Fusion Nuclear Science and Technology Challenges and Required R&D

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With input from the FNST Community

Related publications can be found at www.fusion.ucla.edu

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Albuquerque NM, Sunset

I appreciate this opportunity to visit LANL and talk to you all

- I have had strong interactions and productive collaborations with many scientists at LANL over the past 30 years
- However, this is my first visit to LANL!
  - Every time I scheduled a visit to LANL something urgent happened and I had to cancel
  - I am delighted that I am finally here. I thank you for the invitation and providing me this opportunity.
- LANL has tremendous capabilities and talented researchers who can make substantial contributios to advancing fusion

Fusion Nuclear Science and Technology Challenges and Required R&D

Presentation Outline

- Introduction to the Fusion Nuclear Environment and Fusion Nuclear Components
- FNST R&D Challenges
- Need for Fusion Nuclear Science Facility (FNSF) parallel to ITER; and FNSF Role and Requirements
- Special Technical Topic: Tritium Self Sufficiency, Fuel Cycle and T Extraction/Processing
- Top Level FNST Issues
- Science Based Framework for Moving Forward
- Required near-term R&D

Renewed Interest in Developing a More Credible Roadmap to Timely Realization of Fusion Power

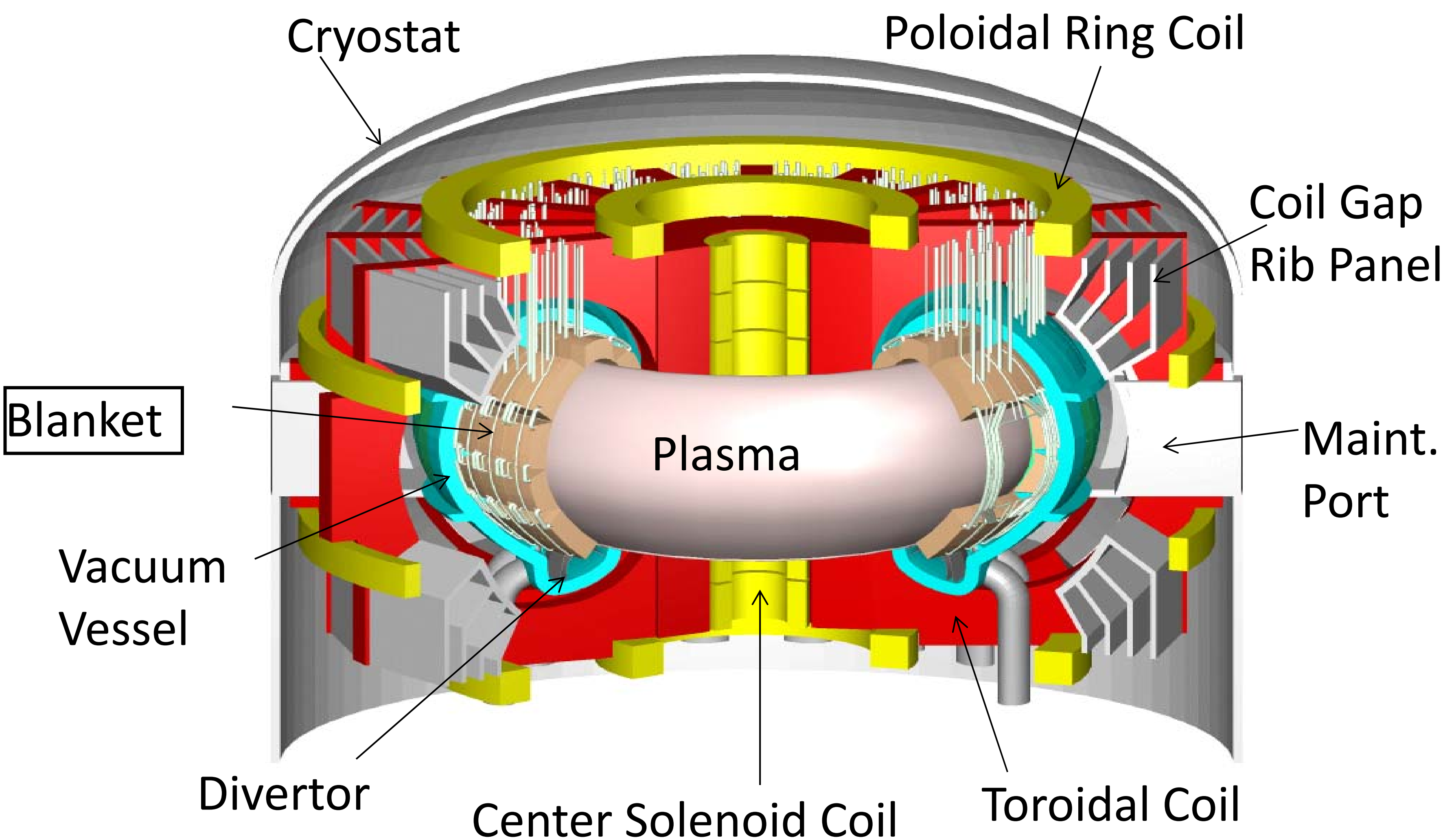
- There were many plans for commercialization of fusion power by the major world fusion programs in the 1970's and 1980's. Such planning activities declined in the 1990's and 2000's *(The world was too busy debating scientific and programmatic issues for ITER!!)*.

- With the beginning of the construction of ITER in 2009, there has been renewed strong interest worldwide in defining in detail a "roadmap" to realizing fusion power on a reasonable time scale. Examples:
  - Series of studies in the US to define pathway to DEMO
  - EFDA in EU has developed a draft plan on missions to DEMO
  - China developed an ambitious plan requested by government
  - IAEA initiated a new series of "DEMO Programme" workshops (the first was held at UCLA October 15-18, 2012)

- **This presentation will discuss the major technical elements and challenges in the roadmap to realizing fusion power and the Central Role of Fusion Nuclear Science and Technology (FNST)**

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)

Fusion Nuclear Science & Technology (FNST)

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

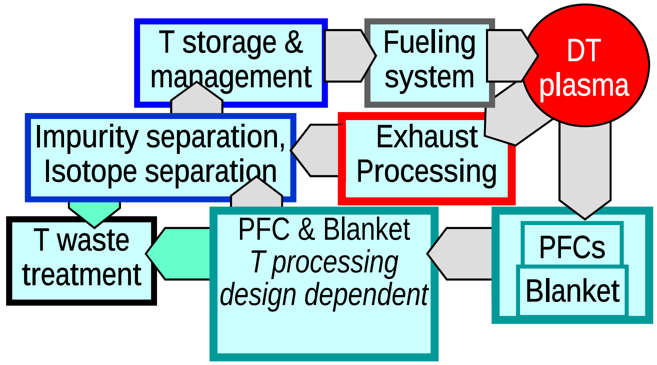
In-vessel Components (Core)

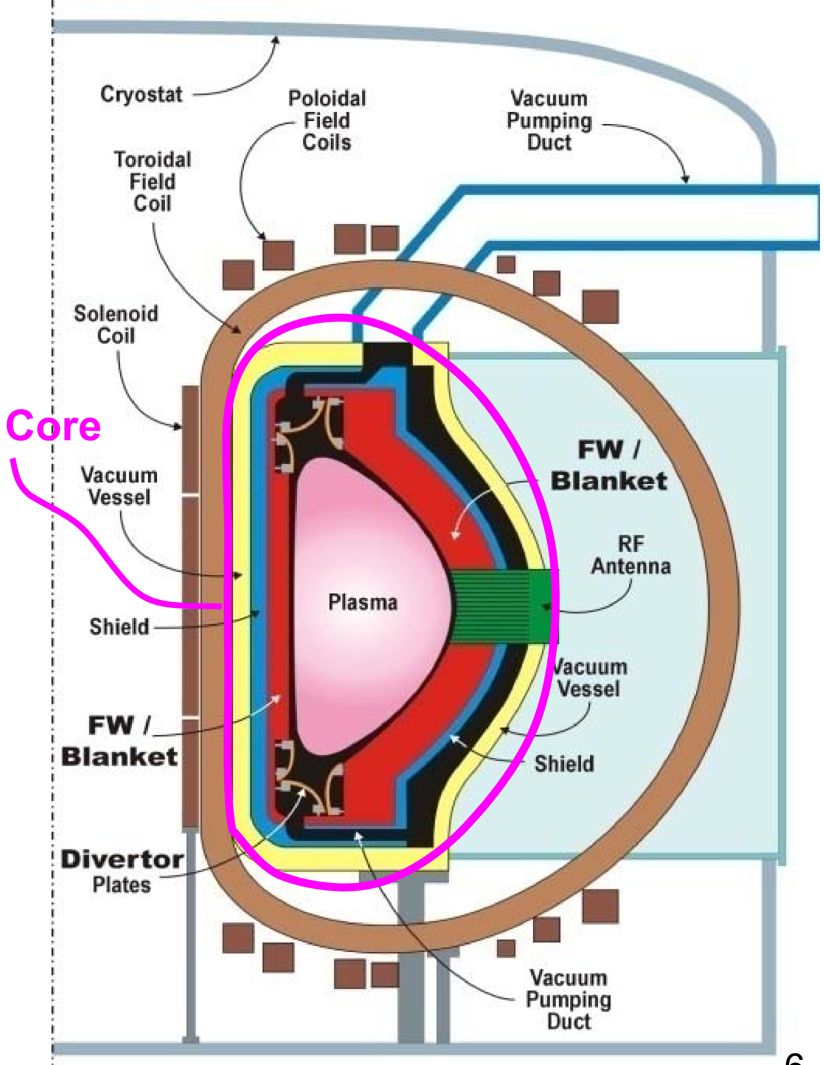
- **Divertor/PFC**
- **Blanket** and **Integral First Wall**
- **Vacuum Vessel** and **Shield**

Key Supporting Systems

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

Tritium Fuel Cycle pervades entire fusion system

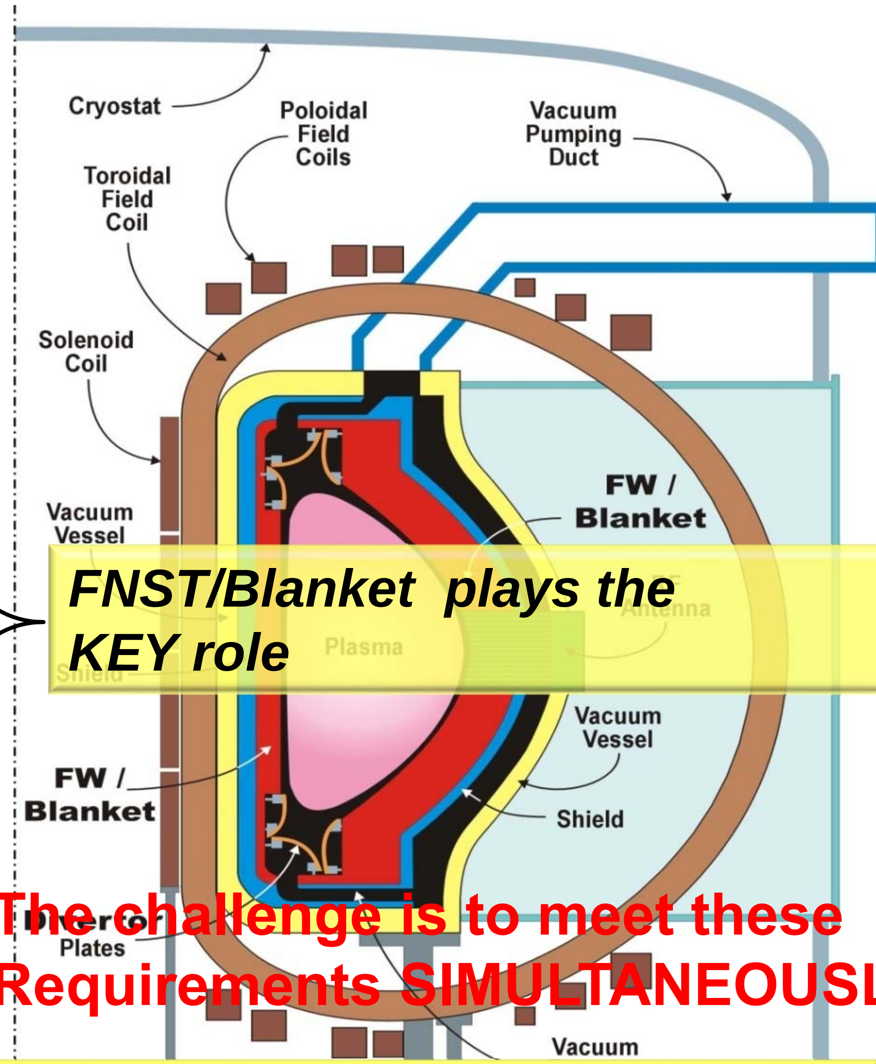




Fusion Goal: Demonstrate that fusion energy can be produced, extracted, and converted under practical and attractive conditions

<u>**Requirements**</u>

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



FNST/Blanket plays the KEY role

The challenge is to meet these Requirements SIMULTANEOUSLY

Yet, FNST has not received the priority and resources needed. E.g. No fusion blanket has ever been built or tested.

R&D Tasks to be Accomplished Prior to Demo

1) Plasma

- Confinement/Burn
- Disruption Control
- Current Drive/Steady State
- Edge Control

2) Plasma Support Systems

- Superconducting Magnets
- Fueling
- Heating
- Diagnostics

3) Fusion Nuclear Science and Technology (FNST)

"In-vessel" Components

- **Divertor and nuclear aspects of heating/CD**
- **Blanket** and **Integral First Wall**
- **Vacuum Vessel** and **Shield**

The nuclear environment also:

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

4) Systems Integration

<u>Where Will These Tasks be Done?!</u>

World programs agree:

- Burning Plasma Facility (ITER) and other plasma devices will address 1, 2, & much of 4
- FNST is the major element missing

- How and Where will Fusion Nuclear Science and Technology (FNST) be developed?
  - Central question for roadmapping
  - Some key differences among world programs strategies

What are the Principal Challenges in the development of FNST?

- The Fusion Nuclear Environment: Multiple field environment (neutrons, heat/particle fluxes, magnetic field, etc.) with high magnitude and steep gradients.

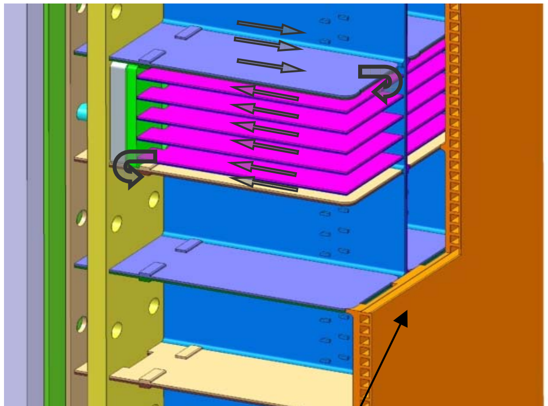
- Nuclear heating in a large volume with sharp gradients
  - *drives most FNST phenomena.*
  - *But simulation of this nuclear heating can be done only in a DT-plasma based facility.*

- Complex configuration with FW/Blanket/Divertor inside the vacuum vessel.

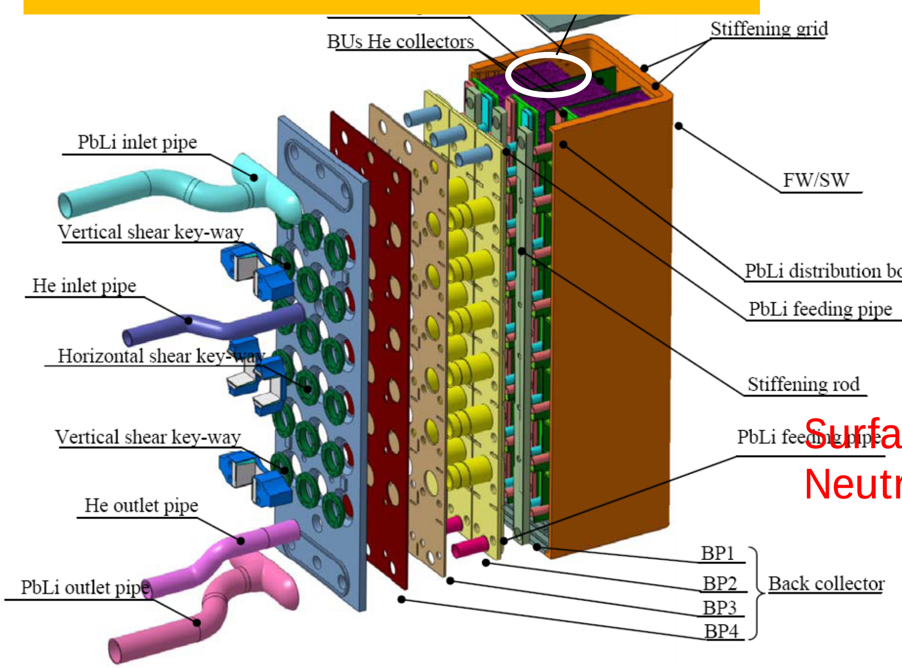
Understanding these challenges is essential to defining a credible roadmap for fusion development

Blanket/FW systems are complex and have many functional materials, joints, fluids, and interfaces

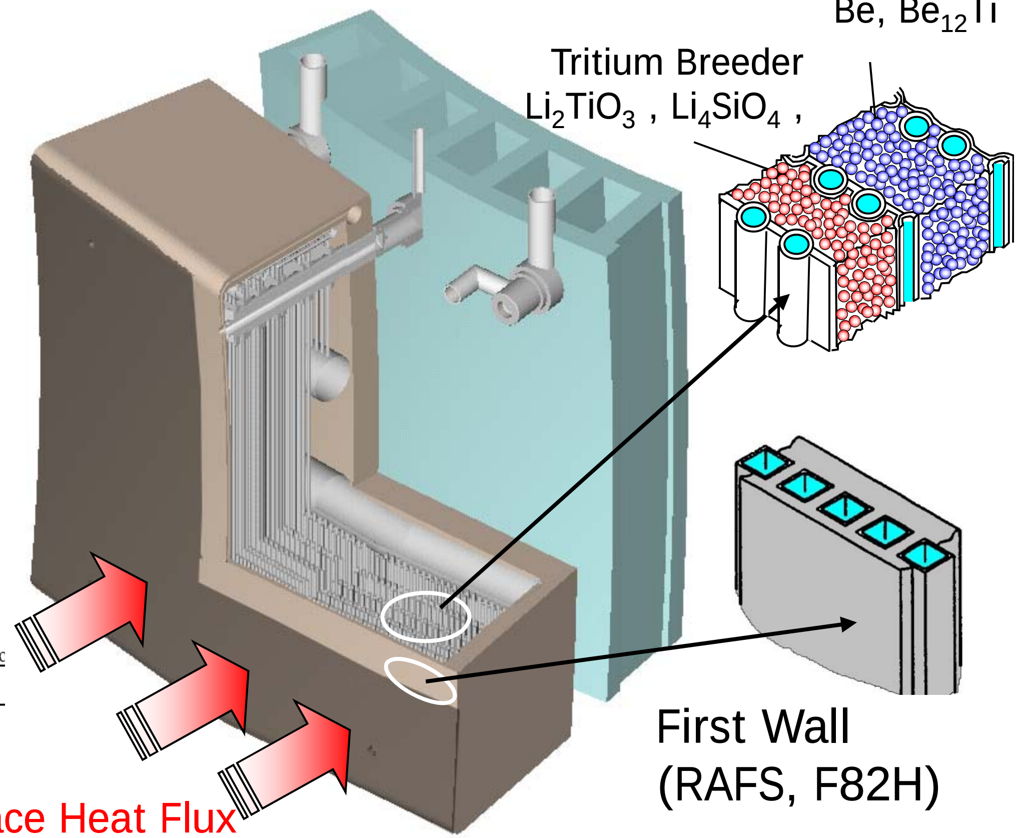
Li, PbLi, Li-Salt flow



E.g. Liquid Breeder Based



E.g. Ceramic Breeder Based



Coolants: He, H_2O, liquid metal or salt

Fusion Nuclear Environment is Complex & Unique

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

- Bulk Heating
- Tritium Production
- Radiation Effects
- 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)*

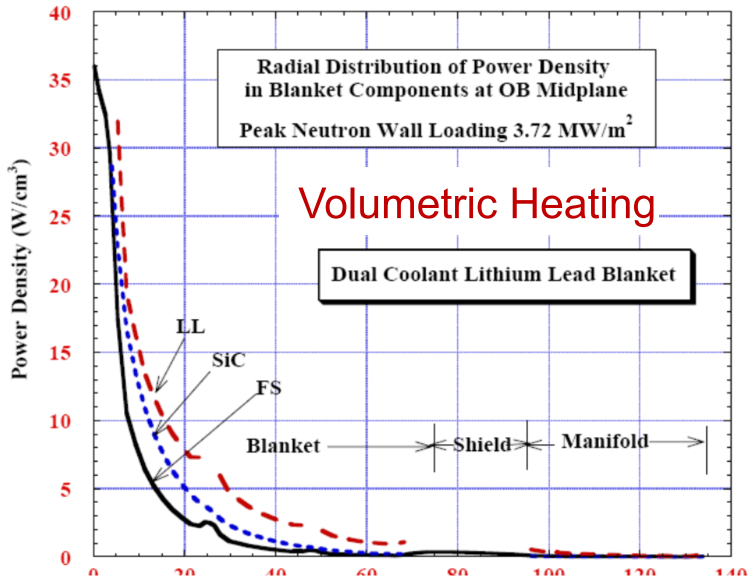
Multiple functions, materials, and many interfaces in highly constrained system

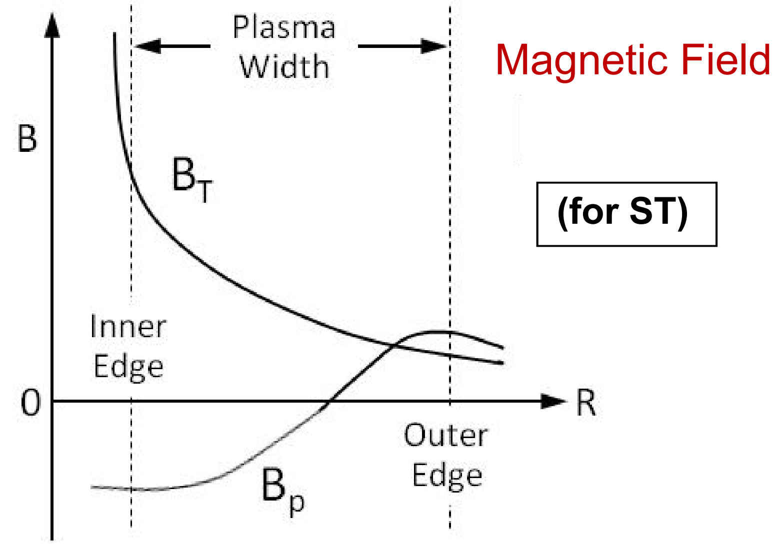
Combined Loads, Multiple Environmental Effects

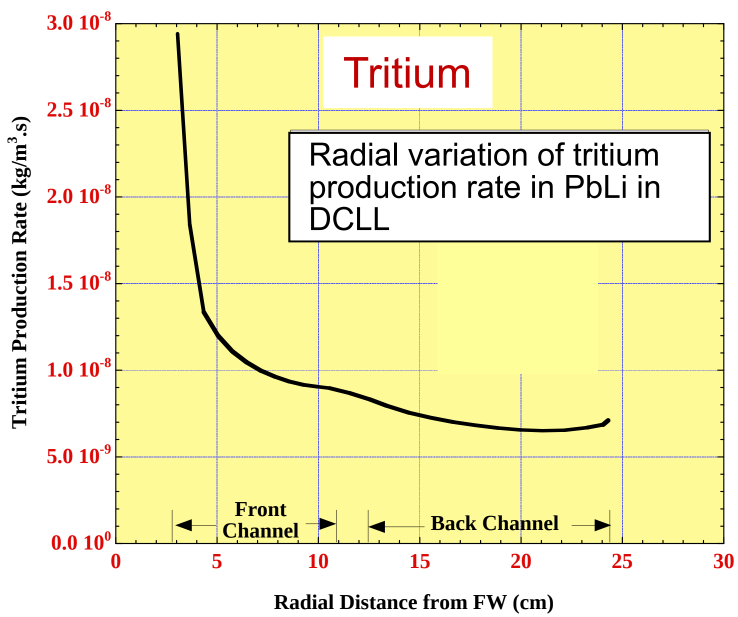
- Thermal-chemical-mechanical-electrical-magnetic-nuclear interactions and synergistic effects
- Interactions among physical elements of components

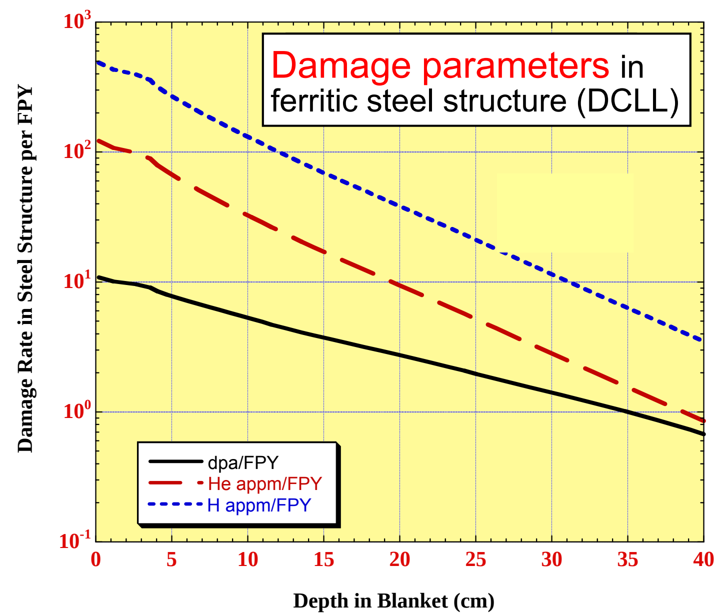
- Many new phenomena YET to be discovered – Experiments are a MUST
- Laboratory experiments need to be substantial to simulate multiple effects
- The full fusion Nuclear Environment can be simulated only in DT plasma–based facility

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.

M. Abdou April 2013

Importance of Bulk Heating and Gradients in the fusion nuclear environment

Simulating nuclear **bulk heating in a large volume with gradients** is necessary to:

1. Simulate the temperature and temperature gradients
   - * Most phenomena are temperature dependent
   - * Gradients play a key role, e.g. :
     - Temperature gradient, stress gradient, differential swelling impact on behavior of component, failure modes
2. Observe key phenomena (and "discover" new phenomena)
   - E.g. nuclear heating and magnetic fields with gradients result in complex mixed convection with Buoyancy forces playing a key role in MHD heat, mass, and momentum transfer
   - For liquid surface divertor the gradient in the normal field has large impact on fluid flow behavior

Simulating nuclear **bulk heating (magnitude and gradient) in a large volume requires a neutron field - can be achieved ONLY in DT-plasma-based facility**

- not possible in laboratory
- not possible with accelerator-based neutron sources
- not possible in fission reactors (limited testing volume, wrong spectrum, wrong gradient)

Conclusions:

- Fusion development requires a DT-plasma based facility to provide the environment for <u>fusion nuclear science experiments</u>.

  The first such facility is called FNSF
- The "first phase" of FNSF must be focused on "Scientific Feasibility and Discovery" – it cannot be for "validation."

CHALLENGE we must face in fusion development

Since the integrated fusion environment, particularly volumetric nuclear heating (with gradients) can be realized only in a DT-Plasma Based Facility:

Then we will have to build the nuclear components in the first DT plasma-based device (first FNSF) from the same technology and materials we are testing:

- ***WITH ONLY LIMITED data from single-effect tests and some multiple-effect tests***
- ***Without data from single-effect and multiple-effect tests that involve Volumetric Nuclear Heating and its gradient***
- ***Without data from synergistic effects experiments***

Conclusions:

1- The Primary Goal of the next step, FNSF (or at least the first stage of FNSF) is to provide the environment for fusion nuclear science experiments.

Trying to skip this "phase" of FNSF is like if we had tried to skip all plasma devices built around the world (JET, TFTR, DIII-D, JT-60, KSTAR, EAST, ,etc) and go directly to ITER (or skipping ITER and go directly to DEMO).

2- The next step, FNSF (or at least the first stage of FNSF) cannot be overly ambitious although we must accept risks. The DD phase of the first FNSF also plays key testing role in verifying the performance of divertor, FW/Blanket and other PFC before proceeding to the DT phase.

Steady State and Transient Heat and EM Loads and DESIGN of Divertor and integrated First Wall/Blanket represent major issue

- First Wall must be **integrated** with the blanket. **Separate** first wall not viable because of reduction in TBR and difficulties in attachment design, reliability, and maintenance. ITER has separate thick FW (70mm SS/water). Reactor studies have much thinner integrated first wall ~10mm (~25mm with 60% helium)

- Current Situation: Large uncertainties exist in Steady State and Transient Heat and EM Loads on Divertor and First Wall.

  Design solutions are yet to be discovered for the higher loadings and transients such as disruptions and ELMS.

  (Reactor studies so far do not incorporate transients into design considerations)

Fusion R&D must emphasize

- Strong coupling between physics and engineering
- Determine with better accuracy a narrower range of heat loads and ability to control transients
- Explore options and concepts for divertor configuration and physics operating mode that can lower heat flux and transients
- Determine the engineering limits of capabilities to handle heat and EM loads
- Pursue Parallel R&D in this area, e.g Solid Wall (W) AND Liquid Walls/Surfaces (Li, Sn-Li,..)

Reliability/Availability/Maintainability/Inspectability (RAMI) is a serious challenge that has major impact on priorities and strategy for fusion R&D

Availability required for each component needs to be high

Component	#	failure rate (1/hr)	MTBF (yrs)	MTTR/type Major (hrs)	MTTR/type Minor (hrs)	Fraction Failures Major	Outage Risk	Component Availability
Toroidal	16	5×10^{-6}	23	10^{4}	240	0.1	0.098	0.91
C								
F								
C								
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	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.884
Fueling	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.998
Tritium System	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.995
Vacuum	3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.998
Conventional equipment- instrumentation, cooling, turbines, electrical plant							[illegible]	0.952
TOTAL SYSTEM (Due to unscheduled maintenances)							0.624	0.615

Two key parameters:
- **MTBF – Mean time between failures**
- **MTTR – Mean time to repair**

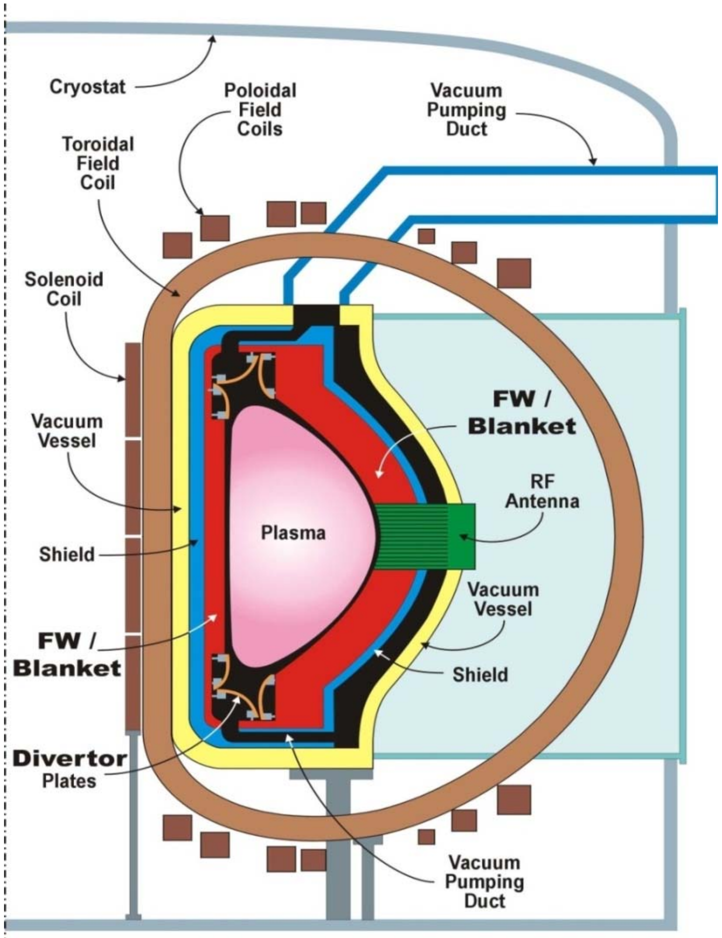
DEMO availability of 50% requires:
- **Blanket/Divertor Availability ~ 87%**
- **Blanket MTBF >11 years**
- **MTTR < 2 weeks**

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!!

This short MTBF / long MTTR issue will be the most serious challenge in FNSF from beginning to end

In addition to the severe nuclear environment, MTBF/MTTR requirements for Blanket & Divertor are driven by **the location *inside* the vacuum vessel:**

- Many failures (e.g. coolant leak) require immediate shutdown, no redundancy possible,
  low fault tolerance – short MTBF
- Limited access, repair/replacement difficult
  long MTTR



Conclusion: Performance, Design Margin, Failure Modes/Rates should now be the focus of FNST R&D, Not a long dpa life

1. Setting goals for MTBF/MTTR is more important NOW than dpa goals for lifetime of materials
2. Current R&D now should focus on:
   - Scientific understanding of multiple effects, performance and failures so that functions, requirements and safety margins can be achieved and designs simplified & improved
   - Subcomponent tests including non-nuclear tests
     (current irradiation data for RAFS small-size specimens is more than sufficient for now)

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.

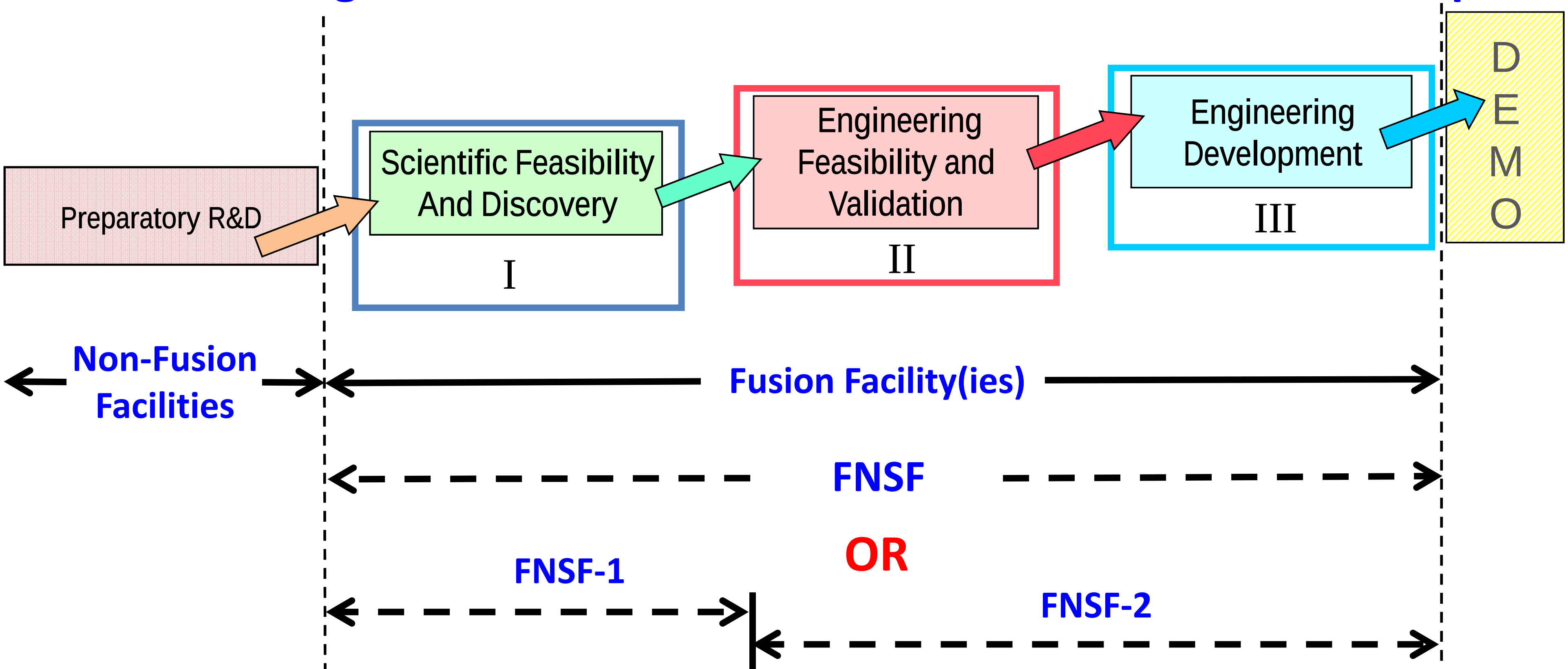
In MFE: small-size, low fusion power can be obtained in a low-Q (driven) plasma device, with normal conducting Cu magnets.

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/m^2 on 10-30 m^2 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).**

Science-Based Pathway to DEMO Must Account for Unexpected FNST Challenges in Current FNST and Plasma Confinement Concepts



- Today, we do not know whether **one** facility will be sufficient to show scientific feasibility, engineering feasibility, and carry out engineering development

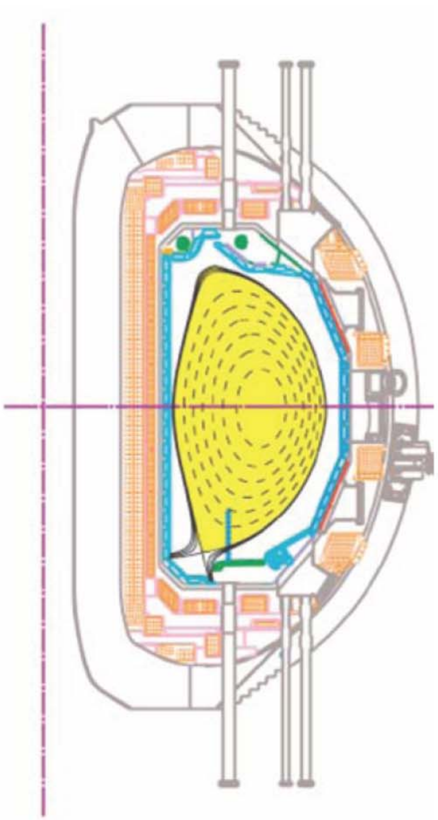
  OR if we will need **two or more** consecutive facilities.

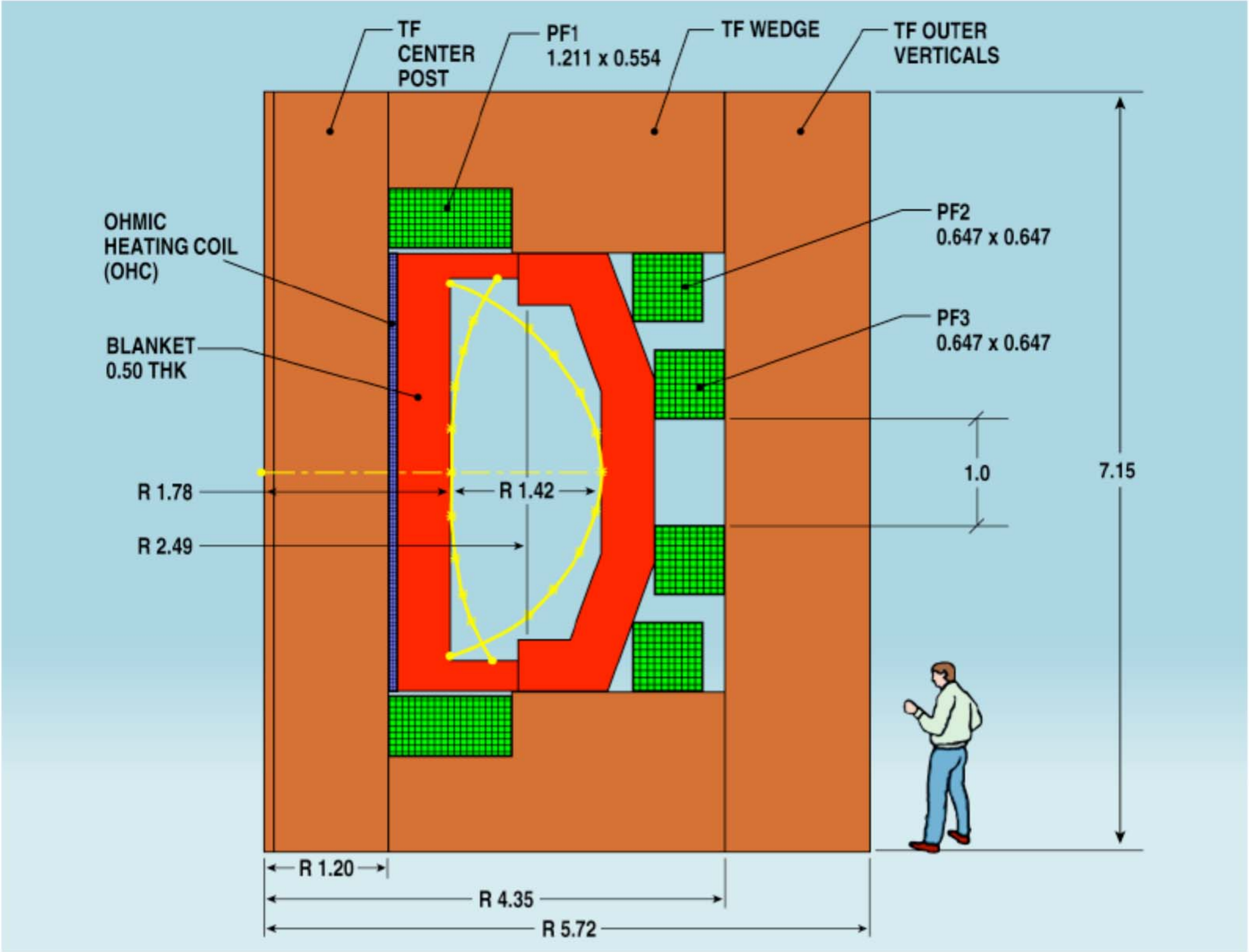
  Maybe multiple FNSF in parallel?!

We will not know until we build one!!

- Only Laws of nature will tell us regardless of how creative we are. We may even find we must change "direction" (e.g. New Confinement Scheme)

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

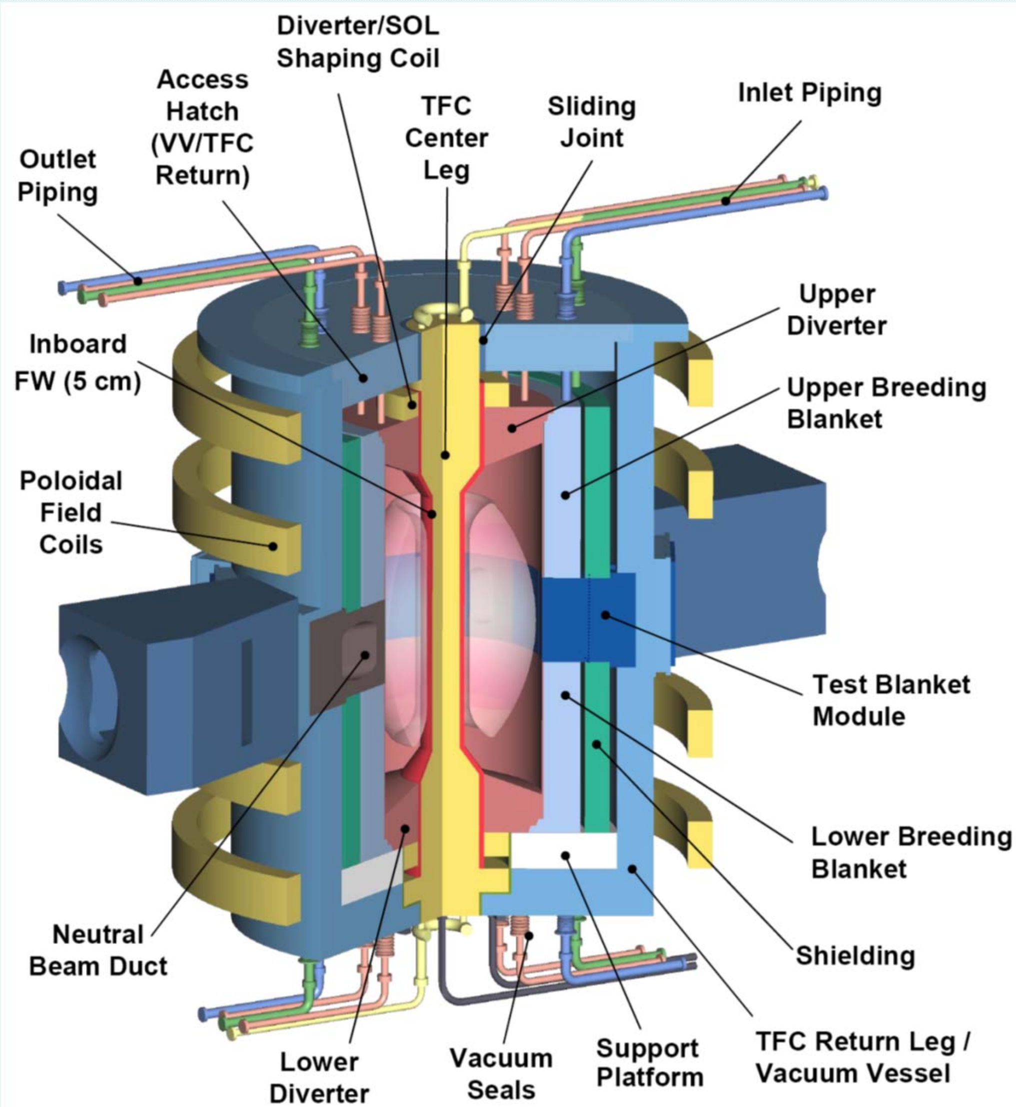
Challenges for Material/Magnet Researchers:

- **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, κ=3, P_{Fusion}=75MW



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

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:

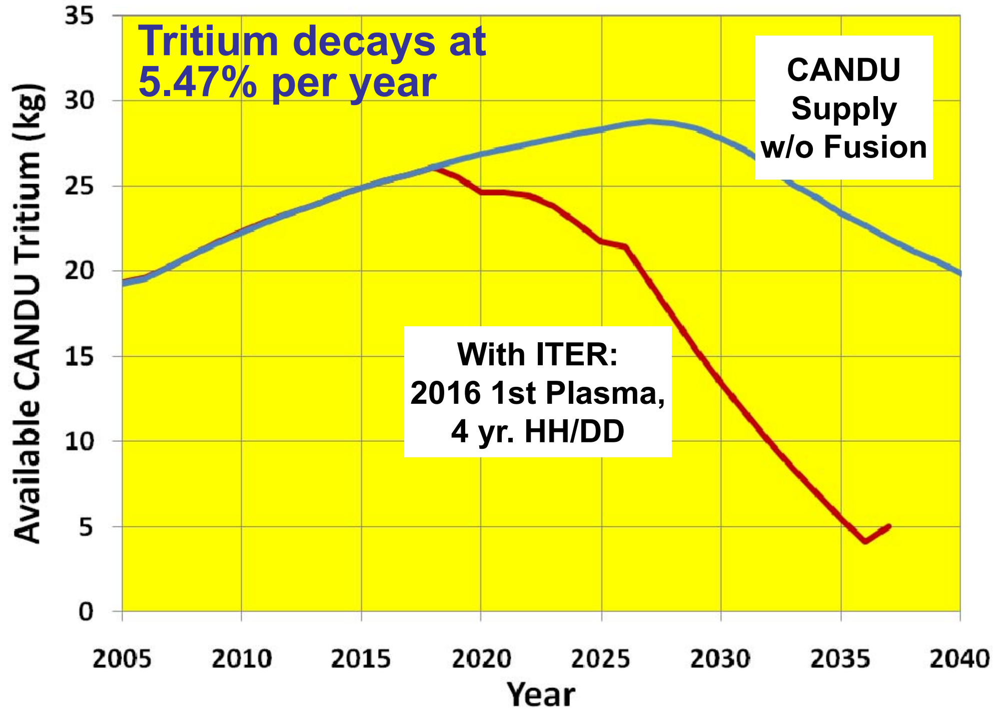
Fission reactors: 2–3 kg/year

$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)

- **A Successful ITER will exhaust most of the world supply of tritium**
- **No DT fusion devices other than ITER can be operated without a breeding blanket**
- **Development of breeding blanket technology must be done in small fusion power devices.**



Two Issues In Building A DEMO:

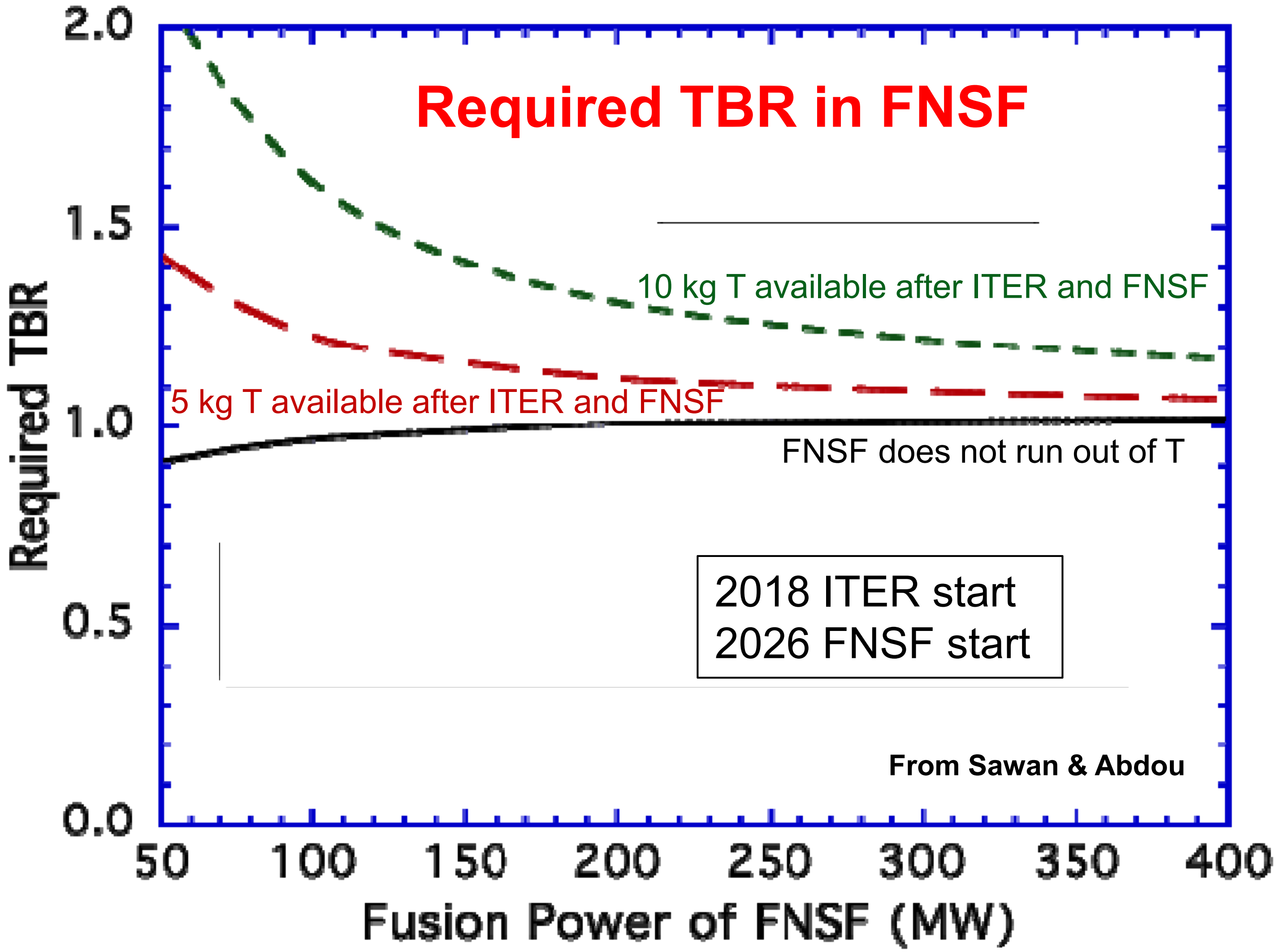
1 – Need Initial (startup) inventory of >10 kg per DEMO
(How many DEMOS will the world build? And where will startup tritium come from?)

2 – Need Verified Breeding Blanket Technology to install on DEMO

FNSF has to breed tritium to:

a) Supply most or all of its consumption

b) Accumulate excess tritium sufficient to provide the tritium inventory required for startup of DEMO



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

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Tritium self-sufficiency condition:
$TBR_a \geq TBR_r$

TBR_a = Achievable tritium breeding ratio

TBR_a is a function of **technology, material** and **physics**.

TBR_r = Required tritium breeding ratio

TBR_r *should exceed unity by a margin required to:*

1) *Compensate for losses and radioactive decay (5.47% per year) of tritium between production and use*
2) *Supply tritium inventory for start-up of other reactors (for a specified doubling time)*
3) *Provide a "reserve" storage inventory necessary for continued reactor operation under certain conditions (e.g. a failure in a tritium processing line)*

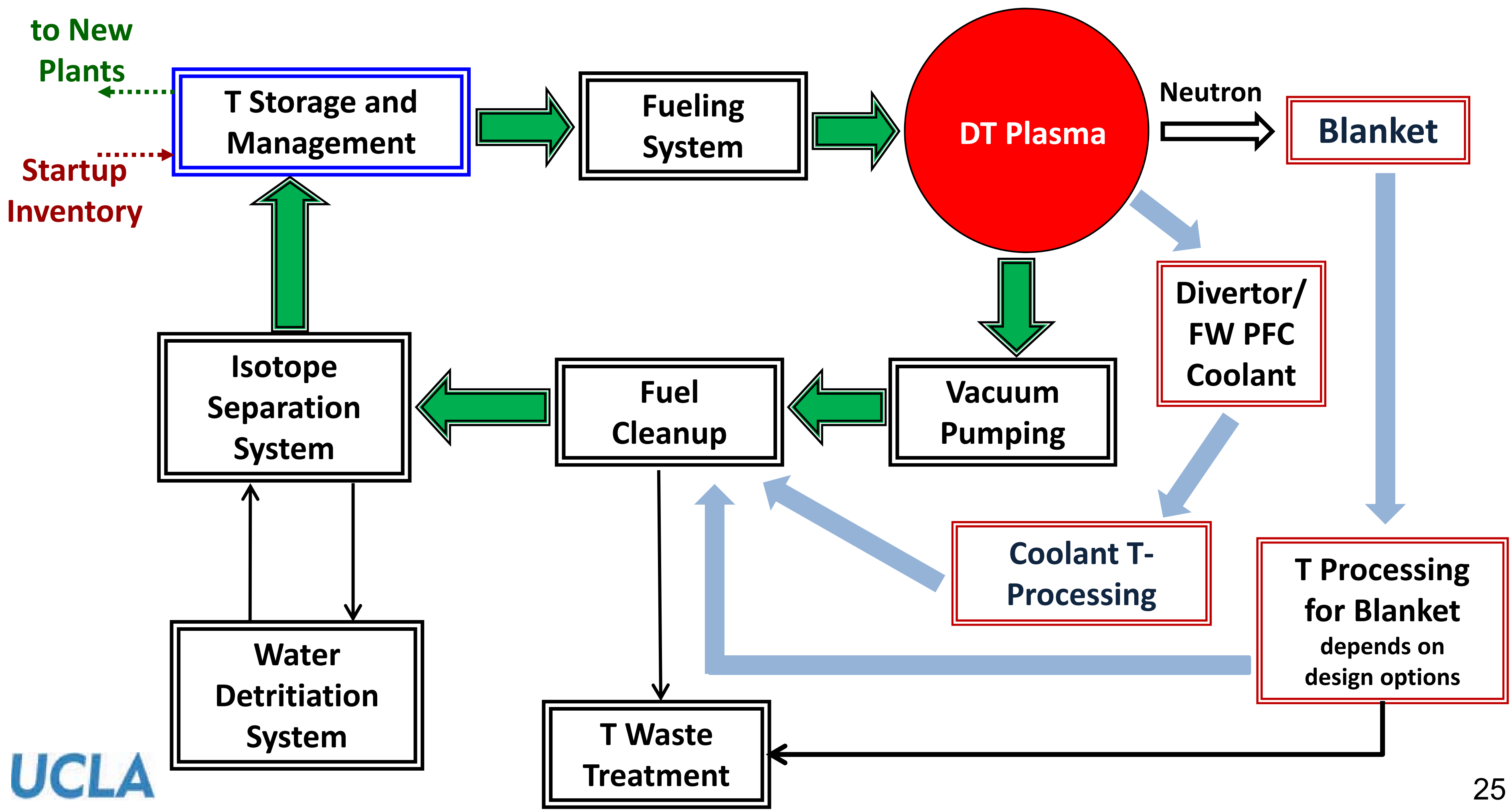
TBR_r depends on many system physics and technology parameters.

Tritium Fuel Cycle

UCLA pioneered dynamic fuel cycle models to predict time-dependent tritium flow rates and inventories and required TBR (collaboration with LANL)

(Dynamic Fuel Cycle Modelling: Abdou/Kuan et al. 1986, 1999; Abdou/Liu 2013)

Simplified Schematic of Fuel Cycle



Key Parameters Affecting Tritium Inventories, and Hence, Required TBR (TBR_r)

1) Tritium burn-up fraction in the plasma (f_b)
2) Fueling efficiency (η_f)
3) Time(s) required for tritium processing of various tritium-containing streams (e.g. plasma exhaust, tritium-extraction fluids from the blanket), t_p
4) "Reserve Time", i.e. period of tritium supply kept in "reserve" storage to keep plasma and plant operational in case of any malfunction in a part (q) of any tritium processing system
5) Parameters and conditions that lead to significant "trapped" inventories in reactor components (e.g. in divertor, FW, blanket)
6) Inefficiencies (fraction of T not usefully recoverable) in various tritium processing schemes, ε
7) Doubling time for fusion power plants (time to accumulate surplus tritium inventory sufficient to start another power plant)

Tritium Burn-up Fraction (f_b)

f_b = fusion reaction rate / tritium fueling rate

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

η_f = fueling efficiency = fraction of injected fuel that enters and penetrates the plasma

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

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

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

τ = particle confinement time

Status

η_f: Recent results: gas fueling is not efficient (η_f ~5%).

Pellet fueling: η_f ~90% on high-field side, 50% for low-field side injection.

Results on ineffectiveness of gas fueling imply significantly smaller R, and hence lower f_b.

$f_b \eta_f$: ITER: ~0.3% selected to size the tritium system; 0.5% expected

Reactors: depends on assumptions on R (subject of current research)

Impact of Tritium Burn-up Fraction and Tritium Processing Time on Tritium Inventory

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

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

$$I_{fe} = f\left(\mathrm{t_p} / \mathrm{f_b} \eta_{\mathrm{f}}\right)$$

t_p is the time for tritium processing (to go through the vacuum pumping, impurity separation, ISS, fuel fabrication and injection). Function of technology, design/cost trade-off

$I_c \equiv$ Tritium inventory in other components, e.g. blanket, PFC

Fusion Program is aiming at minimizing tritium inventories

<u>Why large tritium inventory is unacceptable</u>

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

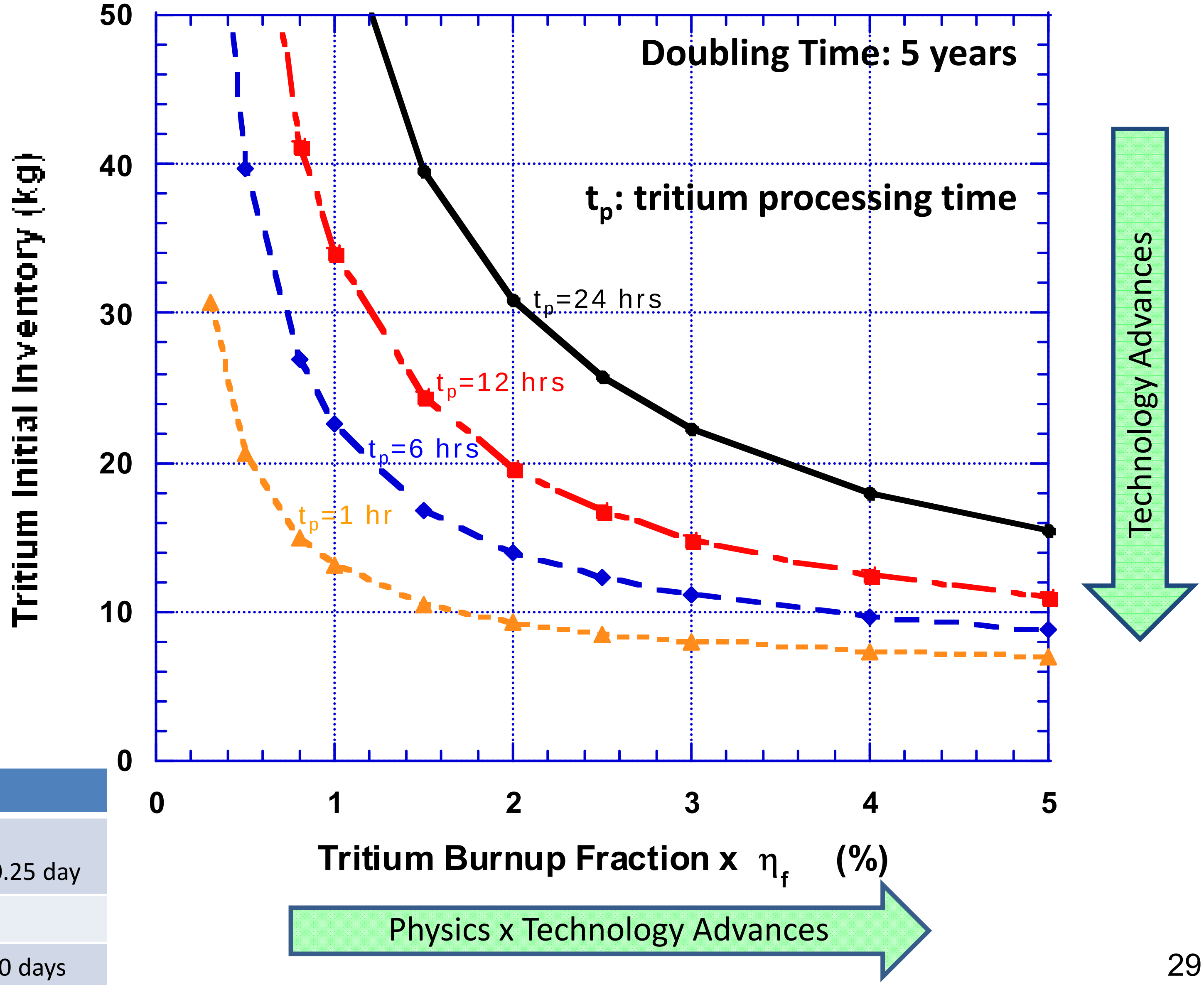
<u>Status on Tritium Processing Time, t_p</u>

1970's-80's Reactor Designs (ANL, FED, etc) : 24 hours ; 1986 TSTA demonstrated < 24 hours

2010 ITER Goal is t_p ~ 1 hour

Reactor: no reliable estimate yet, probably somewhere between ITER and TSTA

Tritium start-up inventories depend strongly on tritium burnup fraction (f_b), tritium fueling efficiency (η_f), and tritium processing time (t_p)

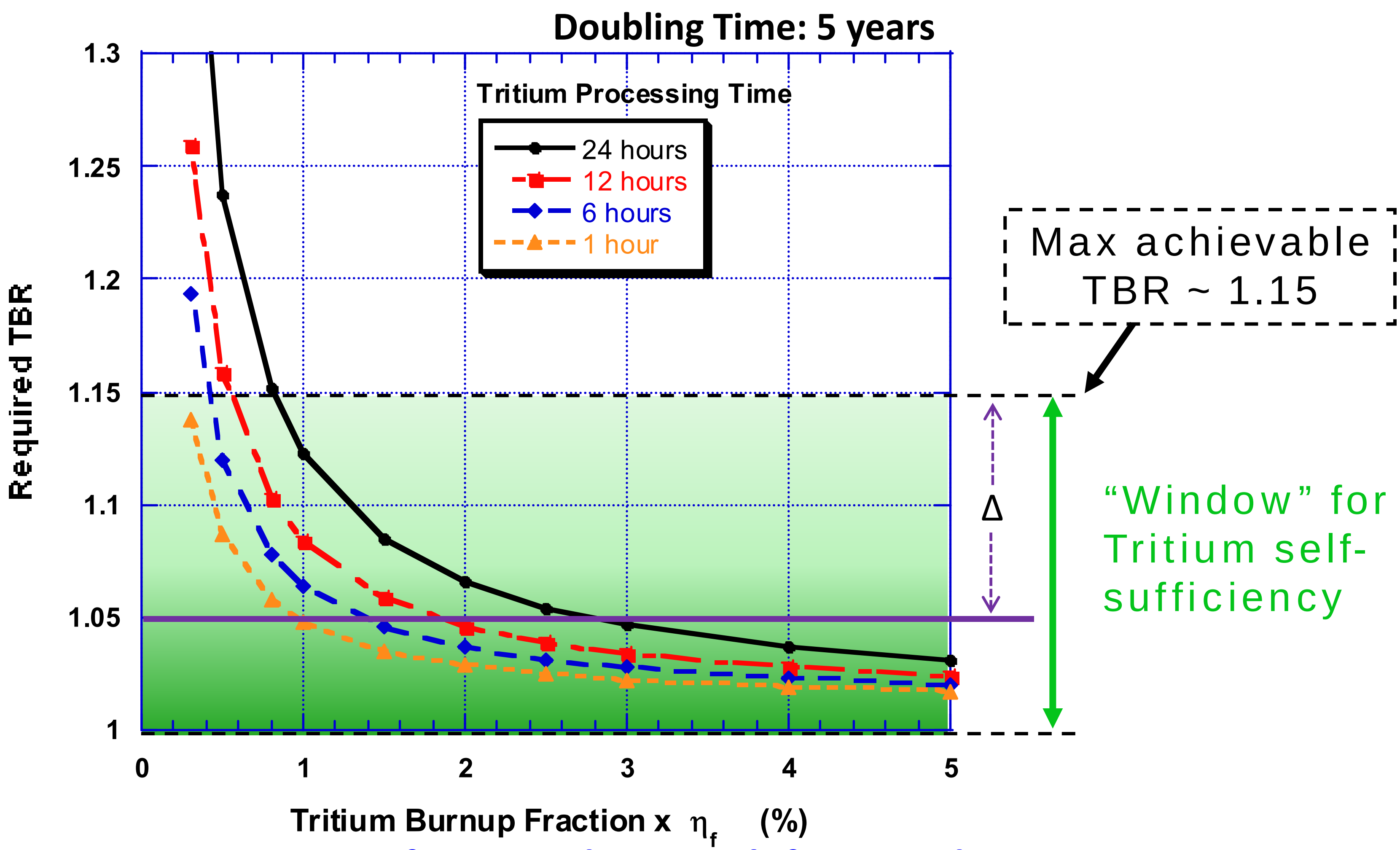


Fusion Power = 3000 MW
Reserve time for outage x fraction of tritium plant failing= 0.25 day
Inefficiency, ε = 0.01%
Blanket mean residence time = 10 days

Attaining Tritium Self-Sufficiency in DT Fusion Imposes Key Requirements on Physics and Technology. The goal for R & D should be to achieve:

T burnup fraction (f_b) x fueling efficiency (η_f) > 5% (not less than 2%)

T processing time (in Plasma exhaust/fueling cycle) < 6 hours



Variation of Required TBR with f_b x η_f and t_p

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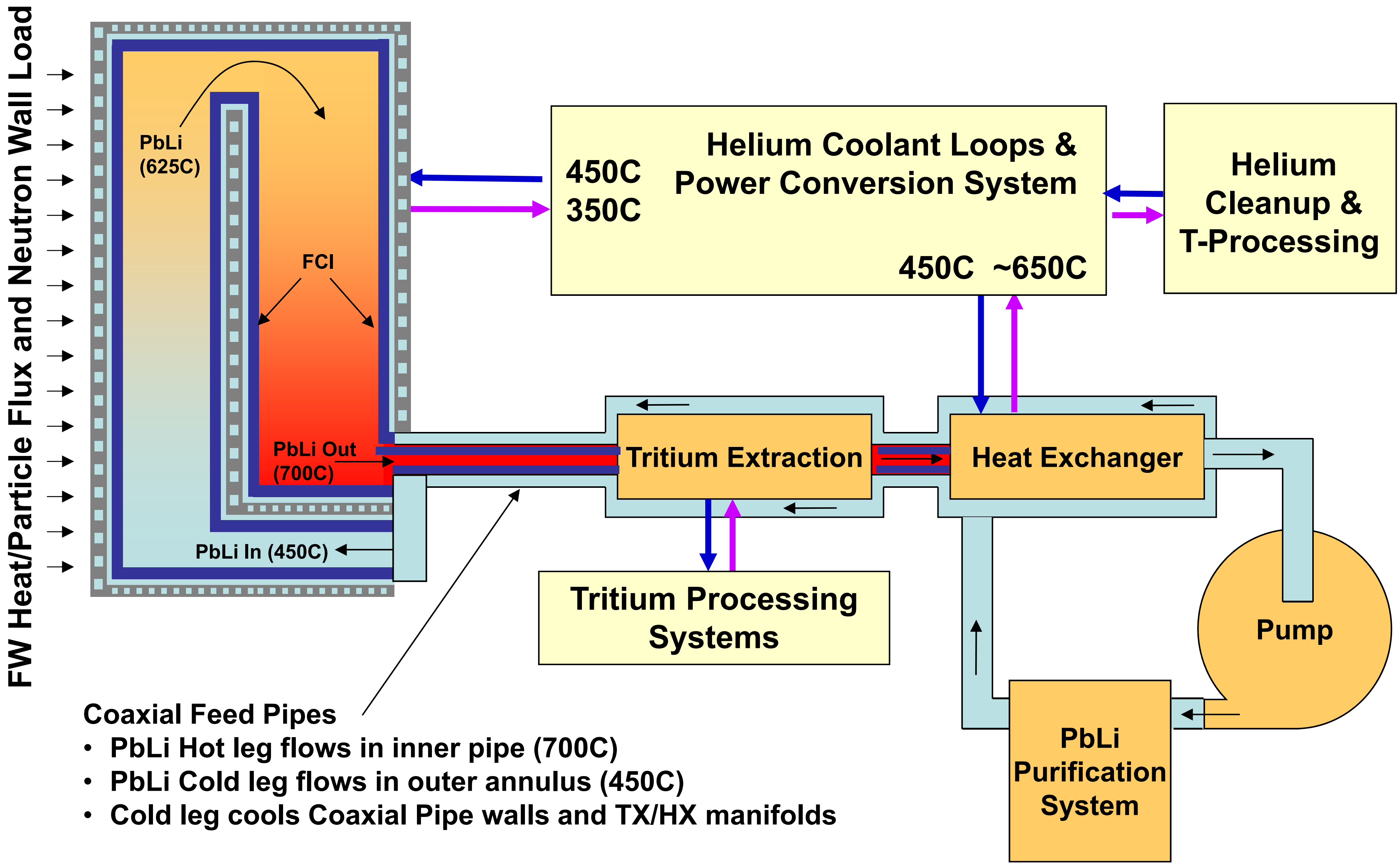
A Simplified DCLL PbLi Transport System



Coaxial Feed Pipes
- PbLi Hot leg flows in inner pipe (700C)
- PbLi Cold leg flows in outer annulus (450C)
- Cold leg cools Coaxial Pipe walls and TX/HX manifolds

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 appm 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, …

Top-Level Technical Issues for FNST/Blanket (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 in both electrically conducting and insulated ducts
4. Interfacial phenomena, chemistry, compatibility, surface erosion & 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/Blanket
(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

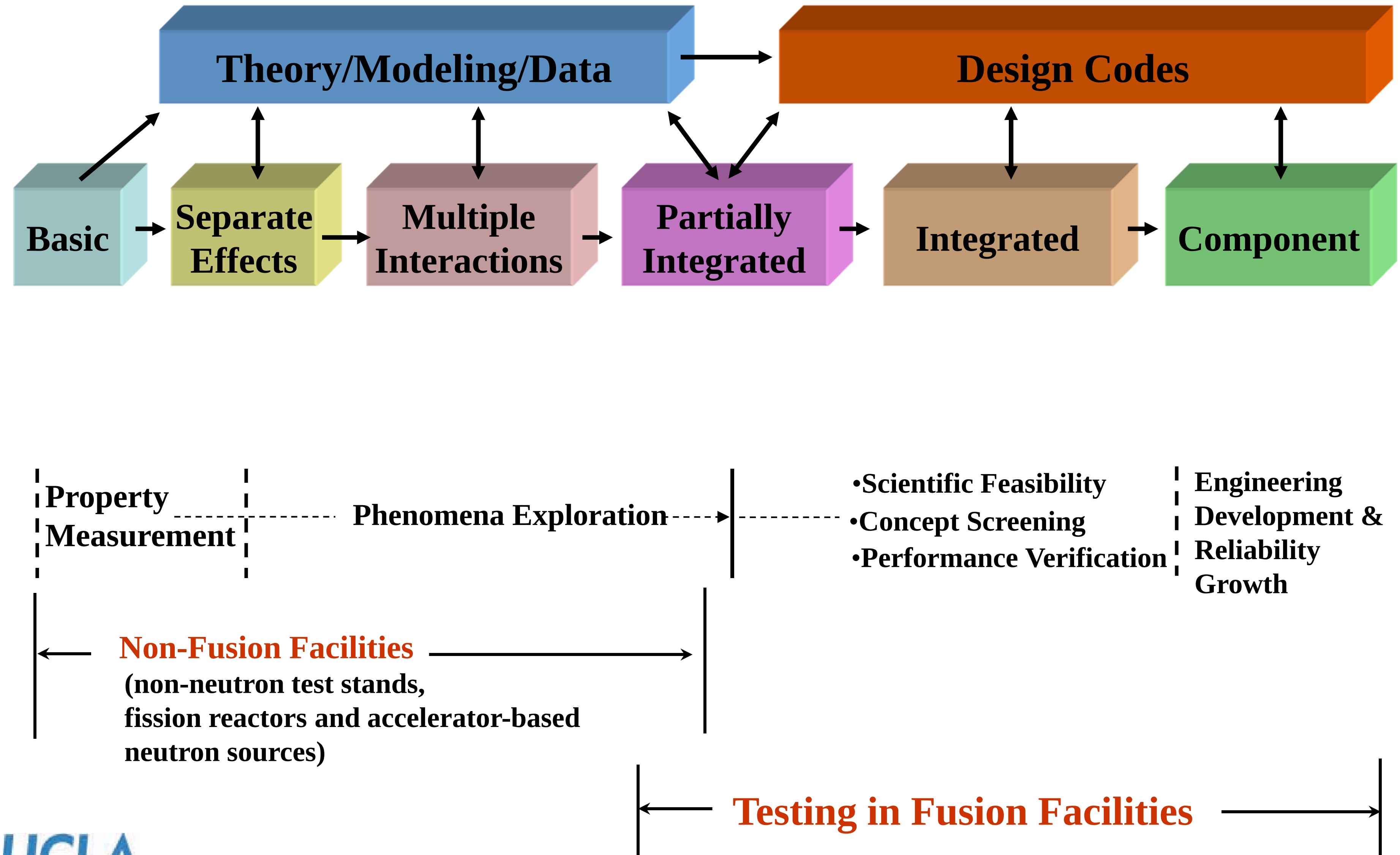
Reliability, Availability, Maintainability, Inspectability (RAMI)

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

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



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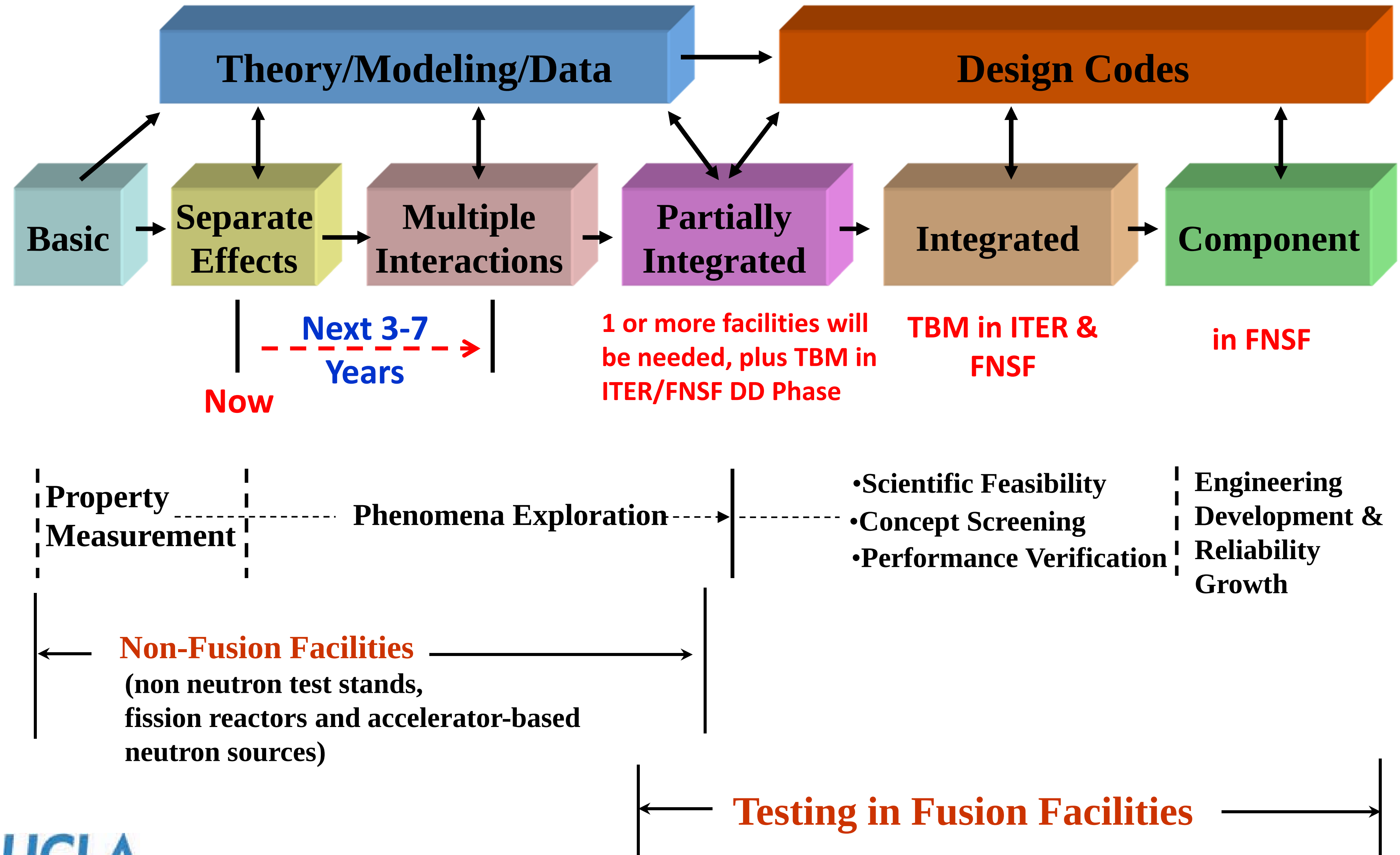
We are now in “Separate Effects” stage. We want to move to “multiple effects/multiple interactions” to discover new phenomena and enable future integrated tests in ITER TBM and FNSF



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KEY R&D Initiatives

- **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 ~ 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").**

We need non-fusion test stands for experiments on single and multiple effects

- Our base to design, understand and interpret integrated testing in fusion facilities

	Neutron Effects*	Nuclear Heating	Thermal-Mechanical-Magnetic-Electrical-Chemical-Interactions	Integrated Synergistic
Non-Neutron Test Stands [PFC/HHF, PSI, LMMHD, Safety]	**no**	**no**	**partial**	**no**
Fission Reactors	**partial**	**partial**	**no**	**no**
Accelerator-Based Neutron Sources	**partial**	**no**	**no**	**no**

* **radiation damage, tritium and helium production, transmutations**

We urgently need multiple lab-scale test stands in thermofluids, thermo-mechanics, tritium, chemistry, etc.

We need extensive modeling activities strongly coordinated with experiments

Need to Build Multiple effect facilities to simulate to the degree possible all conditions

- **Blanket Thermomechanics &Thermofluid Test Facilities**
  - Simulated surface and volume heating, reactor-like magnetic fields
  - Test mockups and ancillary systems of prototypical size, scale, materials
- **Tritium Recovery, Transport, and Extraction Facility**
  - Unit cell mockups exposed to fission neutrons
  - Coolant loops coupled to ex-situ tritium processing and chemistry systems
- **Fuel Cycle Development Facility**
  - DEMO relevant plasma exhaust pumping, processing and fueling techniques (complement to ITER T facility)
- **Remote Handling Development Facility**
  - Develop, test, improve remote handling and maintenance systems and operations

But recognize their limitation – especially nuclear heating

Examples of Near-Term R&D that LANL Should Be Encouraged To Do

- **Tritium**
  - Fuel Cycle Modeling (in collaboration with UCLA)
  - Tritium Extraction from PbLi (Vacuum Permeator)
  - Multiple-Effect Tritium Extraction and Fuel Cycle Facilities identified in the previous slide

- **Insulators Development (need radiation resistance & reliability)**
  - Can we develop inorganic insulators for high-temperature (~200-400°C) operation in Normal Cu Coils (important for FNSF)
  - Can we develop inorganic insulators for low-temperature (4 K) operation in superconducting magnets? (important for DEMO and beyond)

- **Radiation Effects on the electric and mechanical properties of Copper at (~200-400°C)**
  - Critical for FNSF: high conductivity copper alloy for AT magnets and nearly pure Cu for ST central solenoid

Examples of Near-Term R&D that LANL Should Be Encouraged To Do (cont.)

- Demountable Coils: Development of joints for normal conducting magnets (for FNSF)
- Better data and definition of criteria for reweldability of Vacuum Vessel (need better than the currently vague 1 appm He criteria)
- Contribute to identifying Failure Modes in Divertors and Blankets
- Truly Challenging Tasks (for the ***geniuses*** and ***adventurers***!)
  a) Unit Cell Experiments of SB blankets (and LM too) in fission reactors have been proposed. Is there a way to do this with an accelerator-based neutron source? (I do not think there is, but it is worth exploring). The requirement is ~0.2 – 0.5 m^3 with neutron flux of >10^{18} n/m^2 s
  b) Are there ways to simulate Nuclear Heating and Gradients in a large volume (> 0.5 m x 0.5 m x 0.5 m) with neutron flux of > 10^{18} n/m^2s with prototypical gradients?

Research Initiatives that establish the foundation for FNST and make dramatic progress towards FNSF & DEMO

Testing in the Integrated Fusion Environment (100-1000's M)

Scientific Feasibility Testing: ITER TBM Experiments/PIE

Engineering Feasibility Testing in a Fusion Nuclear Science Facility

Multi-Effect/ Partial- Integrated Test Facilities (~5-20M class)

Blanket Mockup Thermomechanical/Thermofluid Test Facility

Tritium Fuel Cycle Development Facility

Blanket Unit Cells in Fission Reactors → Tritium Extraction Testing Facility

Fundamental Research Thrusts (each ~1-3M /year)

Strengthen/Initiate Important Niche Areas →

PbLi Based Blanket Flow, Heat Transfer, and Transport Processes (MHD)

Plasma Exhaust and Blanket Effluent Tritium Processing

Helium Cooling and Reliability of High Heat Flux Surfaces/Blanket/FW

Ceramic Breeder Thermomechanics and Tritium Release

Structural and Functional Materials Fabrication

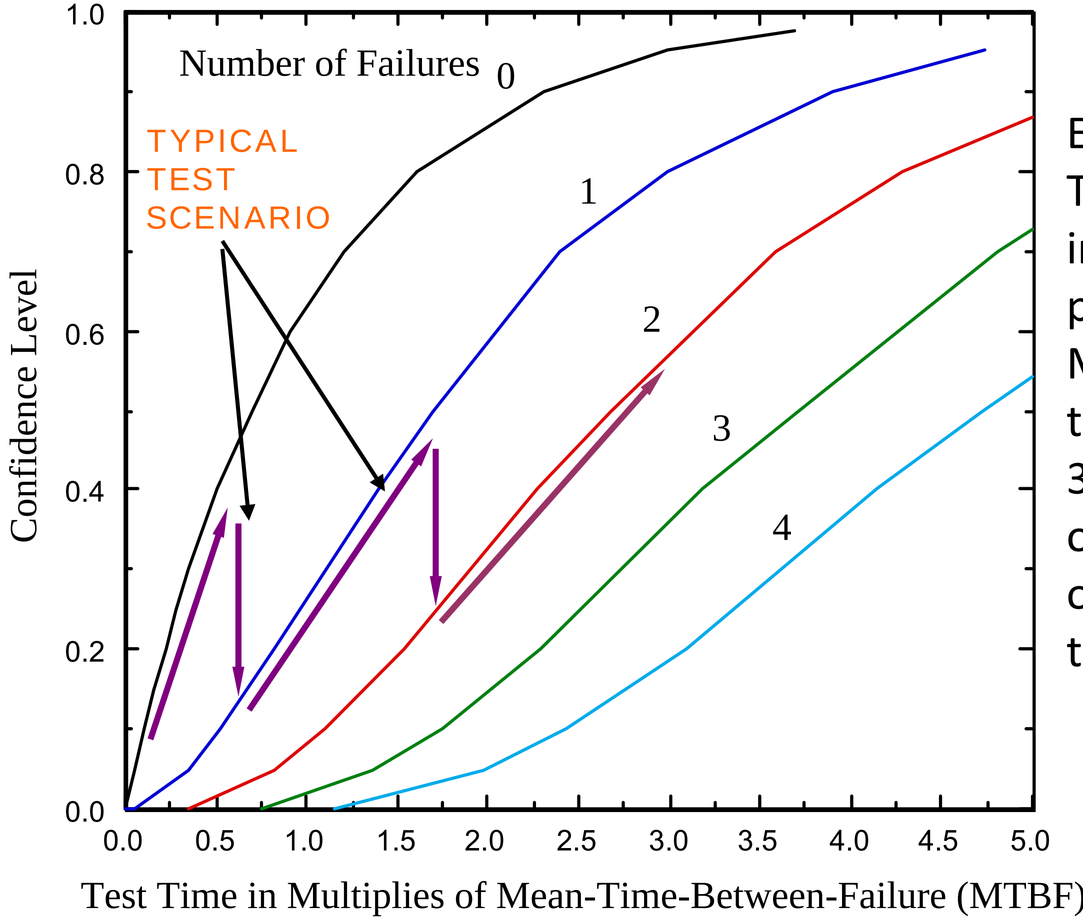
Thank You!

Quantify "Confidence" or "Risk" Level

In fusion development, we must start to quantitatively evaluate "confidence level" (or "risk level") for various options as part of planning.

Example: "Reliability Growth":

There are well established statistical methods to determine confidence level as function of test time (n x MTBF) and test results (e.g. number of failures).



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

Applying this methodology using 80% confidence level shows that blanket tests in ITER alone cannot demonstrate a blanket system availability in DEMO higher than 4%.

M. Abdou et. al., Fusion Technology, vol. 29 (January 1996)