture toughness
 - Microstructural stability
 - Low & high cycle fatigue
 - Oxidation resistance
 - Effects of neutron irradiation (hardening & embrittlement, He)
- ❑ An effort to explore ways to improve the properties of tungsten is being initiated.

Baldwin, Nishijima, Doerner, et. al, courtesy of Center for Energy Research, UCSD, La Jolla, CA



Plasma-Surface Interaction (PSI) Processes temperature dependence



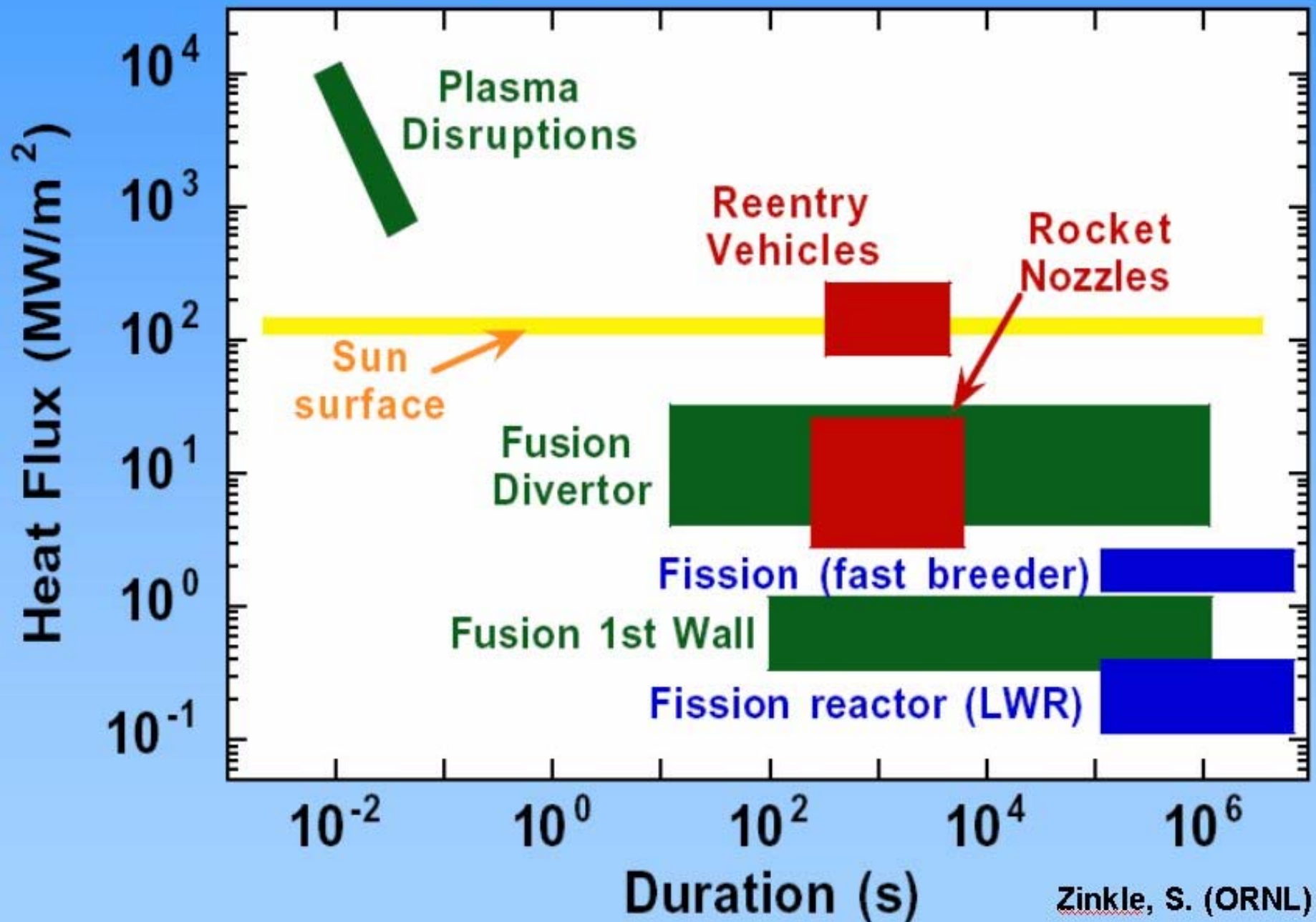
The physical chemistry of PSI processes on high temperature walls will determine the strong interaction between wall and plasma in DEMO (or FNSF).

near term concerns

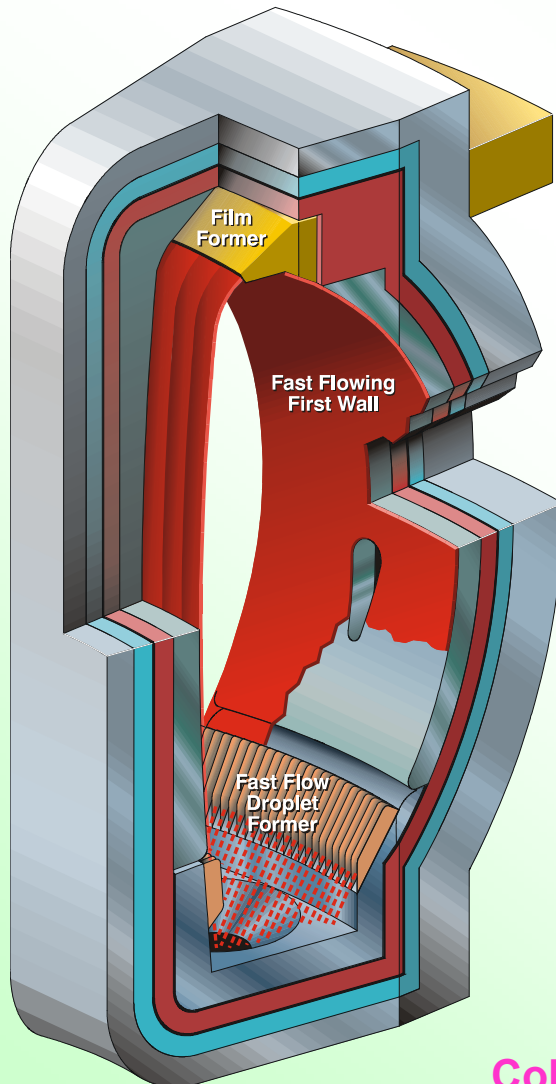
- .. **Prediction/modeling** of damage from ions, neutrons & thermal gradients at high temperature, related tests, benchmark data
- Deploying actively-cooled PFCs and **large area "hot" walls**
- ..

*more complete presentation of critical issues in backup slides

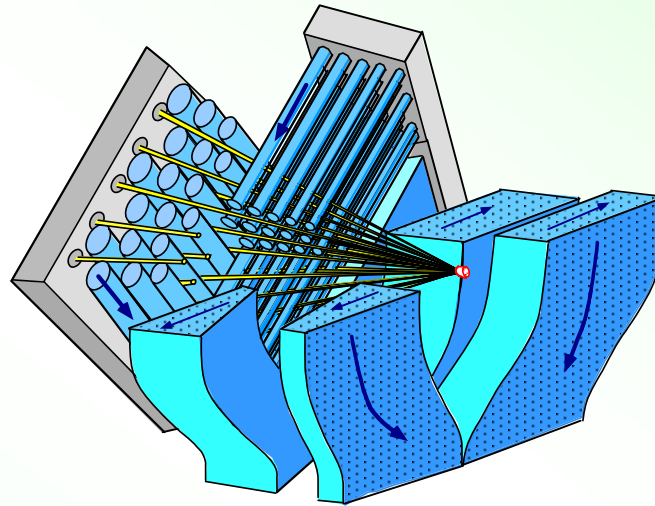
Comparison of Heat Fluxes



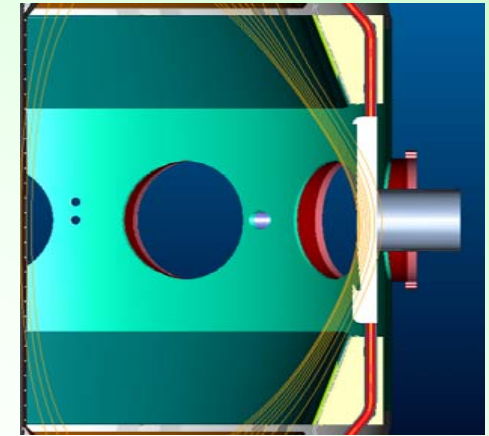
Liquid Walls (“Free Surface”) Concepts have been Considered in MFE & IFE to solve PFC Issues



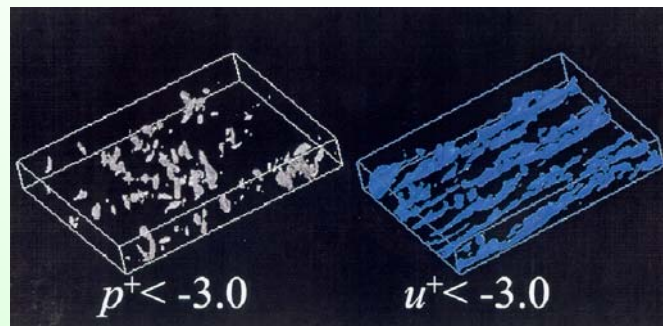
APEX CLIFF



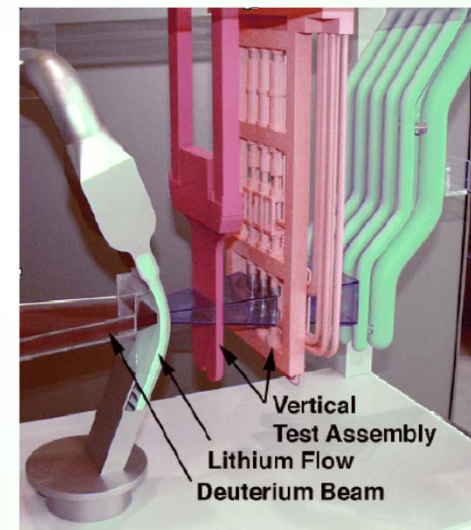
HYLIFE-II



ALPS/APEX NSTX Li module



DNS Free Surface Simulation
Collaboration with non-fusion scientists
US-Japan Collaboration



IFMIF

Why Consider Liquid Walls for Divertors?

- ◆ Tungsten (W) is currently considered the only reactor relevant PFC material, but it has issues
 - embrittlement below 700C,
 - surface damage in DT+He plasmas (see right)**Can W be the only option we pursue? Risky!**

- ◆ **Liquid walls** have a completely different set of advantages and issues
 - Continuously renewed surface: **immune** to erosion, particle and neutron damage
 - Can potentially do two functions:
pump particles & remove heat
 - Much thinner mechanical construction of the plasma-coolant interface possible
 - Disruptive forces on LW not structural issue
 - PMI issues include effect of sputtering + evaporation on plasma and LW Op. Temp.
 - Liquid surface can move and interact electromagnetically with plasma/field

Tungsten surface after long-term plasma exposure

- Structures a few tens of nm wide
- Structures contain nano bubbles



100 nm (VPS W on C) (TEM)

NAGDIS-II: pure He plasma

N. Ohno et al., in IAEA-TM, Vienna, 2006,
TEM - Kyushu Univ., $T_s = 1250$ K, $t = 36,000$ s, 3.5×10^{27} He⁺/m², $E_{ion} = 11$ eV