Challenges and Development Pathways for Fusion Nuclear Science and Technology

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Challenges and Development Pathways for Fusion Nuclear Science and Technology

OUTLINE

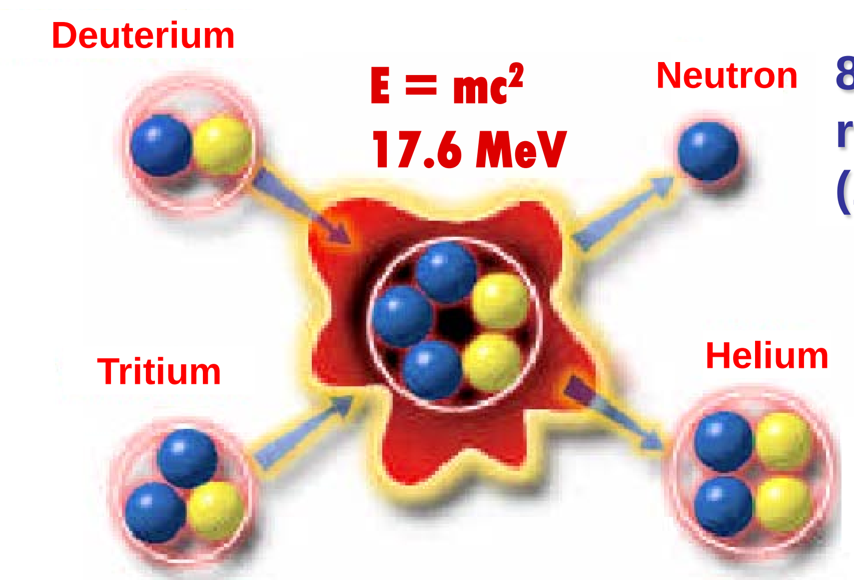
- Fusion Research Transition to Fusion Science and Engineering
- DEMO Goal, ITER
- FNST definition and Blanket Principles and Interactions
- Blanket Types and Technical Issues
- Science-Based Framework for FNST Development
- Blanket Testing in ITER
- Need for a New Fusion Nuclear Facility (FNSF/CTF/VNS)
- Reliability/AVAILABILITY/Maintainability (RAMI)
- Tritium Supply
- Analysis of Progress and Challenges for key Issues

  e.g. - Tritium Self-Sufficiency

  - Fluid-Material interaction (Interfacial Phenomena)
- Summary

What is fusion?

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



80% of energy release (14.1 MeV) → **Used to breed tritium and close the DT fuel cycle**

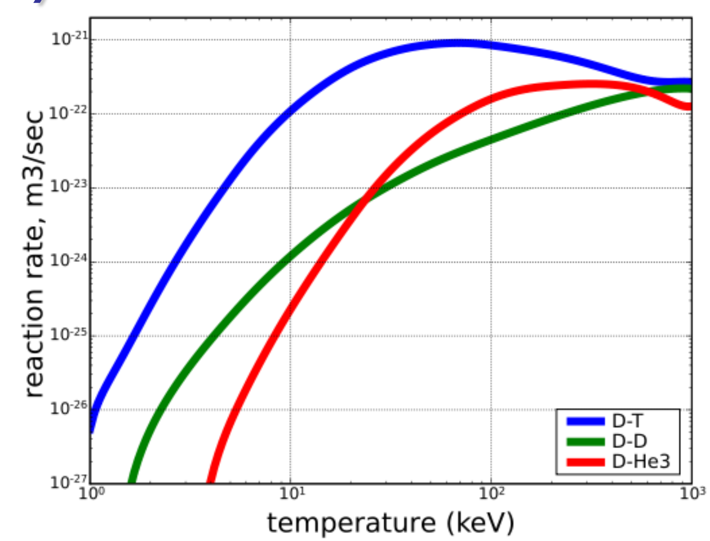
Li + n → T + He

Li in some form must be used in the fusion system

20% of energy release (3.5 MeV)

Illustration from DOE brochure

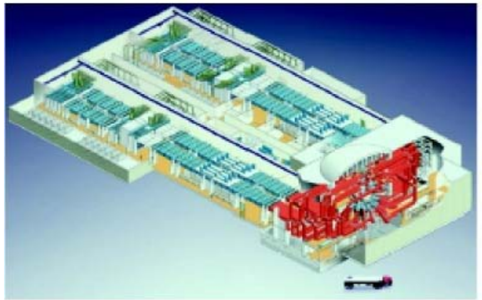
- **Deuterium and tritium is the easiest, attainable at lower plasma temperature, because it has the largest reaction rate and high Q value.**
- **The World Program is focused on the D-T Cycle.**



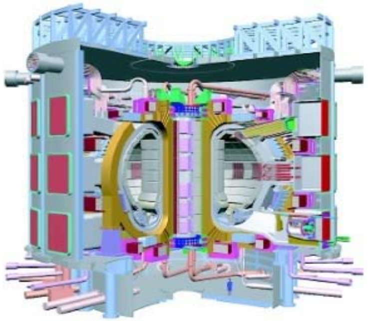
Fusion Research is about to transition from Plasma Physics to Fusion Science and Engineering

- **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

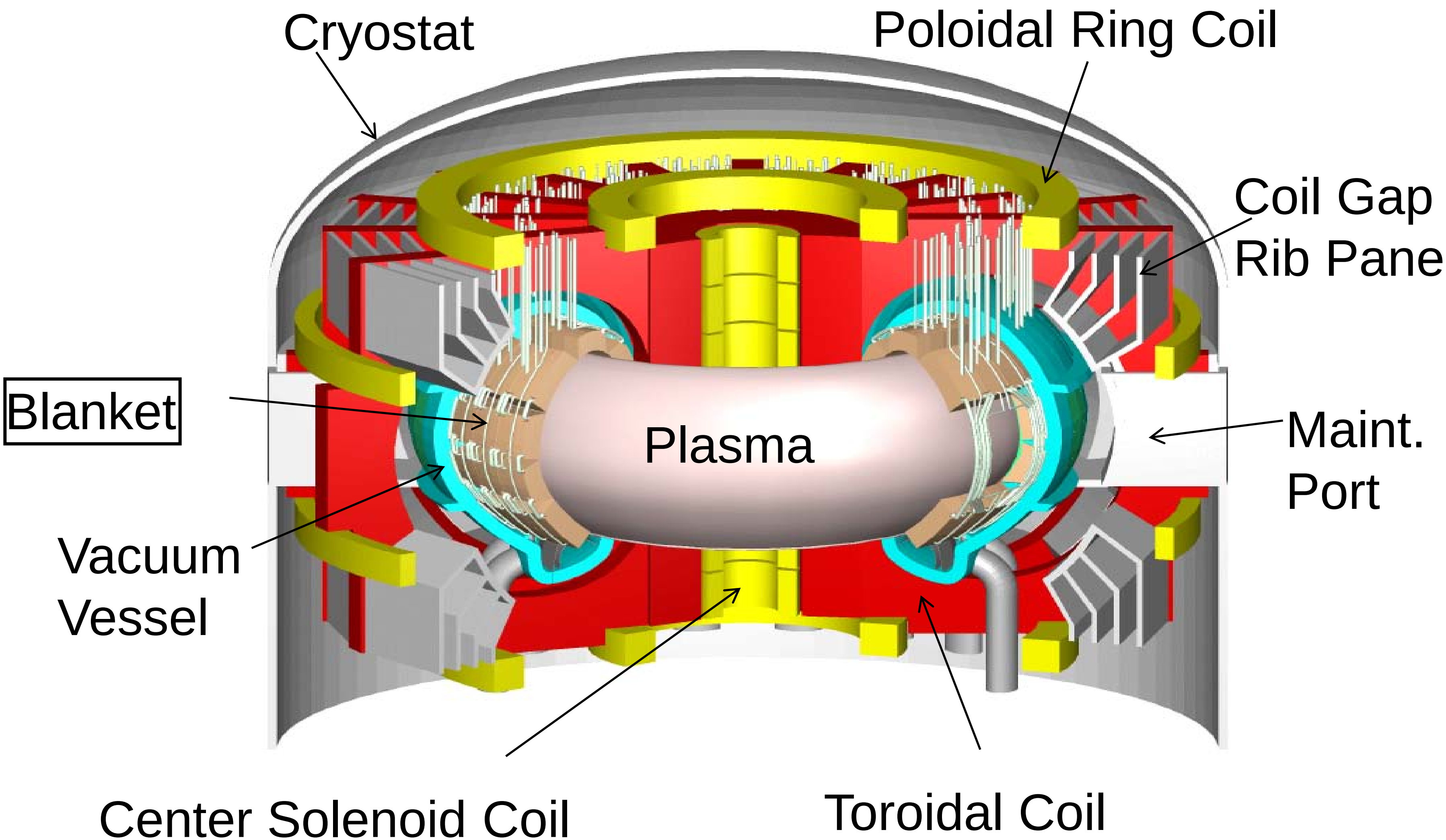
- **ITER is a major step forward for fusion research. It will demonstrate:**
  1. **Reactor-grade plasma**
  2. **Plasma-support systems (S.C. magnets, fueling, heating)**

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

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)

ITER

- The World has started construction of the **next step** in fusion development, a device called ITER.
- ITER will demonstrate the **scientific and technological feasibility** of fusion energy for peaceful purposes.
- ITER will produce **500 MW** of fusion power.
- Cost, including R&D, is ~15 billion dollars.
- **ITER is a collaborative effort among Europe, Japan, US, Russia, China, South Korea, and India. ITER construction site is Cadarache, France.**
- ITER will begin operation in hydrogen in ~2019. **First D-T Burning Plasma in ITER in ~ 2026.**

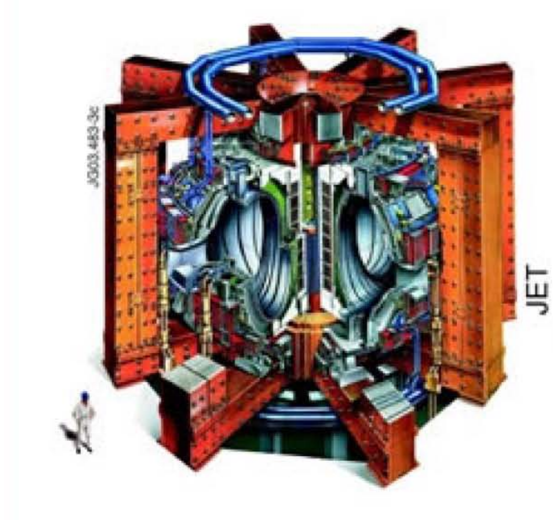
ITER is a reactor-grade tokamak plasma physics experiment - A huge step toward fusion energy

- Will use D-T and produce neutrons
- 500MW fusion power, Q=10
- Burn times of 400s
- Reactor scale dimensions
- Actively cooled PFCs
- Superconducting magnets

By Comparison, JET

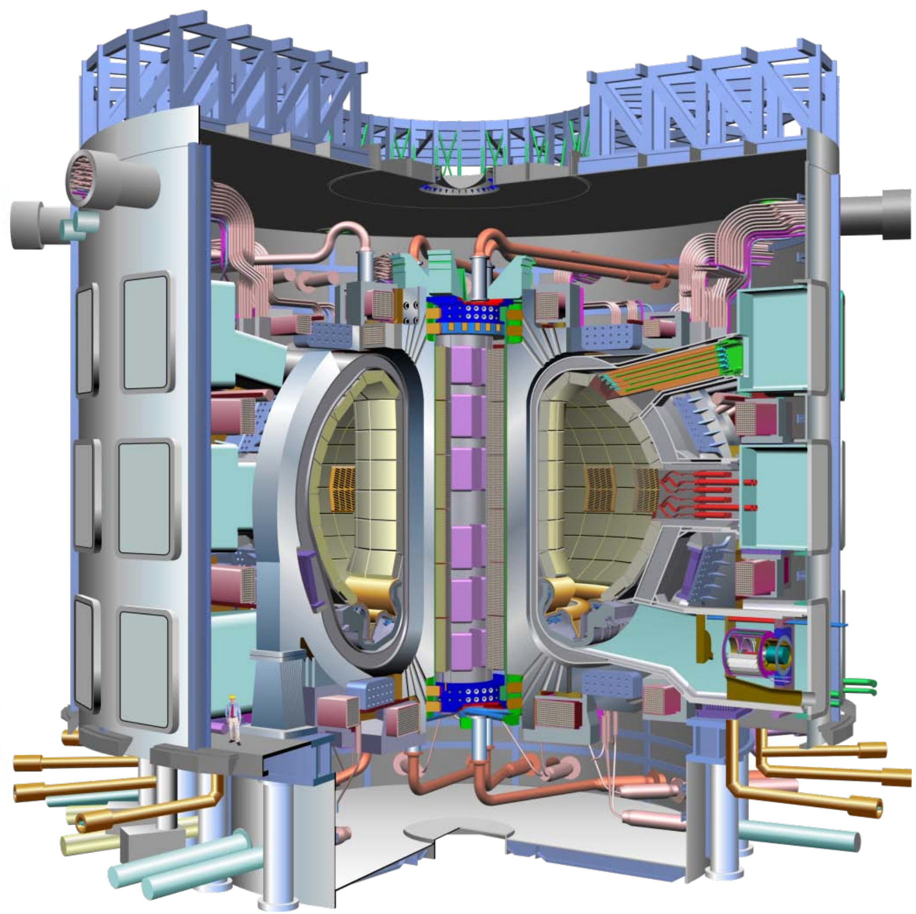
- ~10 MW
- ~1 sec
- Passively Cooled

~15 m



JET

~29 m



ITER

New Long-Pulse Confinement and Other Facilities Worldwide will Complement ITER

China

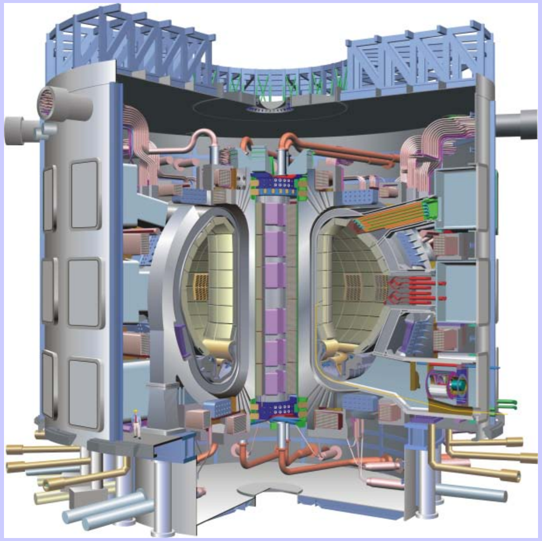
EAST

Europe

W7-X (also JT-60SA)

India

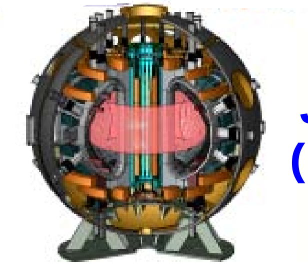
SST-1



ITER Operations:

34%	Europe
13%	Japan
13%	U.S.
10%	China
10%	India
10%	Russia
10%	S. Korea

Japan (w/EU)



JT-60SA (also LHD)

South Korea

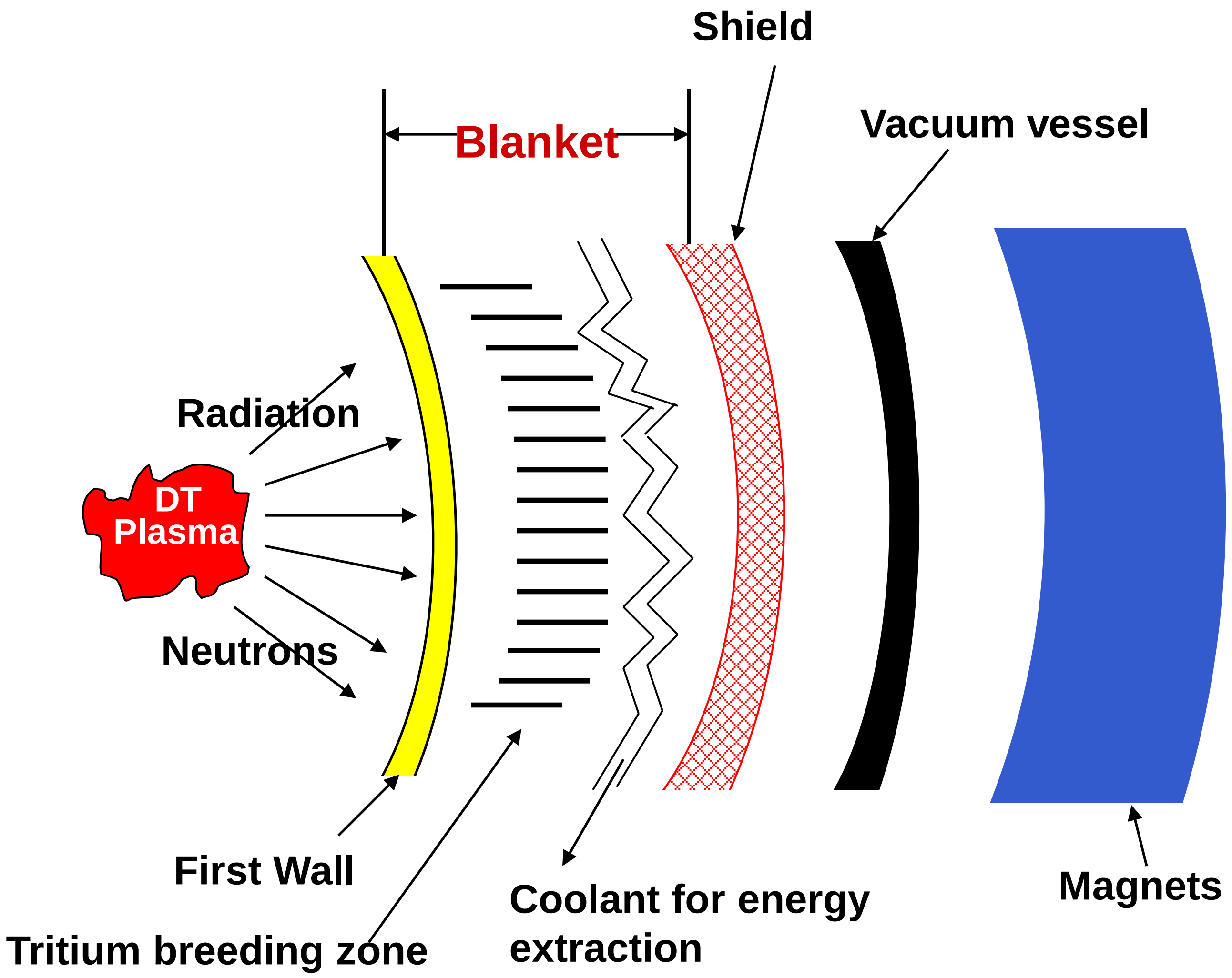
KSTAR

U.S.

Being planned

Fusion Nuclear Science &Technology Testing Facility (FNSF/CTF/VNS)

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



Lithium-containing Liquid metals (Li, PbLi) are strong candidates as breeder/coolant. Lithium ceramics are candidates for breeder with He cooling

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

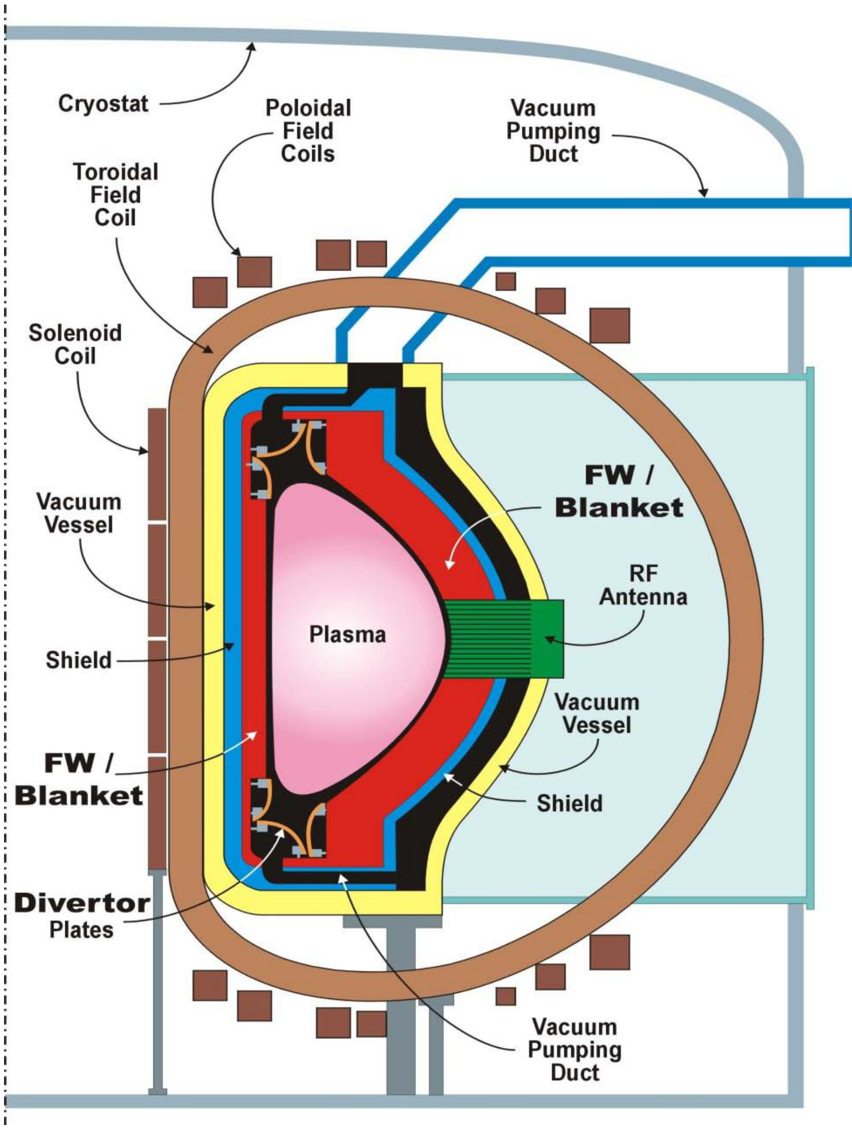
FNST includes the scientific issues and technical disciplines as well as materials, engineering and development of fusion nuclear components:

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



Fusion Nuclear Science and Technology (FNST)

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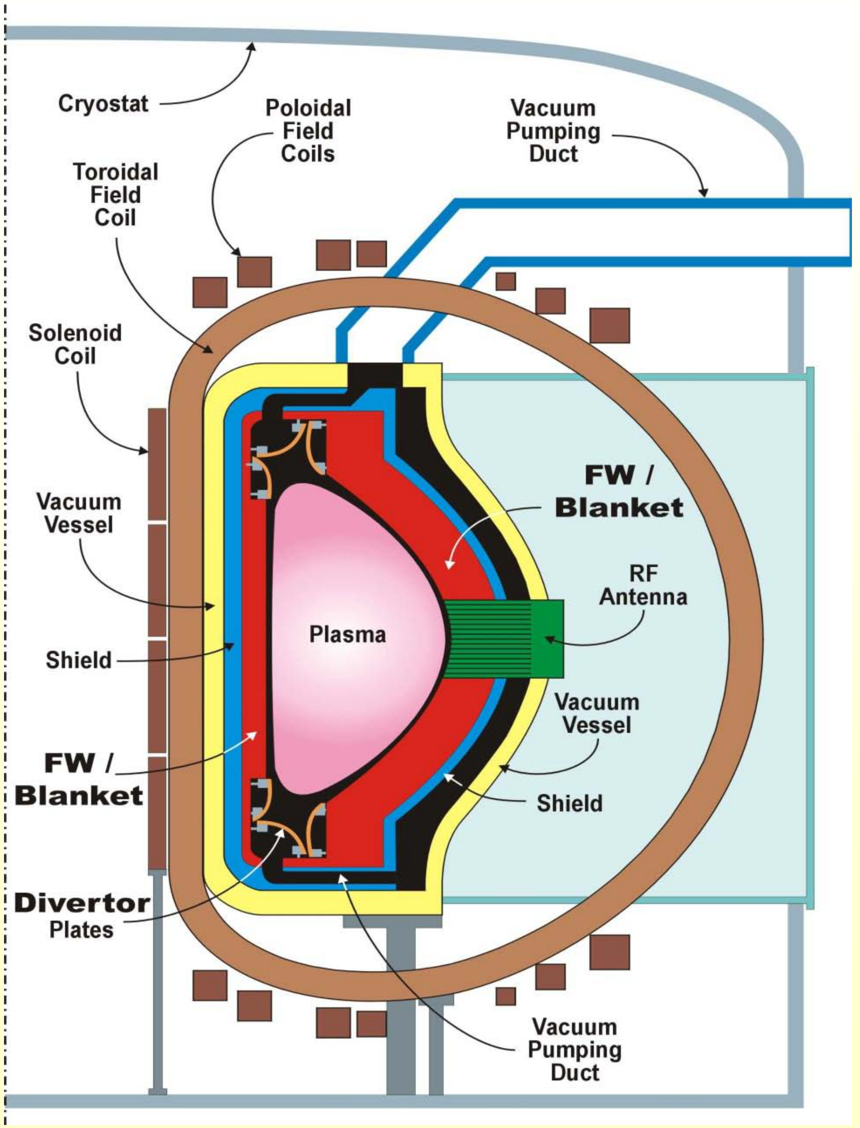
From the edge of Plasma to TF Coils:

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

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

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

b- repair/replacement take long time



FNST research is responsible for advancing and providing state-of-the-art predictive capabilities for many technical disciplines required for the fusion program

- neutron/photon transport
- neutron-material interactions
- plasma-surface interactions
- heat/mass transfer
- thermofluid physics and MHD
- thermal hydraulics
- tritium release, extraction, inventory and control
- tritium processing
- 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

R&D for Fusion Nuclear Science and Technology is a "Grand Challenge" not only because of the multi-function, multi-physics, multi-engineering requirements and issues but also because of the complex and unique thermo-magneto-vacu-tritu-nuclear environment of fusion

Neutrons (fluence, spectrum, spatial and temporal gradients)
- Radiation Effects (at relevant temperatures, stresses, and loading)
- Bulk Heating
- Tritium Production
- Activation and Decay Heat

Heat Sources (magnitude, gradient)
- Bulk (from neutrons)
- Surface (from particles and radiation)

Particle Flux (energy, density, gradients)

Magnetic Field (3-component with gradients)
- Steady Field
- Time-Varying Field

Mechanical Forces
- Normal (steady, cyclic)
- Off-Normal (pulsed)

Thermal / Chemical / Mechanical / Electrical / Magnetic / Nuclear Interactions and Synergistic Effects
- Combined environmental loading conditions
- Interactions among physical elements of components

The kind of training needed to perform research and engineering within these highly constrained fusion nuclear components takes many years of education and experience.

This is why ISFNT has particularly encouraged the participation of young scientists and established an award for this purpose.

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.

Blanket Concepts
(many concepts proposed worldwide)

A. Solid Breeder Concepts

- Always separately cooled
- Solid Breeder: Lithium Ceramic (Li_2O, Li_4SiO_4, Li_2TiO_3, Li_2ZrO_3)
- Coolant: Helium or Water

B. Liquid Breeder Concepts

Liquid breeder can be:

a) **Liquid metal** (high conductivity, low Pr): Li, or $^{83}Pb\ ^{17}Li$

b) **Molten salt** (low conductivity, high Pr): Flibe $(LiF)_n \cdot (BeF_2)$, Flinabe (LiF-BeF_2-NaF)

B.1. Self-Cooled

- Liquid breeder is circulated at high enough speed to also serve as coolant

B.2. Separately Cooled

- A separate coolant is used (e.g., helium)
- The breeder is circulated only at low speed for tritium extraction

B.3. Dual Coolant

- FW and structure are cooled with separate coolant (He)
- Breeding zone is self-cooled

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:

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

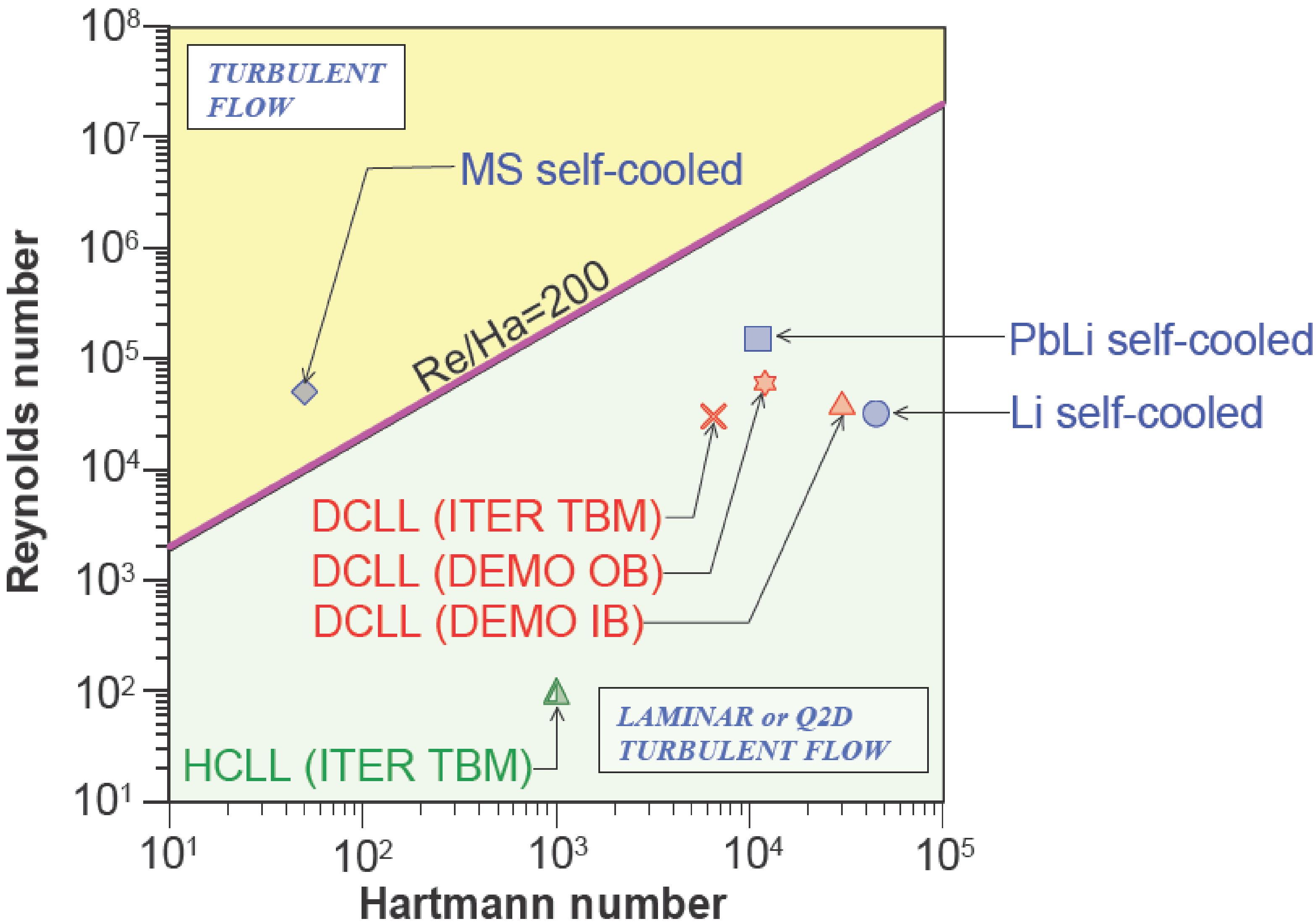
- Any induced current in the liquid results in an additional body force in the liquid that usually opposes the motion. This body force must be included in the Navier-Stokes equation of motion:

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

- 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

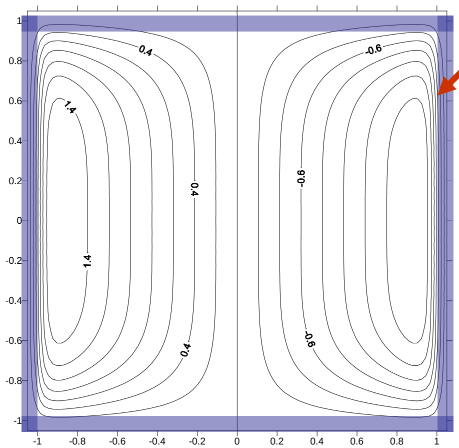
MHD Characteristics of Fusion Liquid Breeder Blanket Systems



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

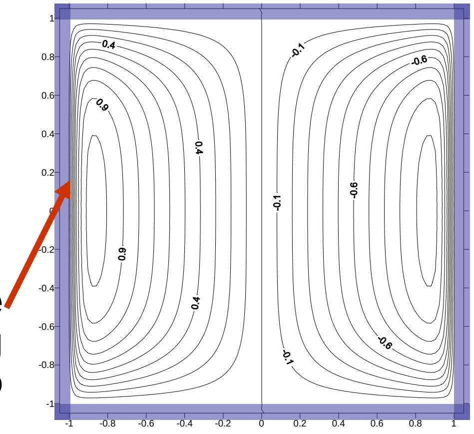
A perfectly insulated "WALL" can solve the problem, but is it practical?

Conducting walls



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

Insulated walls



All current must close in the liquid near the wall – net drag from jxB force is zero

- Net JxB 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 (~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

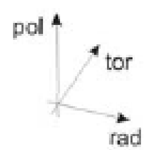
Separately-cooled LM Blanket

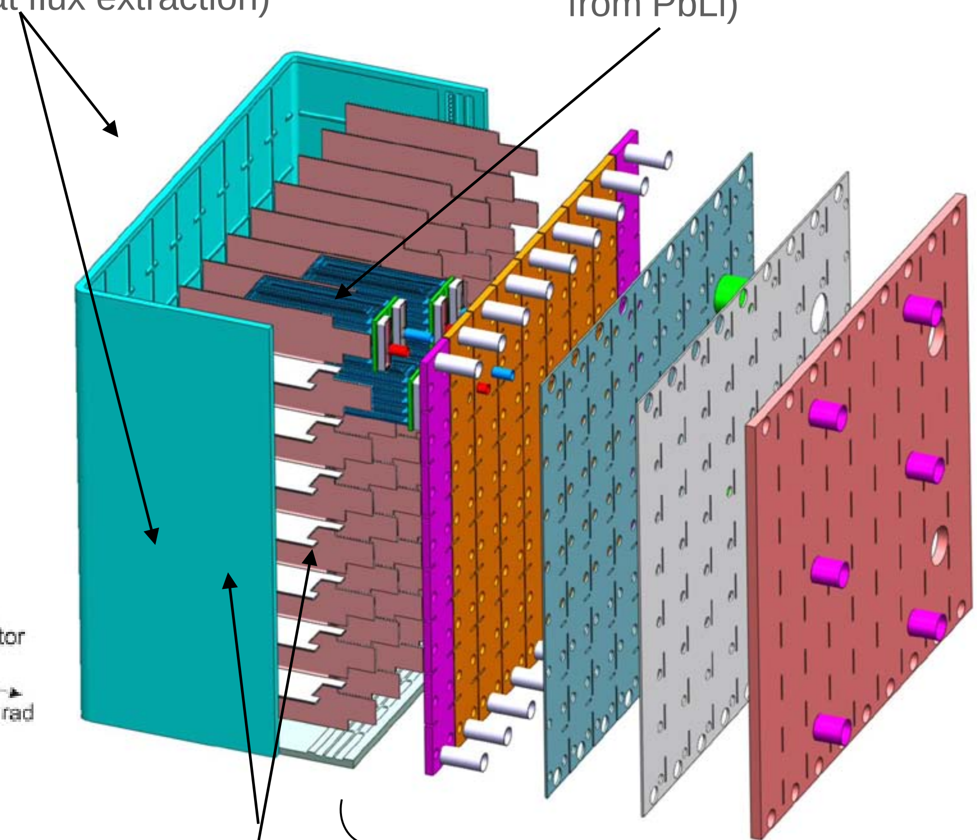
Example: PbLi Breeder / Helium Coolant with RAFM

- 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



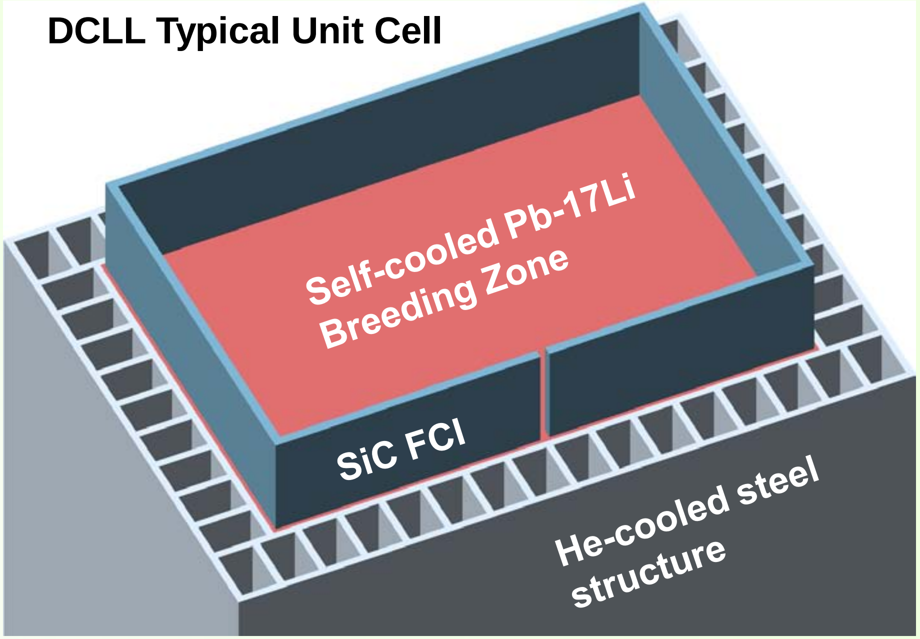


Drawbacks: Tritium Permeation and limited thermal efficiency

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**

FCI does not serve structural function



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

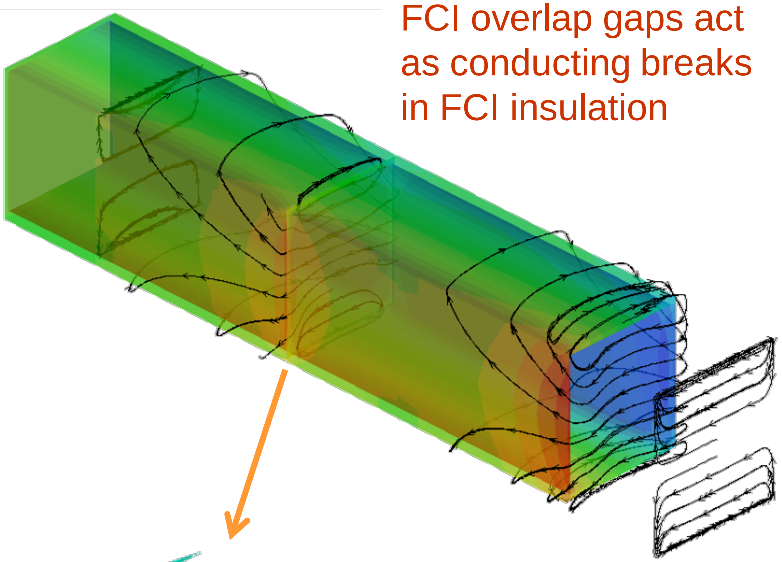
High pressure drop is only one of the MHD issues for LM blankets; MHD heat and mass transfer are also of great importance!

Instabilities and 3D MHD effects in complex detailed geometry and configuration with magnetic and nuclear fields gradients have major impact:

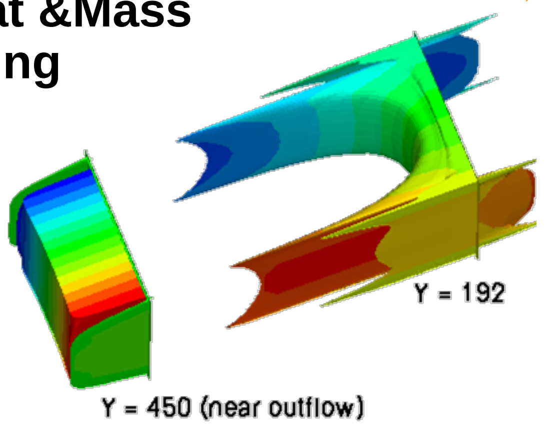
- **Unbalanced pressure drops (e.g. from insulator cracks) leading to flow control and channel stagnation issues**
- **Unique MHD velocity profiles and instabilities affecting *transport of mass and energy.***

Accurate Prediction of MHD Heat &Mass Transfer is essential to addressing important issues such as:

- **thermal stresses,**
- **temperature limits,**
- **failure modes for structural and functional materials,**
- **thermal efficiency, and**
- **tritium permeation.**



FCI overlap gaps act as conducting breaks in FCI insulation



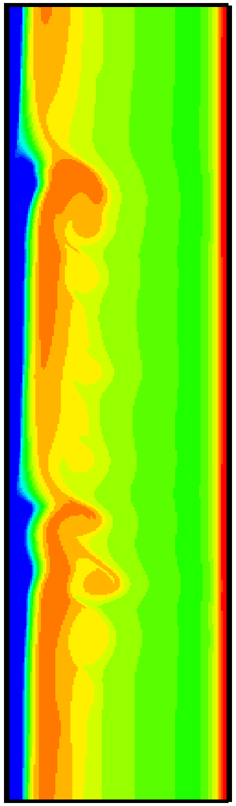
and hence disturb current flow and velocity, and redistribute energy

Courtesy of Munipalli et al.

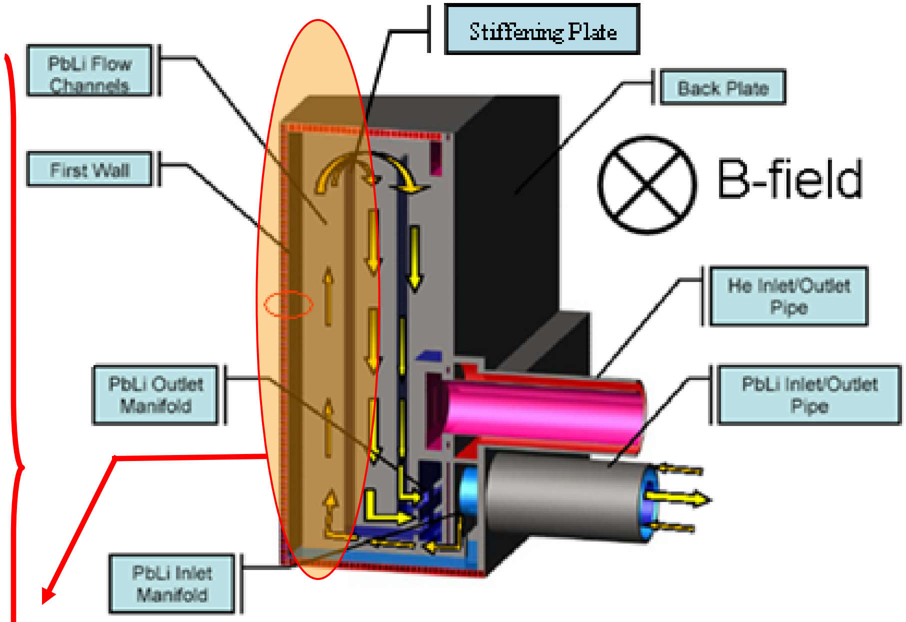
(Ha=1000; Re=1000; σ=5 S/m, cross-sectional dimension expanded 10x)

Buoyancy effects in DCLL blanket

L=60, Ha=100, Re=10,000, Gr=4x10^8, Pr=0.01, a/b=1, m=1, r=6.32



DCLL DEMO blanket, US



Parameter	ITER	DEMO OB
Ha	6500	12,000
Re	30,000	60,000
Gr	7.0×10^{9}	3.5×10^{12}

Vorticity distribution in the buoyancy-assisted (upward) poloidal flow

Caused by $q'''(r) = q'''_{\max} Exp(-\alpha r)$

and associated $\Delta T = \dfrac{q'''_{\max} a^2}{k} \sim 10^3 K$

Can be 2-3 times stronger than forced flows. Forced flow: 10 cm/s. Buoyant flow: 25-30 cm/s.

In buoyancy-assisted (upward) flows, buoyancy effects may play a positive role due to the velocity jet near the "hot" wall, reducing the FCI ΔT.

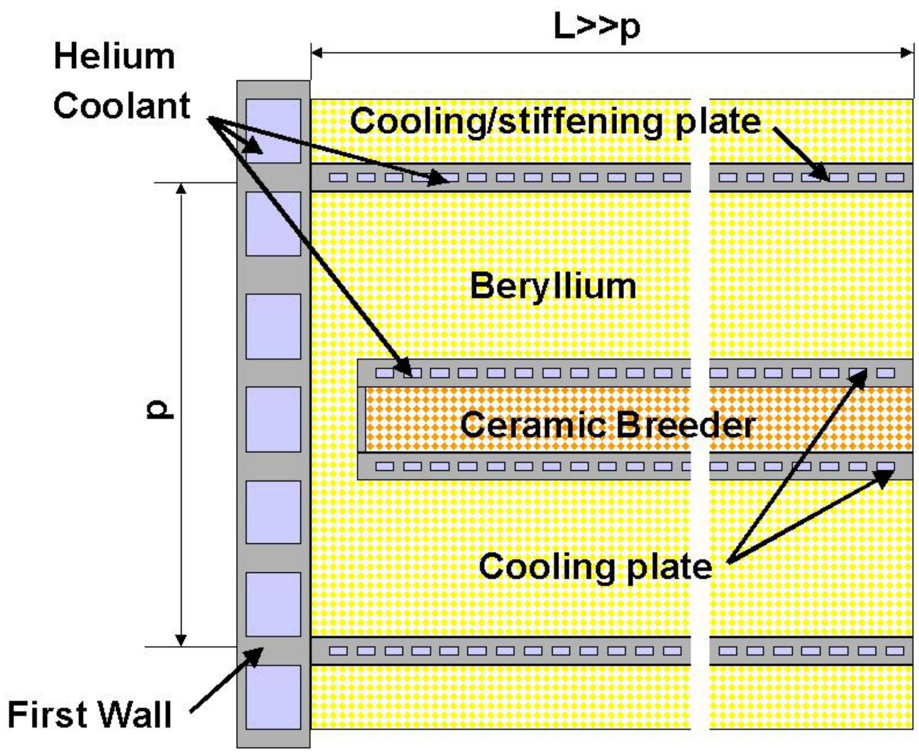
In buoyancy-opposed (downward) flows, the effect may be negative due to recirculation flows.

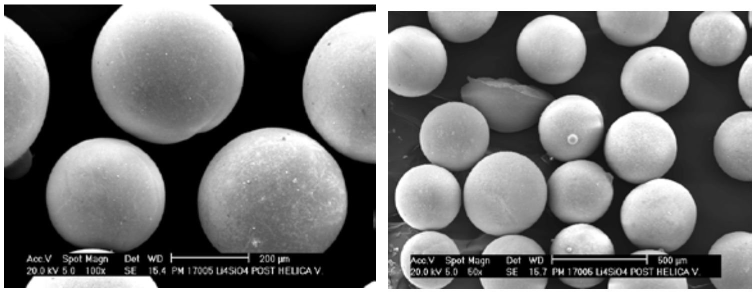
Effect on the interface T, FCI ΔT, heat losses, tritium transport.

Solid breeder blankets utilize immobile lithium ceramic breeder and Be multiplier for tritium self-sufficiency

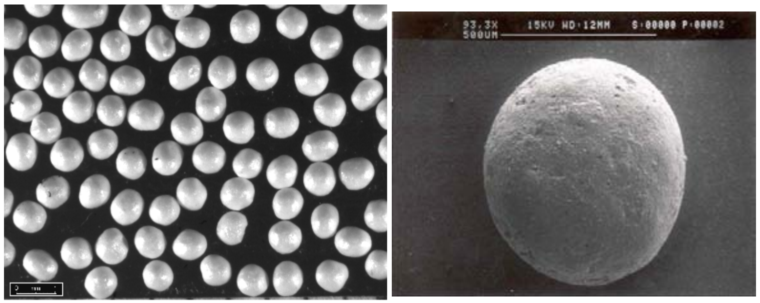
Material Functions

- **Beryllium** (pebble bed) for neutron multiplication
- **Ceramic breeder** (Li_4SiO_4, Li_2TiO_3, Li_2O, etc.) for tritium breeding
- **Helium purge** to remove tritium through the "interconnected porosity" in ceramic breeder
- **High pressure Helium** cooling in structure (advanced ferritic)

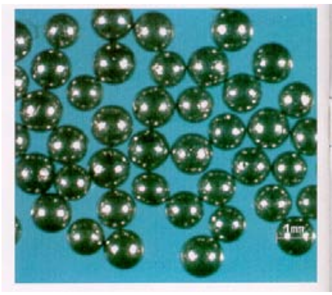




0.2- 0.4 mm Li_4SiO_4 pebbles (FZK)



0.6 – 0.8 mm Li_2TiO_3 pebbles (CEA)

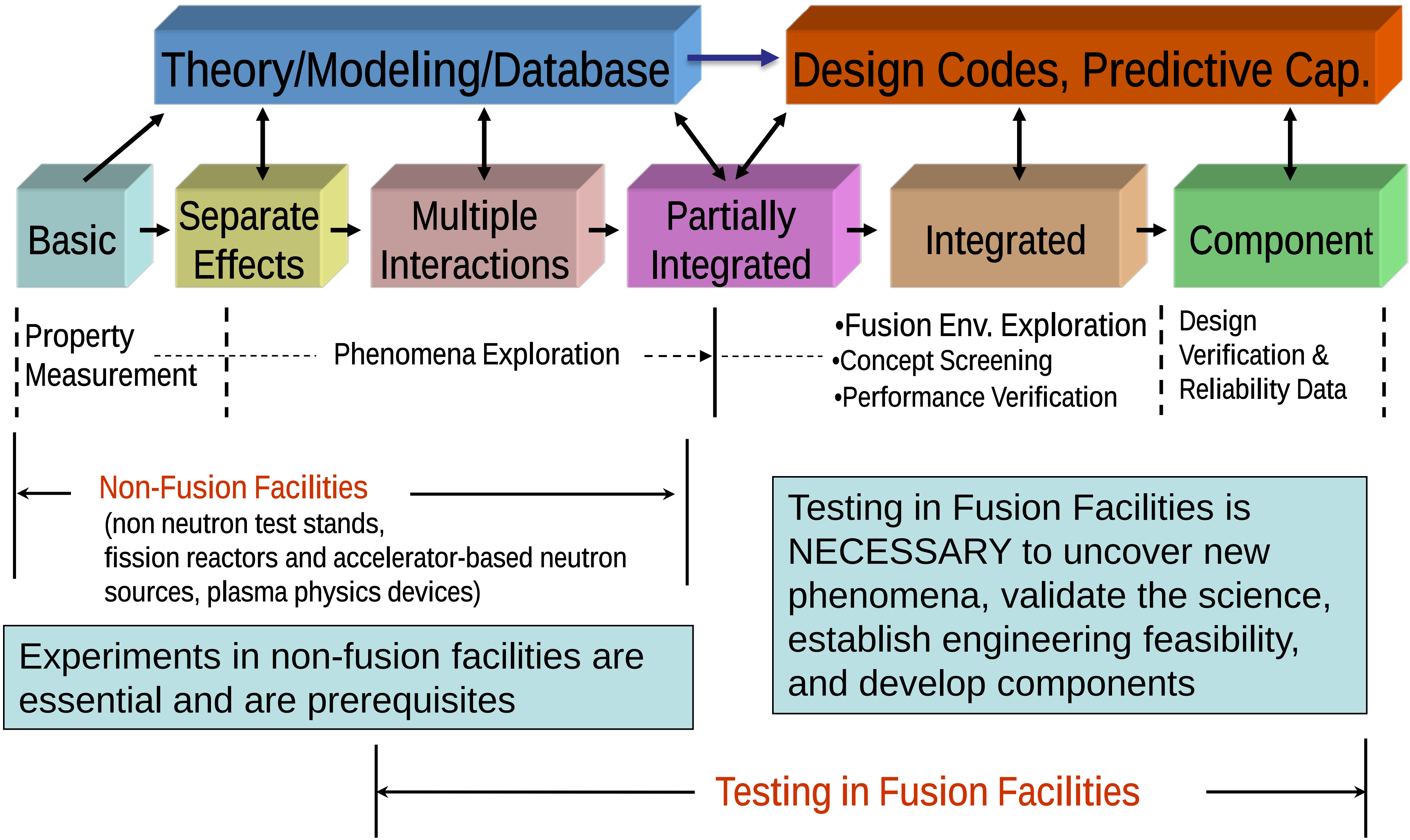


NGK Be-pebble

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**

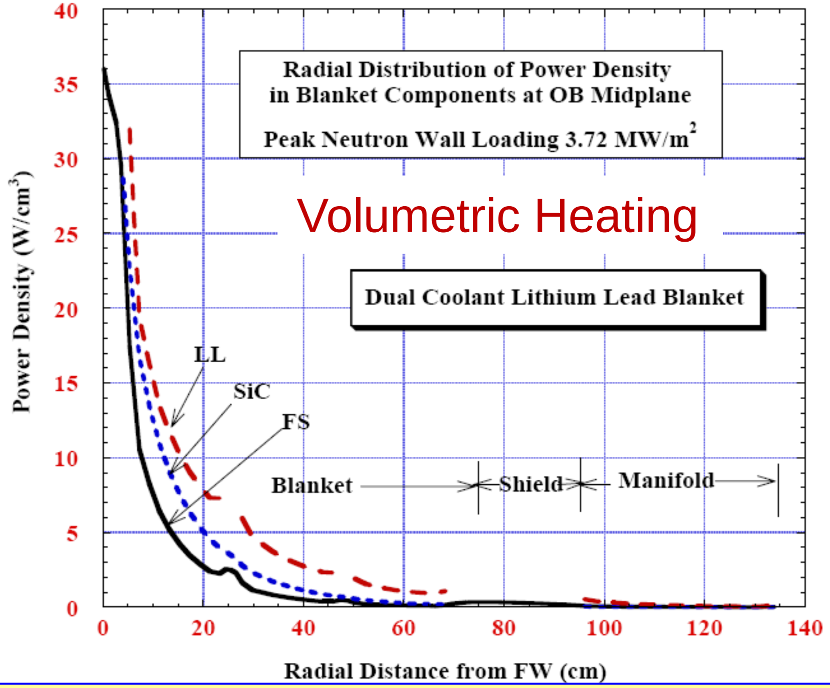
Science-Based Framework for FNST R&D involves modeling and experiments in non-fusion and fusion facilities

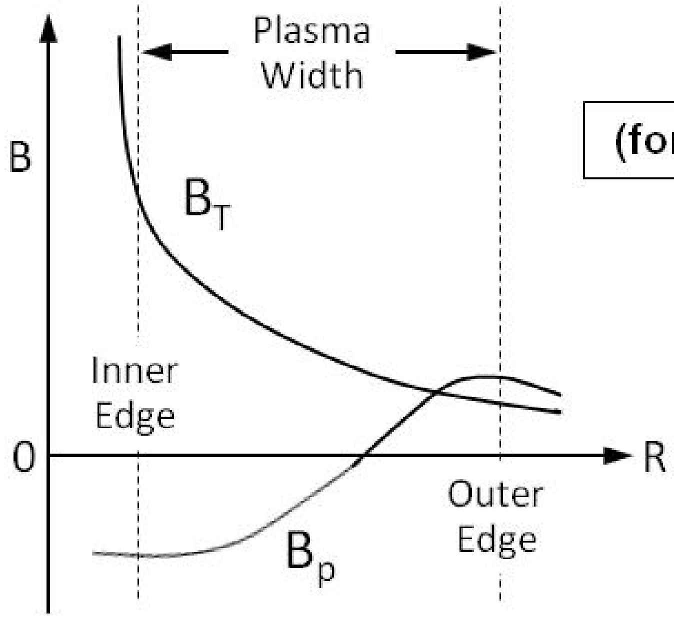


Fusion environment is unique and complex: multi-component fields with gradients

- 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

Fusion "Break-in" & Scientific Exploration	Engineering Feasibility & Performance Verification	Component Engineering Development & Reliability Growth	DEMO
Stage I	Stage II	Stage III	
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	

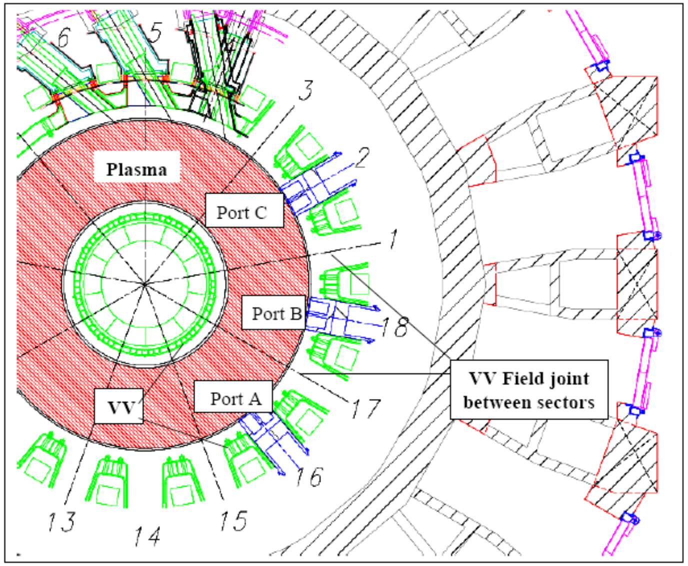
- Initial exploration of coupled phenomena in fusion environment
- Screen and narrow blanket design concepts

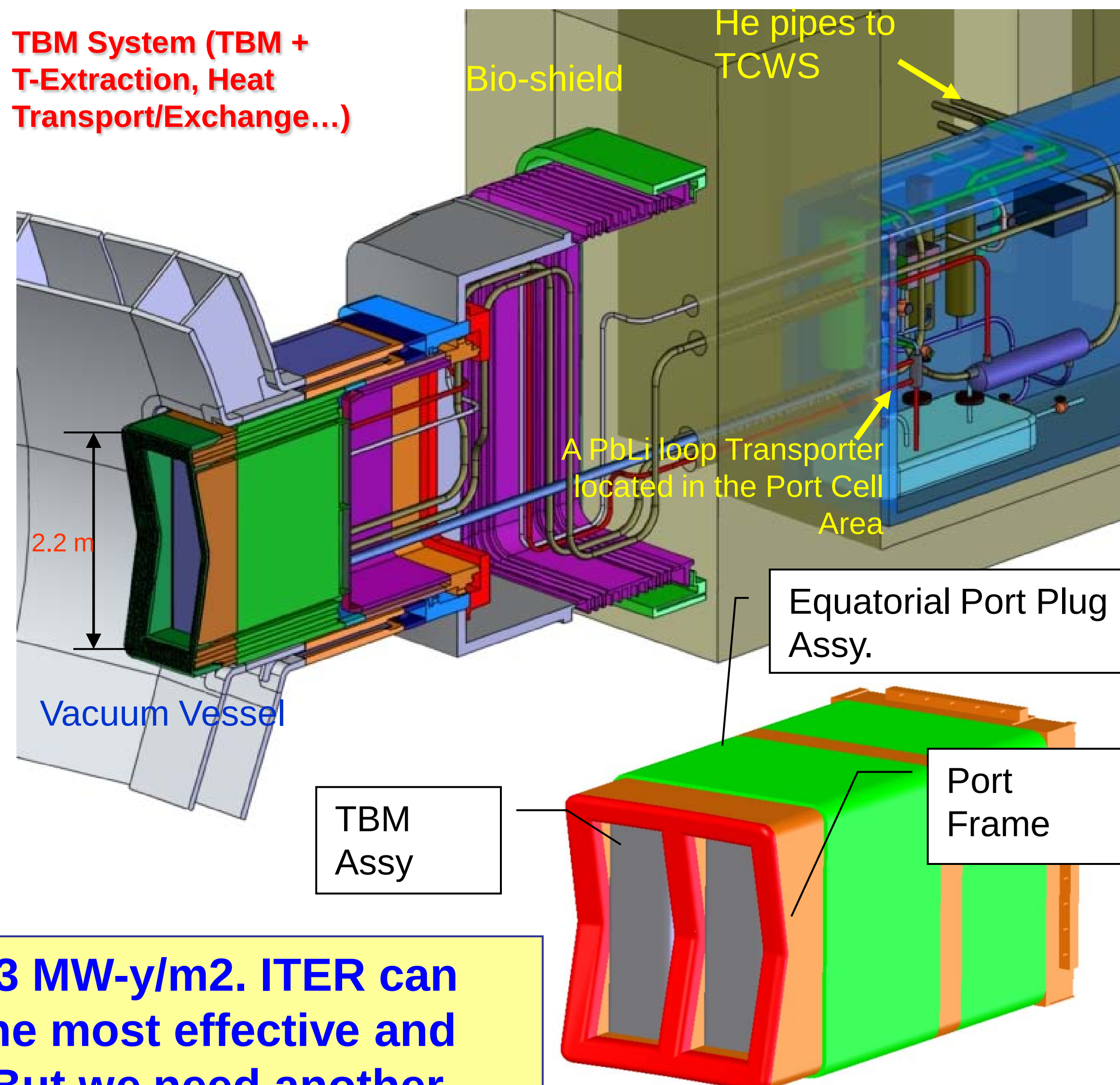
- Establish engineering feasibility of blankets (satisfy basic functions & performance, up to 10 to 20 % of lifetime)
- Select 2 or 3 concepts for further development

- 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.

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

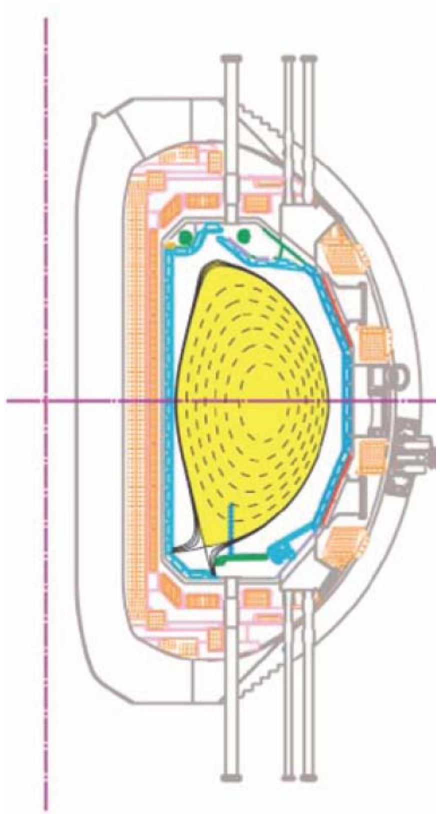
  – Equivalent in IFE: reduced target yield (and smaller chamber radius?)

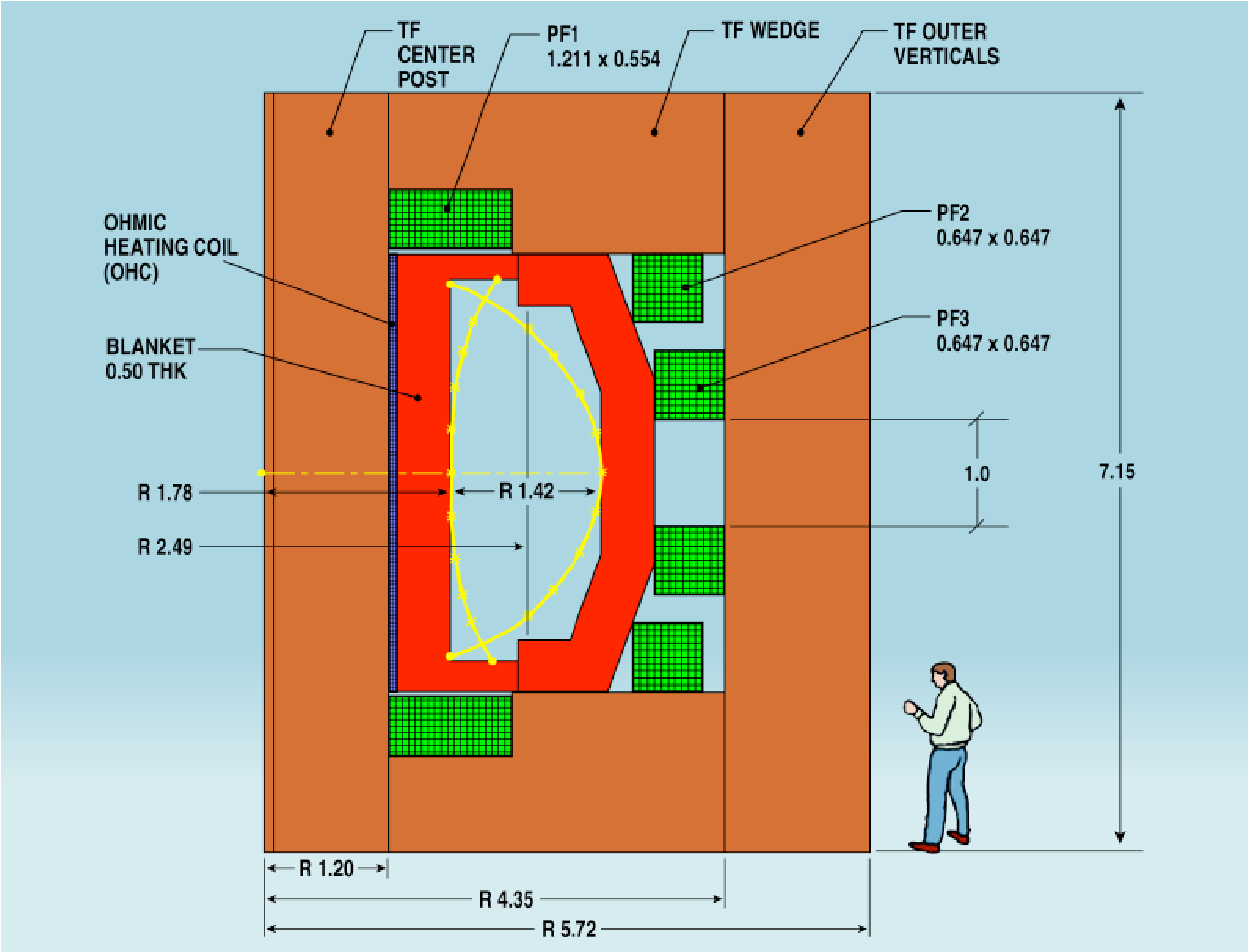
- There are at least TWO classes of Design Options for FNSF:

  – 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)





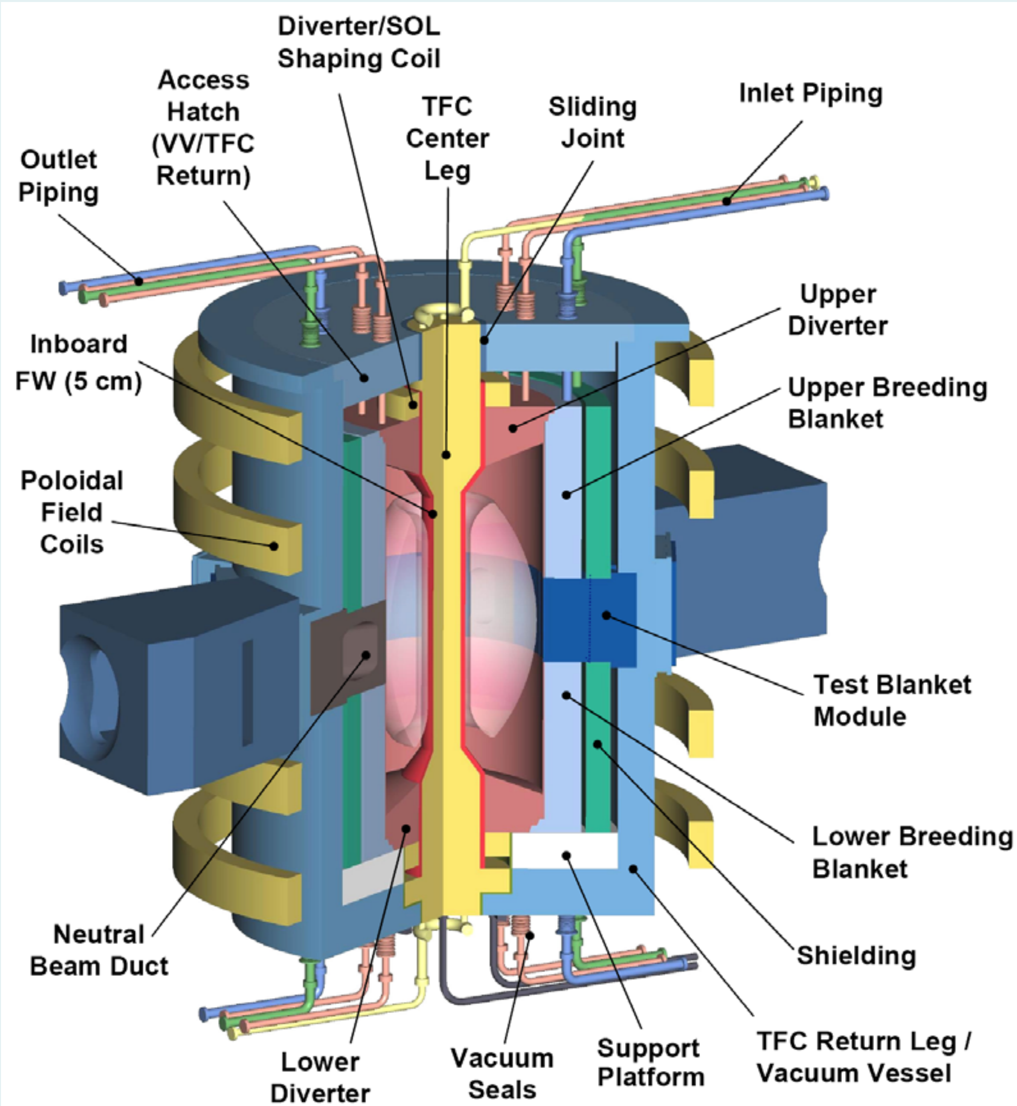
- High elongation, high triangularity double null plasma shape for high gain, steady-state plasma operation

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/m²]	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}/m³]	**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 [m²]	14		
Blanket A [m²]	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

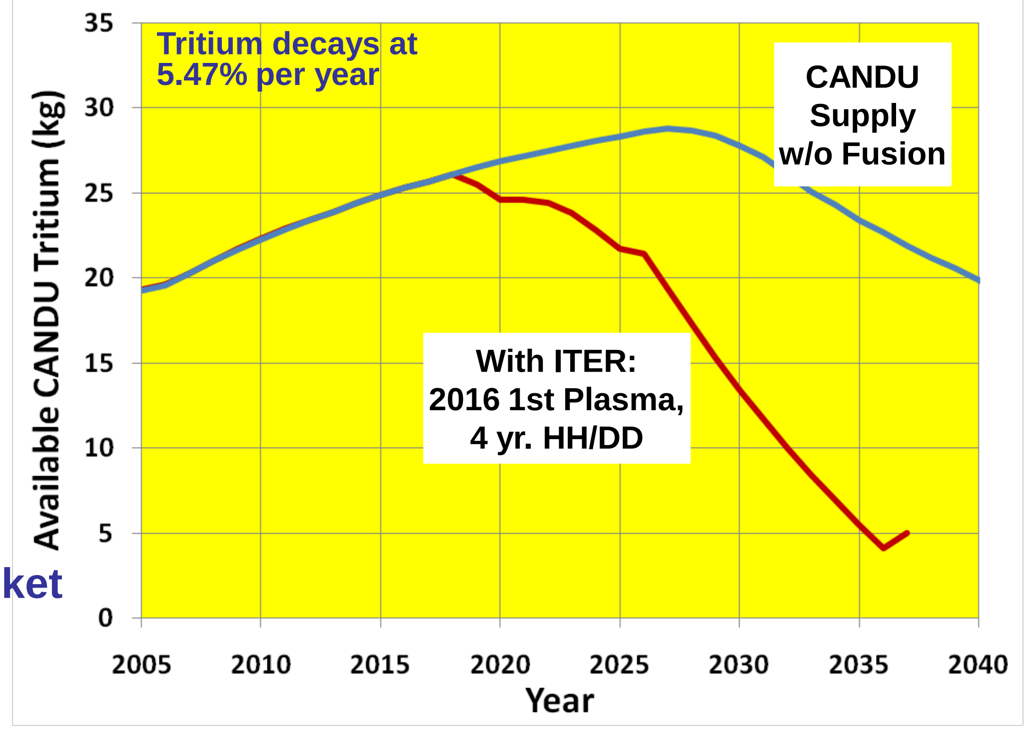
$84M-$130M/kg (per DOE Inspector General*)

*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	Number	Failure rate in hr^{-1}	MTBF in years	MTTR for Major failure, hr	MTTR for Minor failure, hr	Fraction of failures that are Major	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

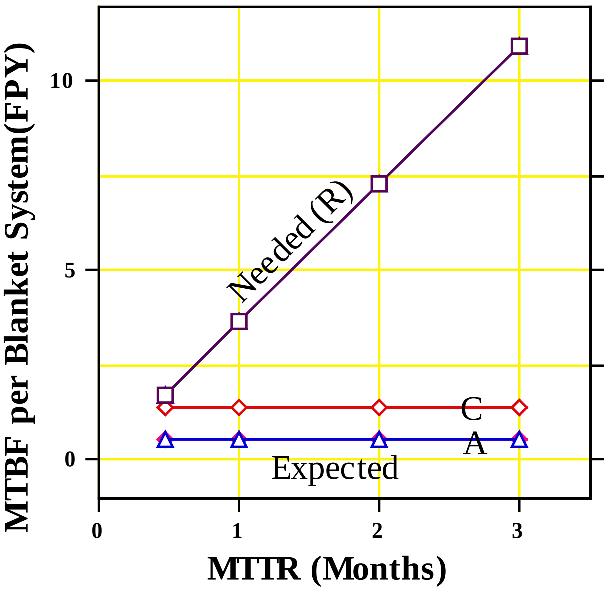
DEMO availability of 50% requires: Divertor Availability ~ 87%
Blanket availability ~88% and blanket MTBF >11 years.

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

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!).



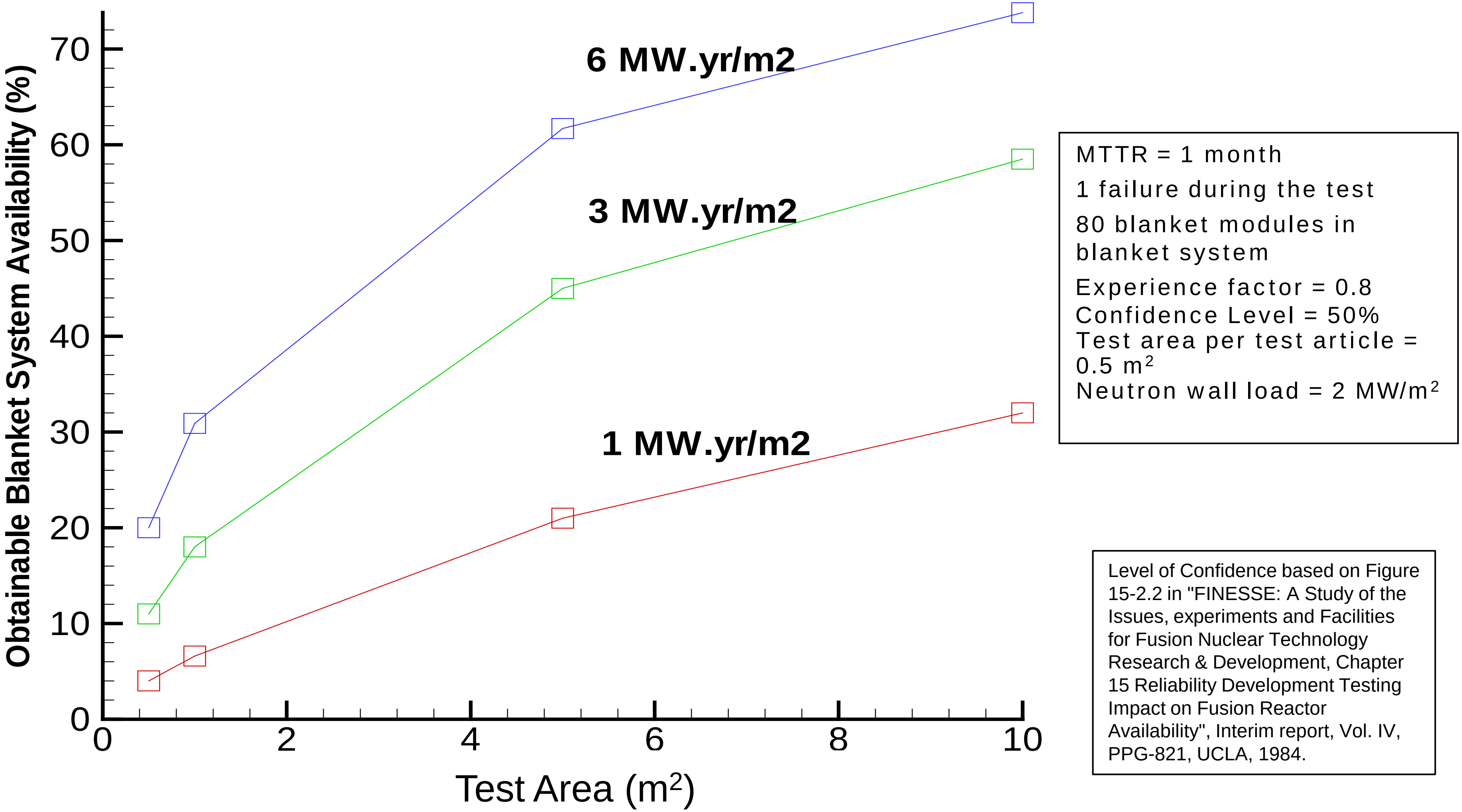
MTBF required >> achievable
Need MTTR < 2 weeks

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

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



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·y/m^2

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

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 an
3. **MHD Thermofluid** ph in electrically-conducting liquid coolar
4. Structural materials **pe** **ler the effect of radiation and**
5. Functional materials pro **adiation and high temperature an** um multipliers, flow channel inserts, electric and therma
6. **Fabrication and joini**
7. **Fluid-materials inter** emistry, compatibility, surface er
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

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.

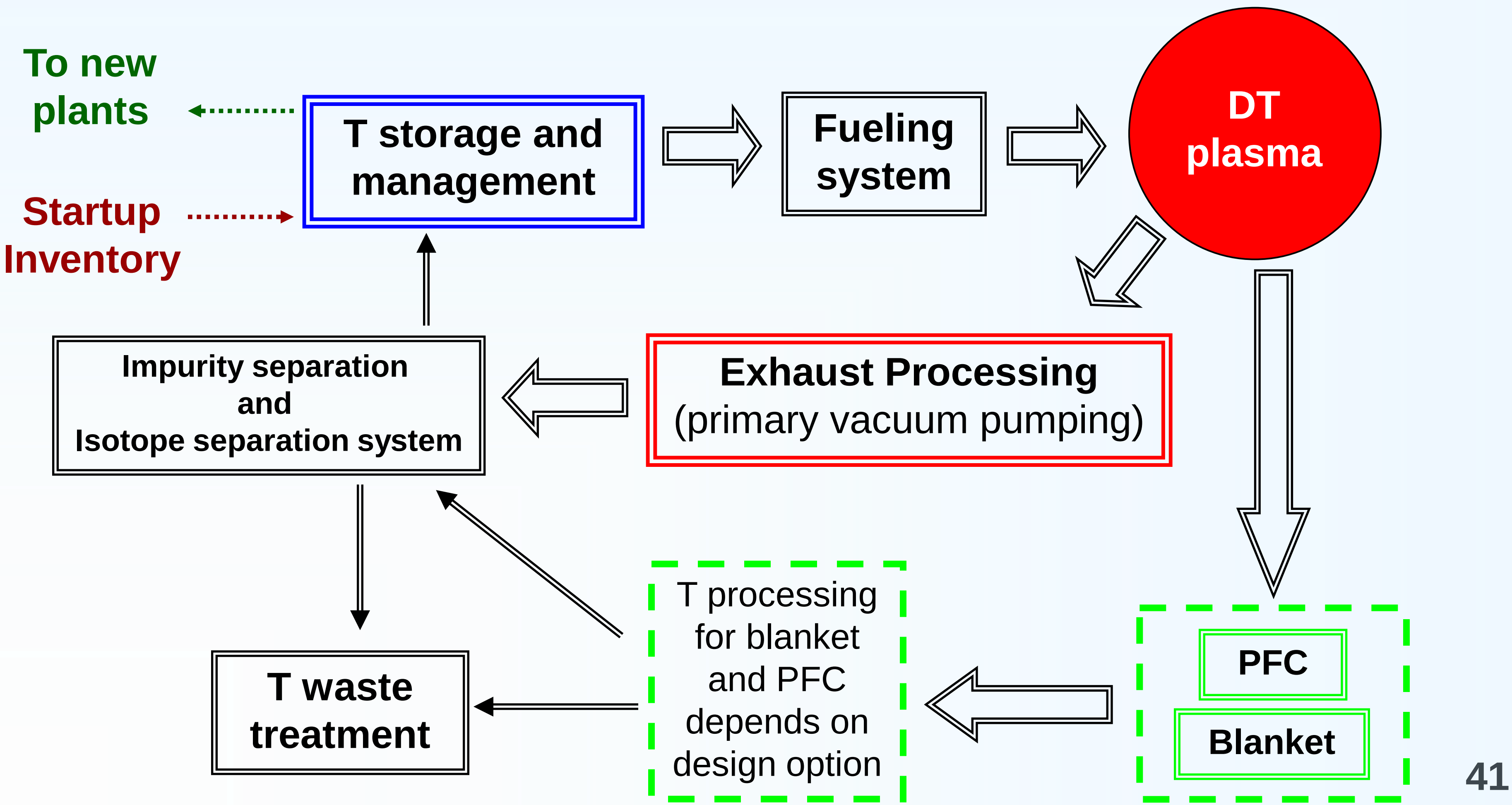
Λa = Achievable tritium breeding ratio

Λa is a function of technology, material and physics.

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

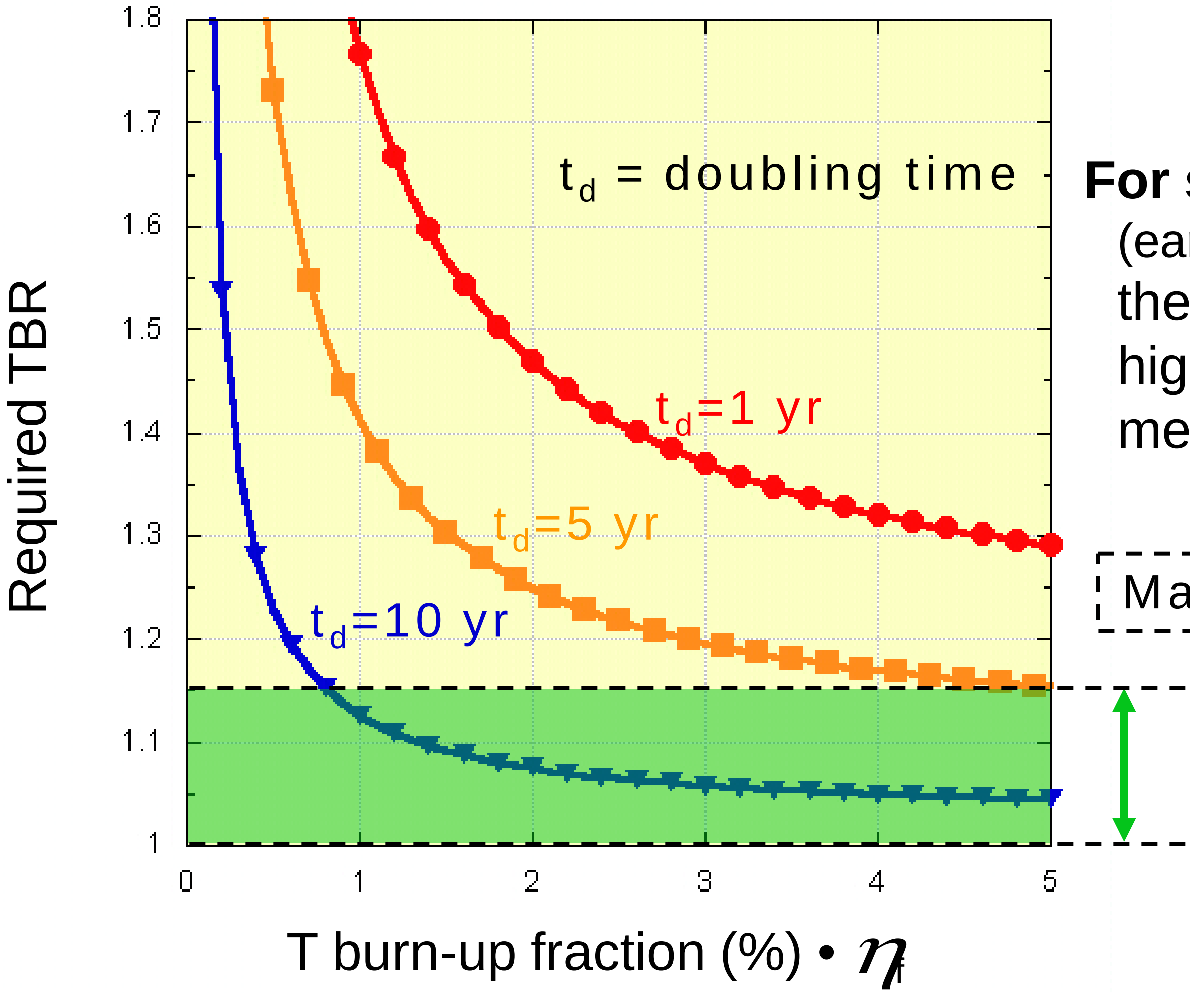
- Safety
- "Start-up" inventory from external sources not available
- Required tritium breeding ratio becomes much higher

Tritium 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

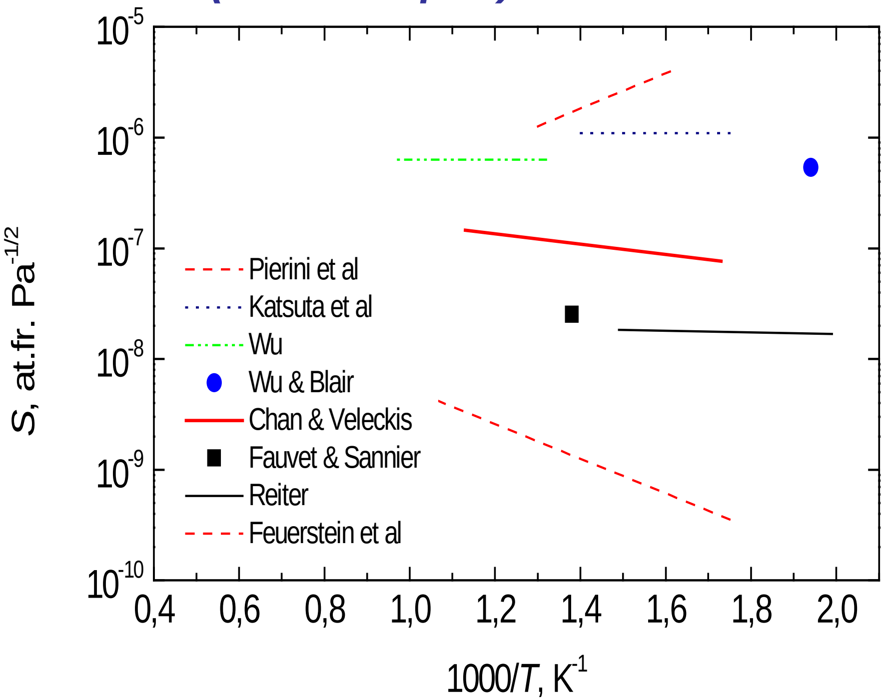
Tritium extraction, inventory, and control in fusion systems

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

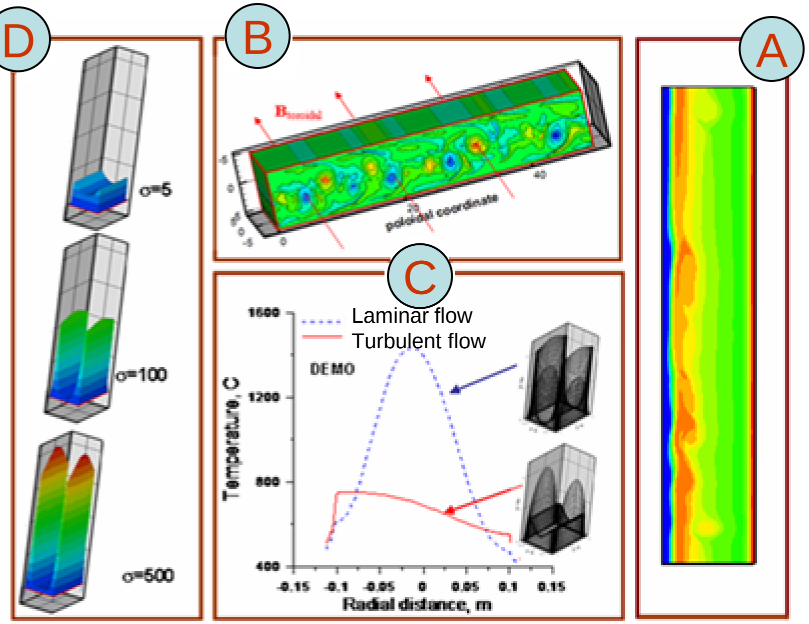
- Much better understanding and advances of phenomenological models for LM fluid flow in the fusion environment with magnetic field and nuclear heating.

- 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.

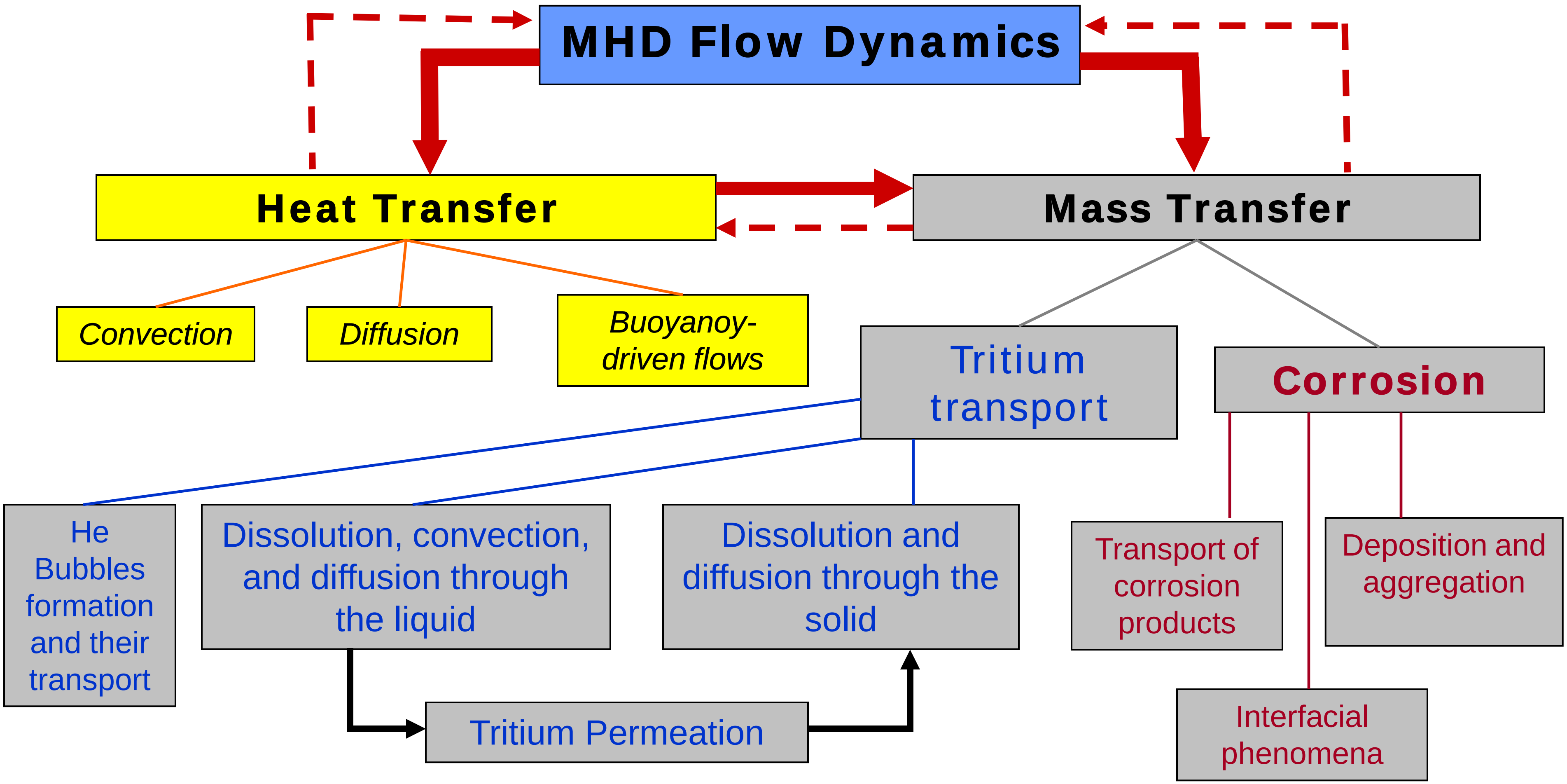
Corrosion rate for samples with and without a magnetic field

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.

Summary of Key Points

❑ 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**