Briefing to Ed Synakowski OFES
Germantown, MD Dec. 9, 2009

the role of
Fusion Nuclear Science & Technology
in establishing the credibility of fusion

Richard Nygren (Sandia), Mohamed Abdou (UCLA), Phil Sharpe (INL)
and input from Wayne Meier (LLNL)
on behalf of the US-FNST Community

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

Toward the Credibility of Fusion - FNST

Is a fusion energy system even feasible?

Can we show one that is practical?

There is a growing consensus on the following.

- **The feasibility and attractiveness of fusion depend mostly on issues in FNST.**
- **Visible results from R&D in FNST are key in establishing a credible path forward.**
- **Progress in FNST will pace our realization of a DEMO (and FNSF).**

ITER is an invaluable advance for fusion ...

.. but does not provide the necessary operating conditions and capabilities to advance FNST to DEMO.

FNST Briefing:
Outline

Energy system's 3 functions
1. **produce energy** (plasma)
2. **Extract heat,**
3. **Regenerate tritium fuel**

Do this safely and reliably

1. Introduction

Scope of fusion nuclear science and technology (FNST)

Fusion Environment

Science Based Framework for FNST

2. FNST Key Issues and Research

Key Issues Summary - MFE/IFE Synergy

Issue Examples:

PSI, MHD, Tritium Fuel Cycle, Reliability, Safety

3. FNST Development Strategy

Non-fusion Testing, Fusion Testing – TBM & FNSF

4. Closing Summary

Fusion Nuclear Science & Technology (FNST)

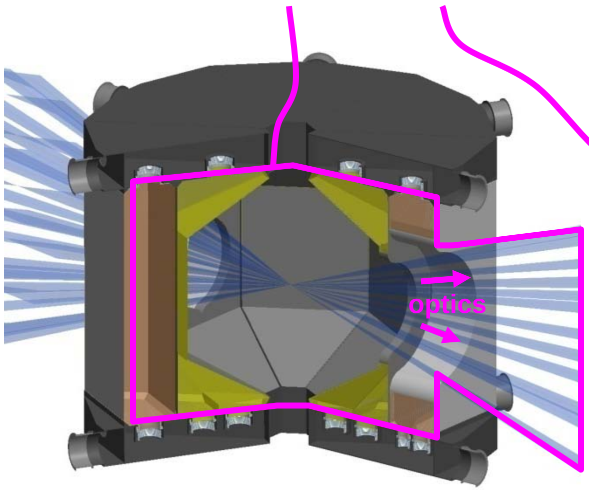
FNST is the **science**, **engineering**, **technology** and **materials**
for the fusion nuclear components that
generate, control and utilize neutrons, energetic particles & tritium.

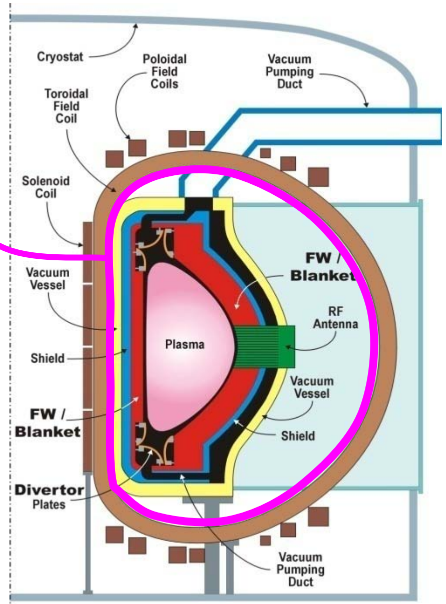
- **Plasma Facing Components**
  divertor, limiter, first wall and nuclear aspects of heating/fueling and final optics (IFE)
- **Blanket** (and integral first wall)
- **Vacuum Vessel and Shield**

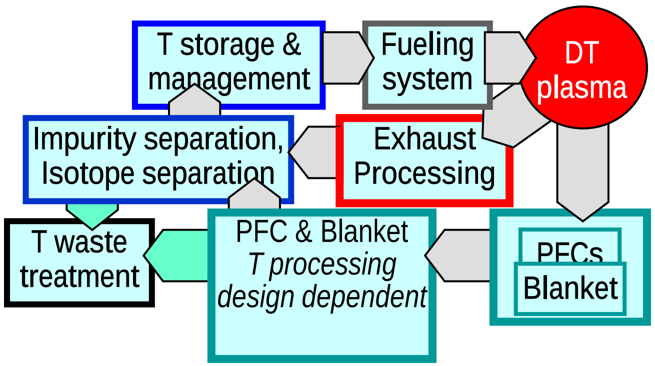
The nuclear environment also affects

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

These are the FNST Core for IFE & MFE







Fusion nuclear environment: multi-field, harsh, unique

Neutrons ***(fluence, spectrum, gradients)***

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

Heat Sources ***(thermal gradients)***

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

Particle, X-ray Fluxes ***(energy, density, gradients)***

Magnetic Fields ***(3-components, gradients)***

- **Steady and Time-Varying Field**

Limited import for IFE

Mechanical Forces

- **Steady, Cyclic, Transient/Pulsed, Failure-caused**

Fusion nuclear environment: complex effects, interactions, and science

Neutrons *(fluence, spectrum, gradients)*
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Mechanical Forces
- Steady, Cyclic, Transient/Pulsed, Failure-caused

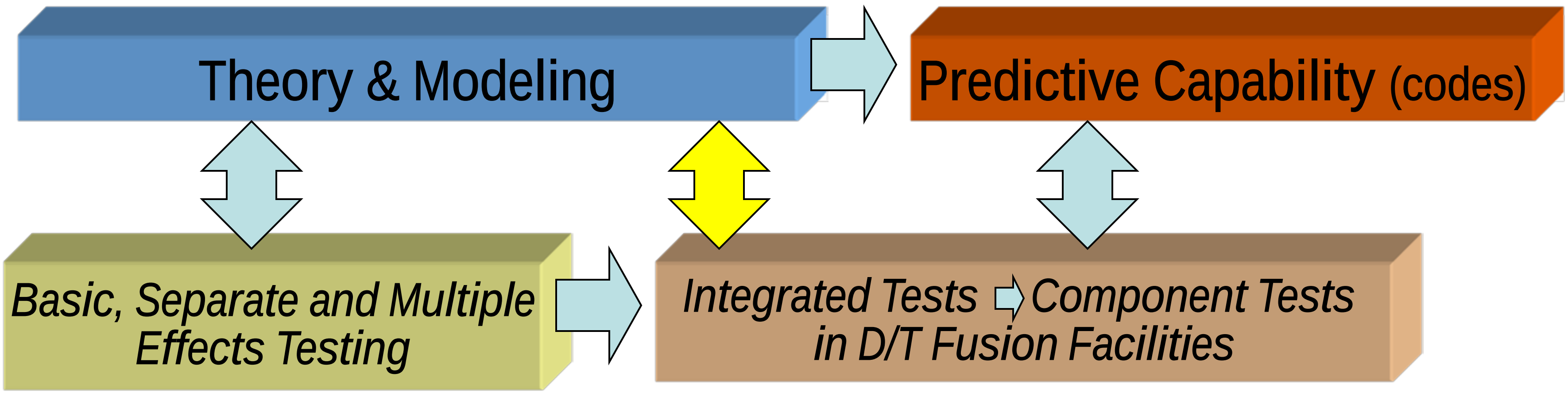
Combined Loads, Multiple Environmental Effects
- Thermal-Chemical-mechanical-electrical-magnetic-nuclear interactions and synergistic effects
- Interactions among physical elements of components

Highly Constrained Multi-Function Components

FNST has a science-based framework for R&D.

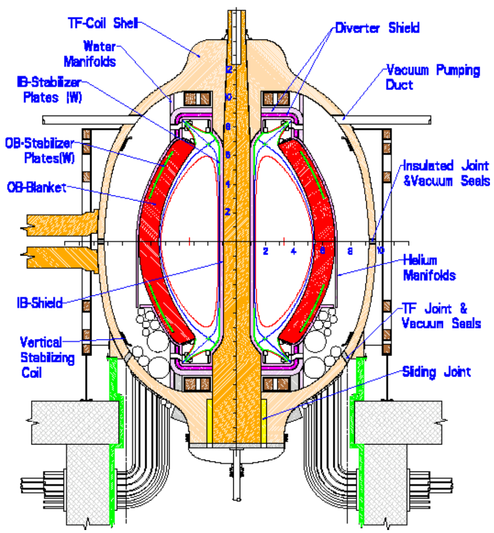
(developed by FNST community, supported by ReNeW)

Through experiments, theory and modeling we understand the materials, processes and changes in fusion nuclear components and develop the capability to predict their performance.

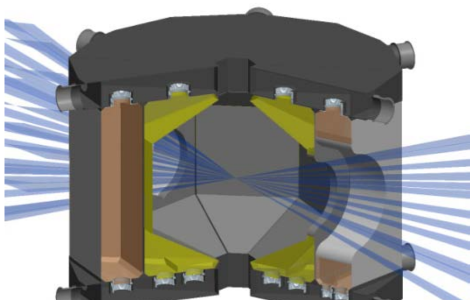


Only with integrated tests in a D/T device can we observe
(a) the breeding and extraction of tritium and
(b) the performance of integrated systems
with
the appropriate temperature distributions (neutron heating) and effects of radiation damage to materials.

To develop FNST we must advance the state-of-the-art and develop <u>highly integrated predictive capabilities</u> for many cross-cutting scientific & engineering disciplines.

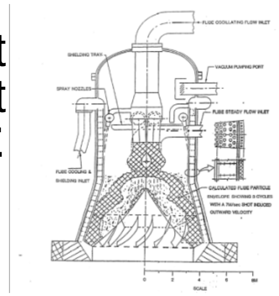


ARIES-ST
Dual Coolant Lithium-Lead (DCLL) Blanket
described later

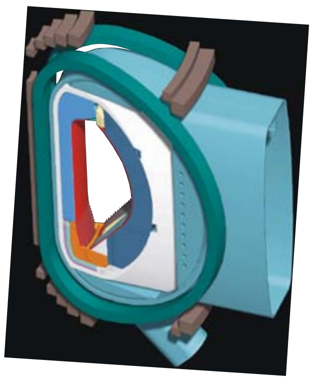


LIFE

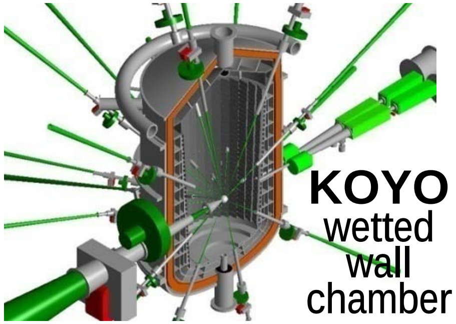
Modular chamber - separate FW & blanket segments
Ferritic steel (or SiC), W-armor coating
Molten salt or LiPb breeder/coolant



Li-Pb breeder-coolant and SiC FW & blanket
HYLIFE



CLIFF: Molten salt (FLiNaBe) breeder-coolant & divertor



KOYO wetted wall chamber

Molten salt (FLiBe) breeder-coolant and stainless steel structure

These predictive capabilities are needed for MFE and IFE, e.g., for design and safety studies, licensing, etc.

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MFE & IFE share many common interests and R&D needs in FNST.

many common interests

List is incorporated in FNST Critical Issues (next)

- **Materials performance -** response to fusion environment
- **Breeding blankets, Neutron multipliers**
- **Tritium concerns**
  recovery, processing, accountability, minimizing inventory
- **Integration** & **high-temperature operation**
- **Corrosion - liquid metals** & **molten salts**
- **Erosion** & **dust**
- **Advanced neutronics tools**
- **Design modeling & tools**
- **Maintenance**
  ease, rapid replacement/repair, robotics
- **Rad-hard diagnostics/instrumentation**

some aspects unique for IFE

- **Geometry not constrained by burn physics**
- **More flexibility for FW threats**
- **No MHD effects (most blanket types)**
- **High DT burn fraction, reduced D/T throughput**
- **Thick liquid FW designs preferred**
- **Easier maintenance - chamber & driver separated**

Critical R&D Issues for FNST (part 1)

Heat and Particle Removal

- **PFCs & plasma-material interactions**, actual operating conditions
- **Thermo-mechanical loads & response** of blanket and PFCs
- **Thermofluid phenomena**, flow and heat transport in liquids
- **Liquid Metal (or salt) MHD effects** - heat transport (limited application for IFE)
- **Fluid-Materials interactions** e.g., corrosion

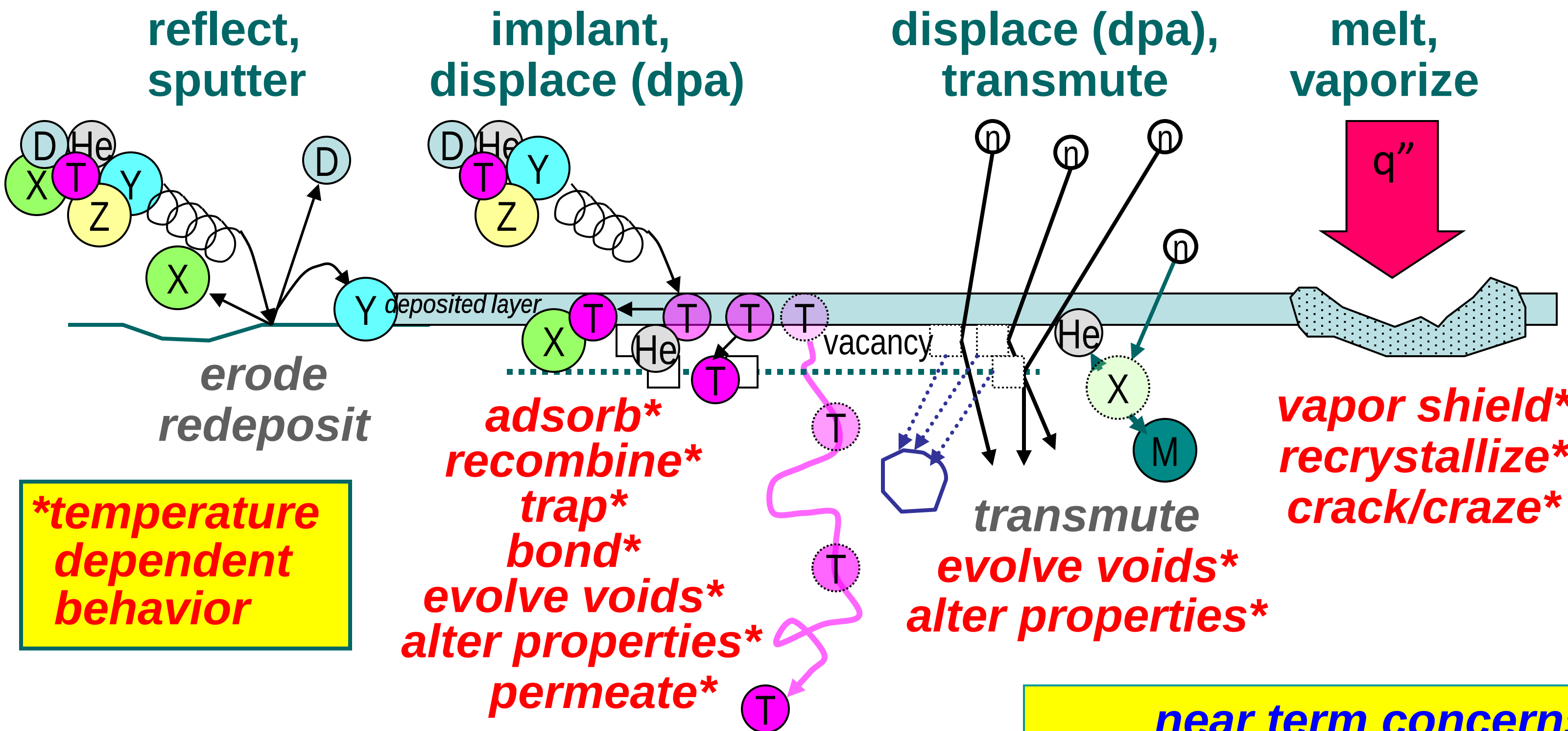
Tritium self-sufficiency

- **D-T fuel cycle** in a practical system
- **Tritium generation, extraction & inventory,** actual operating conditions
- **Tritium implantation, permeation & control** in blanket and PFCs

Three examples of scientific issues follow. FNST has many.

Critical Issues* – Example 1:

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

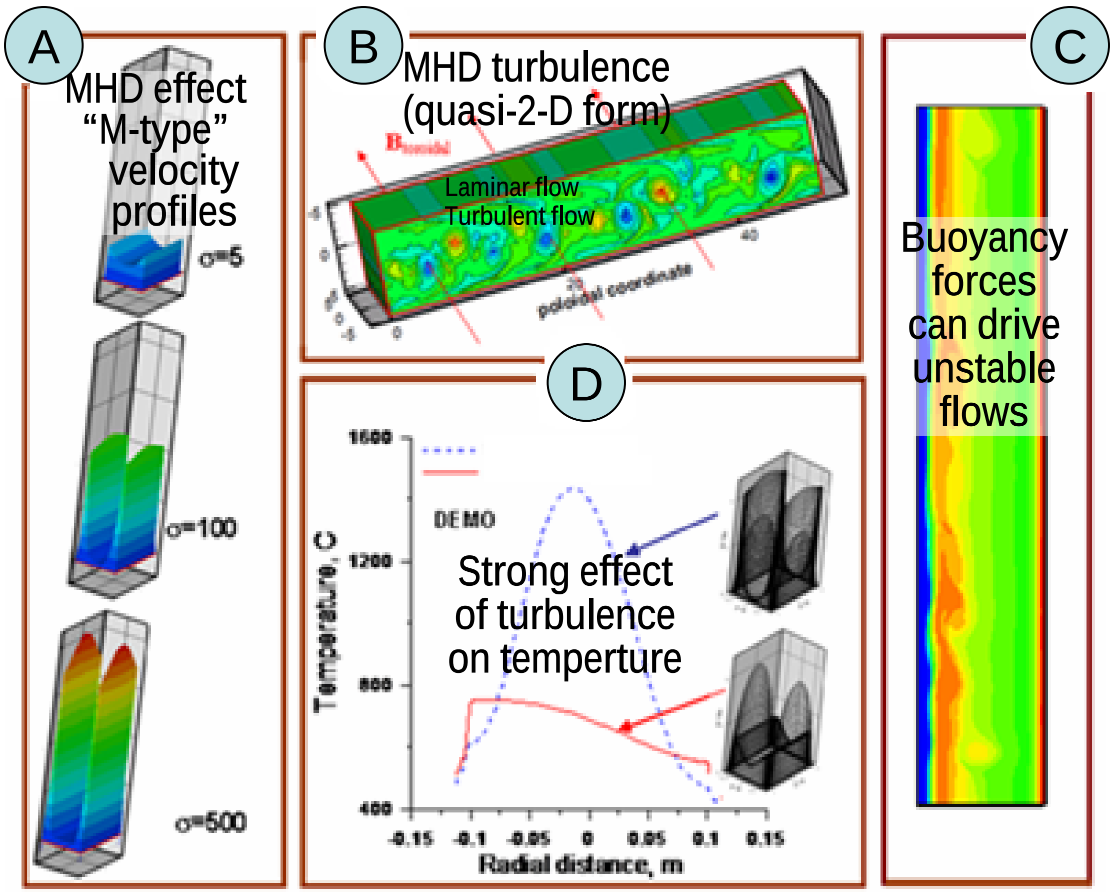
- ..
- Prediction/modeling of damage from ions, neutrons & thermal gradients at high temperature, related tests, benchmark data
- Deploying actively-cooled PFCs and large area “hot” walls
- ..

*more complete presentation of critical issues in backup slides

Critical Issues – Example 2:

Liquid Metal MHD studies (MFE)

MHD effects severely modify flow in liquid metal blankets. Any calculation assuming ordinary fluid flow would produce completely inaccurate flow and heat transfer predictions.



We understand much more *(significant advances).*

Examples (A-D left)

In some areas, solutions with complex 3-D codes are now possible.

Experiments are limited by the capabilities of facilities
(field strength and volume, temperature, instrumentation, etc.)

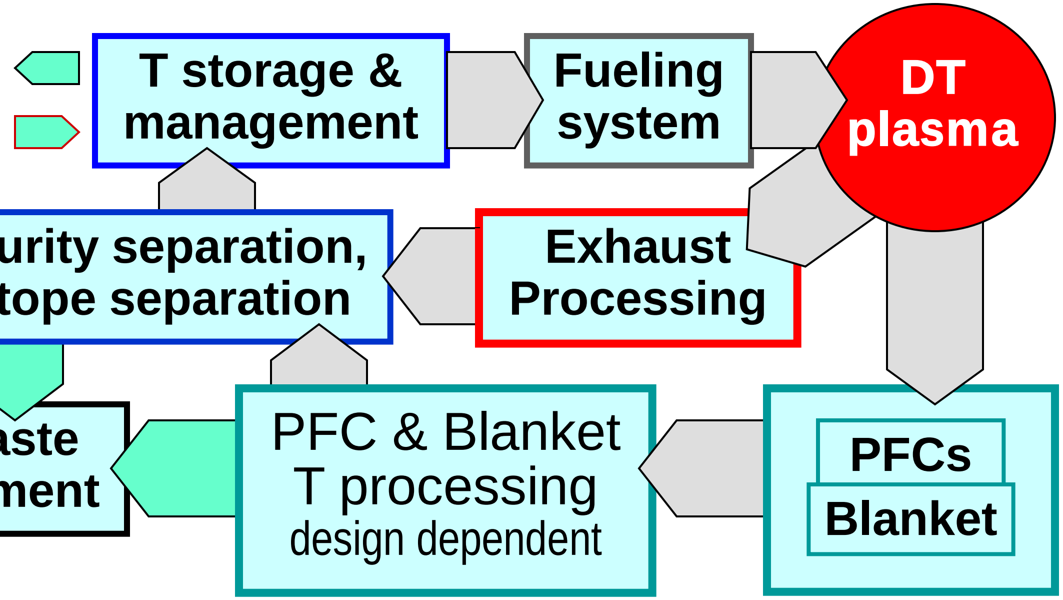
near term concerns

- …
- Need for modeling
- Effects on mass transfer, tritium control, corrosion, ..
- We need to understand MHD-controlled LM flow

Critical Issues – Example 3

Tritium Self Sufficiency

The operational parameters and uncertainties of the many components in the D-T fuel cycle affect the required TBR*.



***Tritium Breeding Ratio (T_{bred}/T_{burned})**

Examples of key parameters:
- *burn-up fraction* • *doubling time* • *reserves (days)*
- *residence time and inventory, each component*
- *Extraction efficiency in plasma exhaust processing*

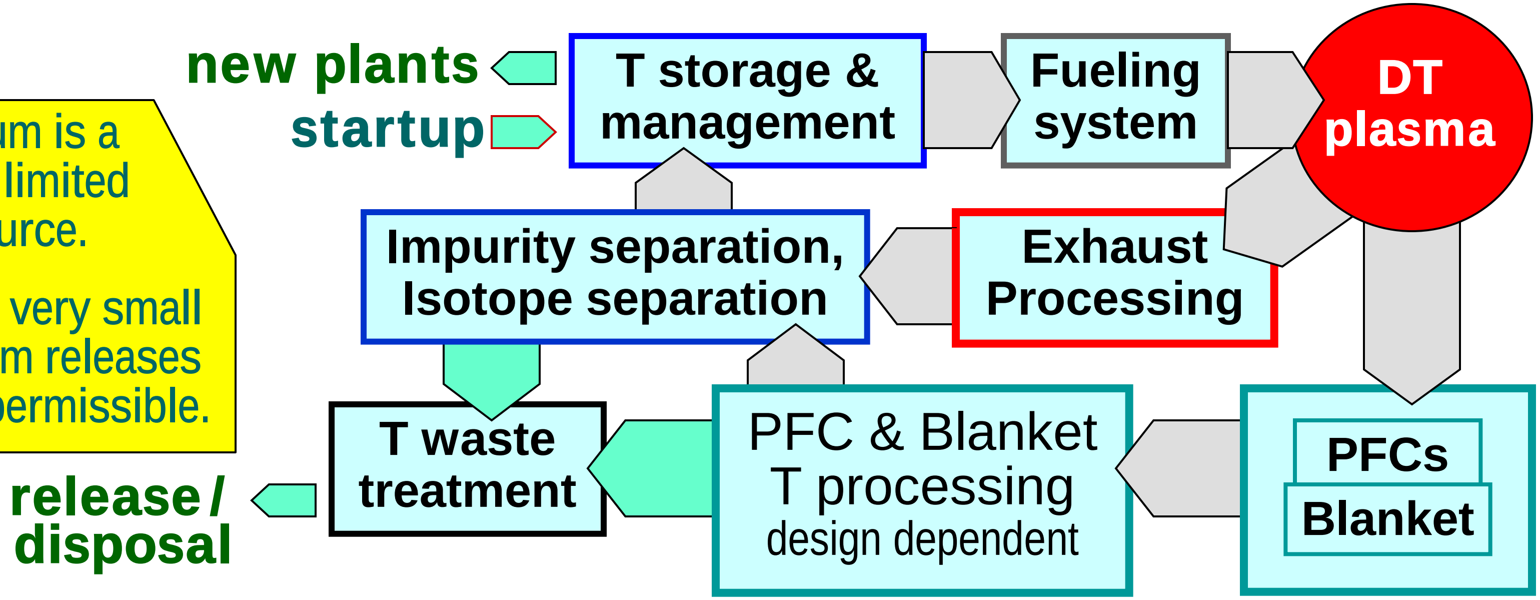
Dynamic Fuel Cycle Modeling: Abdou/Kuan et al. 1986,1999

Critical Issues – Example 3

Tritium Self Sufficiency

The operational parameters and uncertainties of the many components in the D-T fuel cycle affect the required TBR*.

- Tritium is a very limited resource.
- Only very small tritium releases are permissible.



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Critical R&D Issues for FNST (part 2)

Practical and Reliable Systems, Structures, and Components

- **Degradation of materials** (functional & structural), irradiation, other damage
- **Materials engineering** – e.g., joining for reliable components
- **Failure** modes, rates, effects and amelioration
- **Remote maintenance** with acceptable machine downtime

Safe and Environmentally Responsible Facilities

- **Safety Basis** – safety assessment tools/codes, experiment-based validation data for response of materials and systems to postulated accidents, and reliability evaluation for initiating events frequency
- **Waste Minimization** – scientific basis for materials lifecycle management

All fusion nuclear systems must be compatible with plasma operation and power conversion

Practical and Reliable Systems

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

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 C[illegible]	16	5 x10^{-6}	23	10^{4}	240	0.1	0.098	0.91
P[illegible] C[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Magnet supplies	4	1 x10^{-4}	1.14	72	10	0.1	0.007	0.99
Cryogenics	2	2 x10^{-4}	0.57	300	24	0.1	0.022	0.978
Blanket	100	1 x10^{-5}	11.4	800	100	0.05	0.135	0.881
Divertor	32	2 x10^{-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 equi[illegible]							[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**

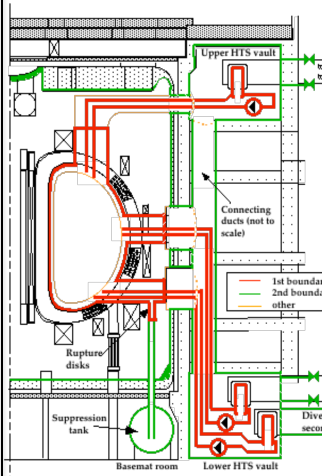
Extrapolation from other technologies shows expected MTBF for fusion blankets/divertor is as short as ~hours/days, and MTTR ~months

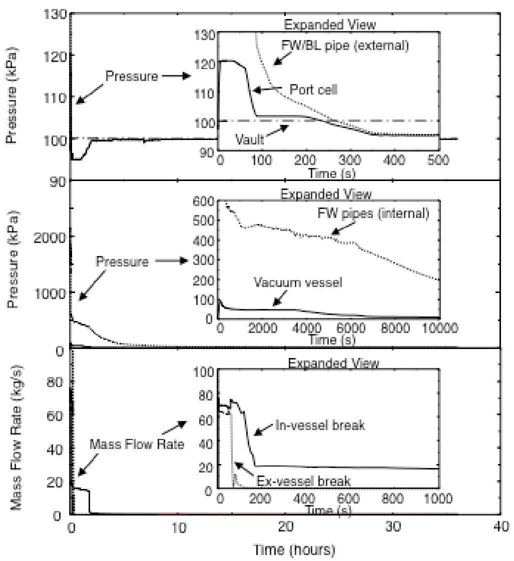
Safety and Environmental Responsibility

Prove the safe and environmentally acceptable attributes of fusion power.

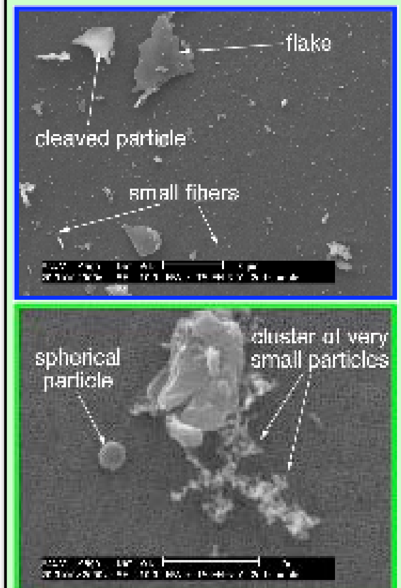
Systems-level Safety Response

Develop, verify, validate safety assessment tools (e.g.,***MELCOR-Fusion***) for regulatory submittals.



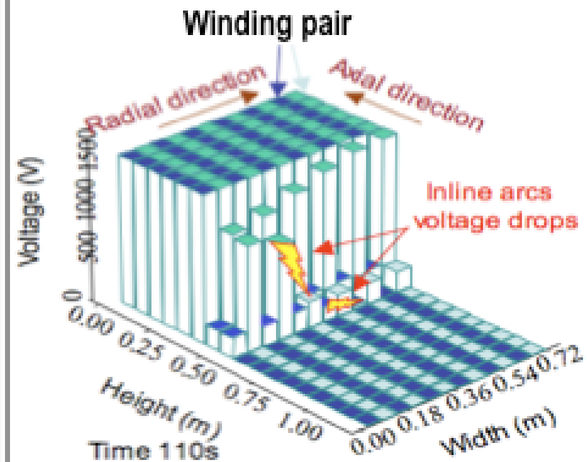


Dust Motion and Reactions

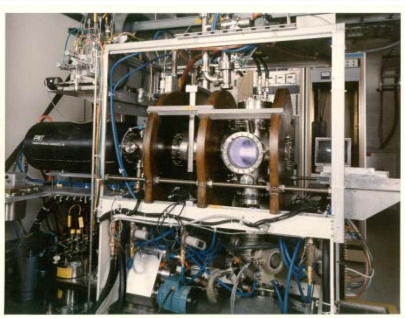


Magnetic Energy Inventory

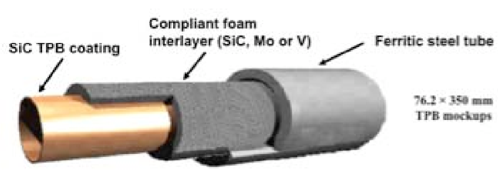
MAGARC simulation of PF coil



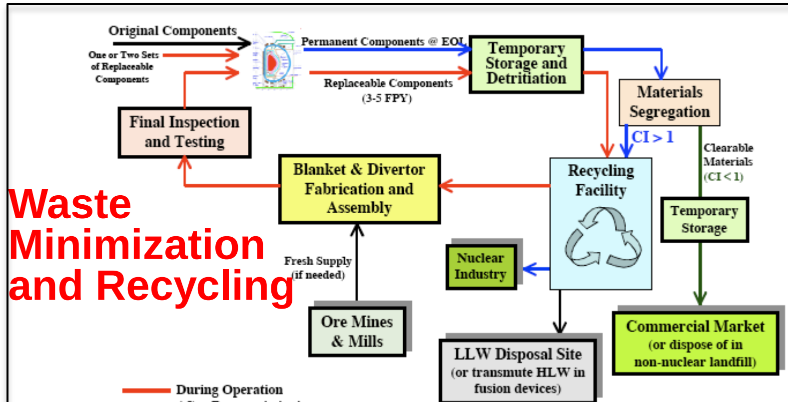
Model & assess magnet systems during fault and accident conditions.



Tritium retention and permeation barriers



Waste Minimization and Recycling



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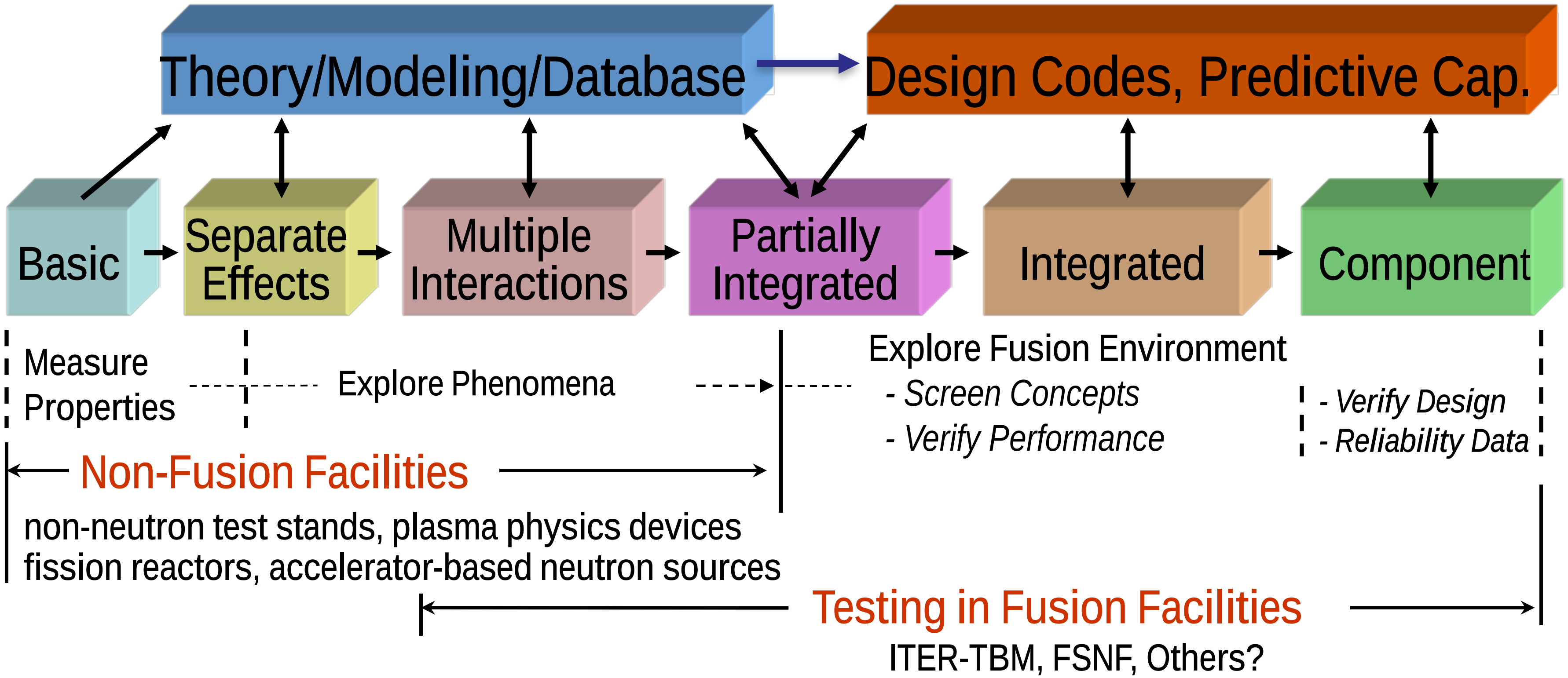


Experiments in non-fusion facilities are essential and are prerequisites.

Testing in fusion facilities is NECESSARY to uncover new phenomena, validate the science, establish engineering feasibility, and develop components.

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

- our base to design, understand and interpret integrated testing -

	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**

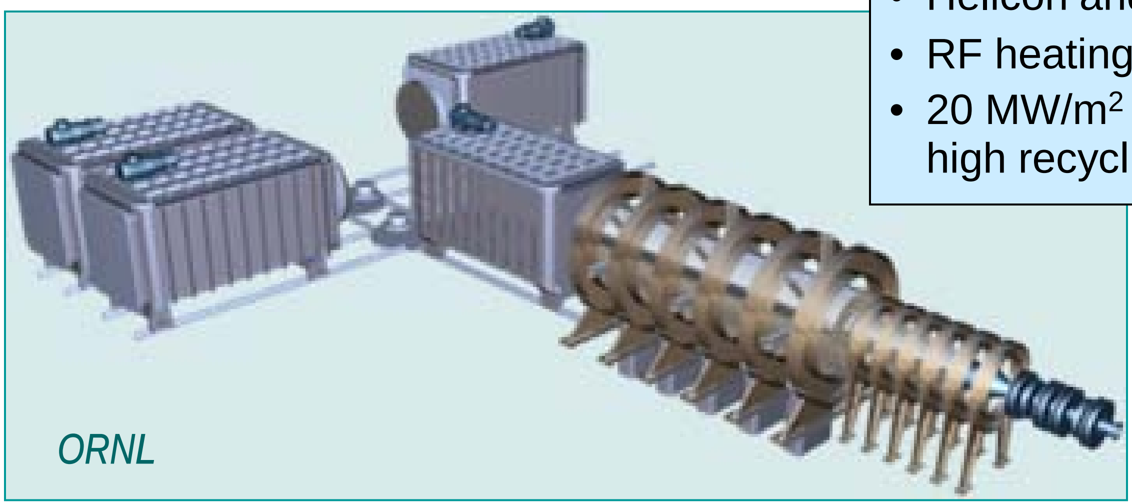
Strong coordination of modeling and experiments is a must.

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

Proposed non-fusion facilities for PFC development

PSI-X *Powerful linear plasma device for PSI and high heat flux testing*

- PMTS - Plasma Materials Test Stand (ORNL) – RF-based source with new magnets *(phased build, Cu magnets, then SC, $$)*
- Focus on plasma-materials interactions
- Having simultaneous heating and ion effects is useful capability.
- Benefit depends on cost and feasibility of PMTS and the opportunity for collaboration, i.e., Magnum-PSI and SAT(s).

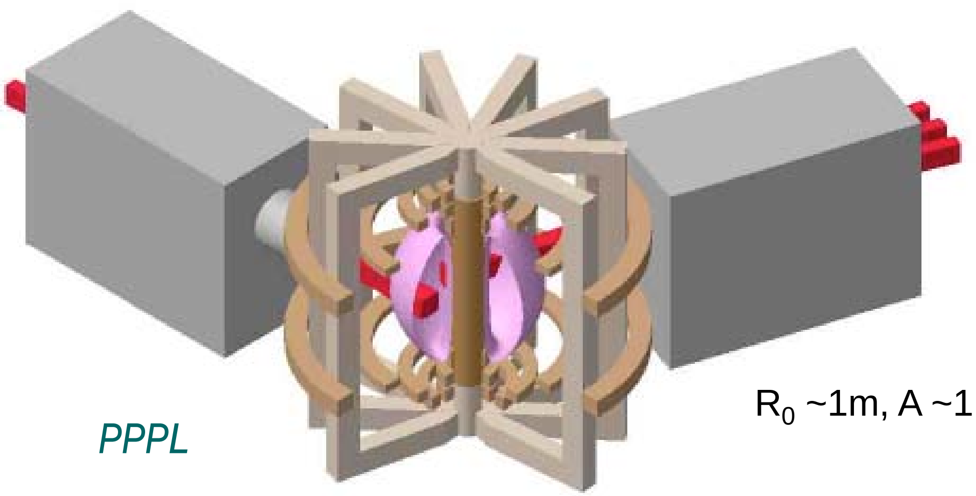


- Helicon and magnetic mirror (1.5m, 1T)
- RF heating, ~100 eV plasma (~100 cm^2)
- 20 MW/m^2 on target, 10^{23-24} $/m^2s$ under high recycling conditions

Proposed non-fusion facilities for PFC development

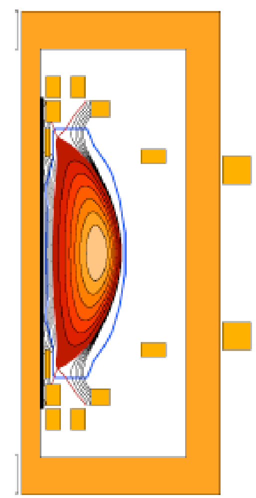
SATs satellites

- NHTX - proposed US H/D spherical torus, flexible configuration for Super-X or LM divertors – high input power, long pulse
- Upgrades and new device(s) likely worldwide, e.g., EAST in near future, ?EU SAT later
- Development/deployment of actively-cooled PFCs
- Facility/experiments with “hot wall” important
- Benefit depends on cost and feasibility of new devices and access and opportunity for PFC experiments.



PPPL

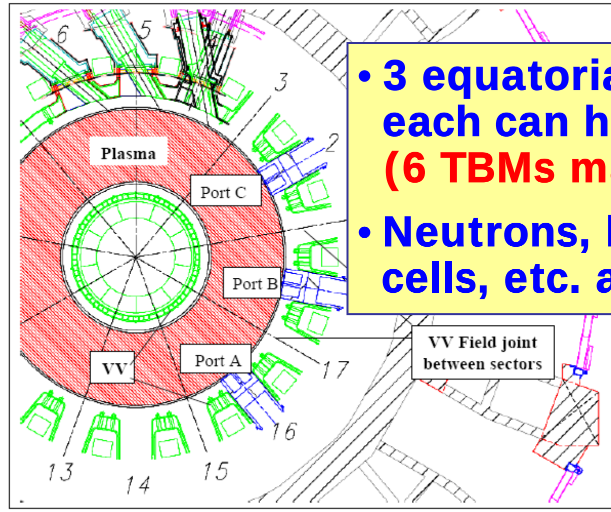
R_0 ~1m, A ~1.8



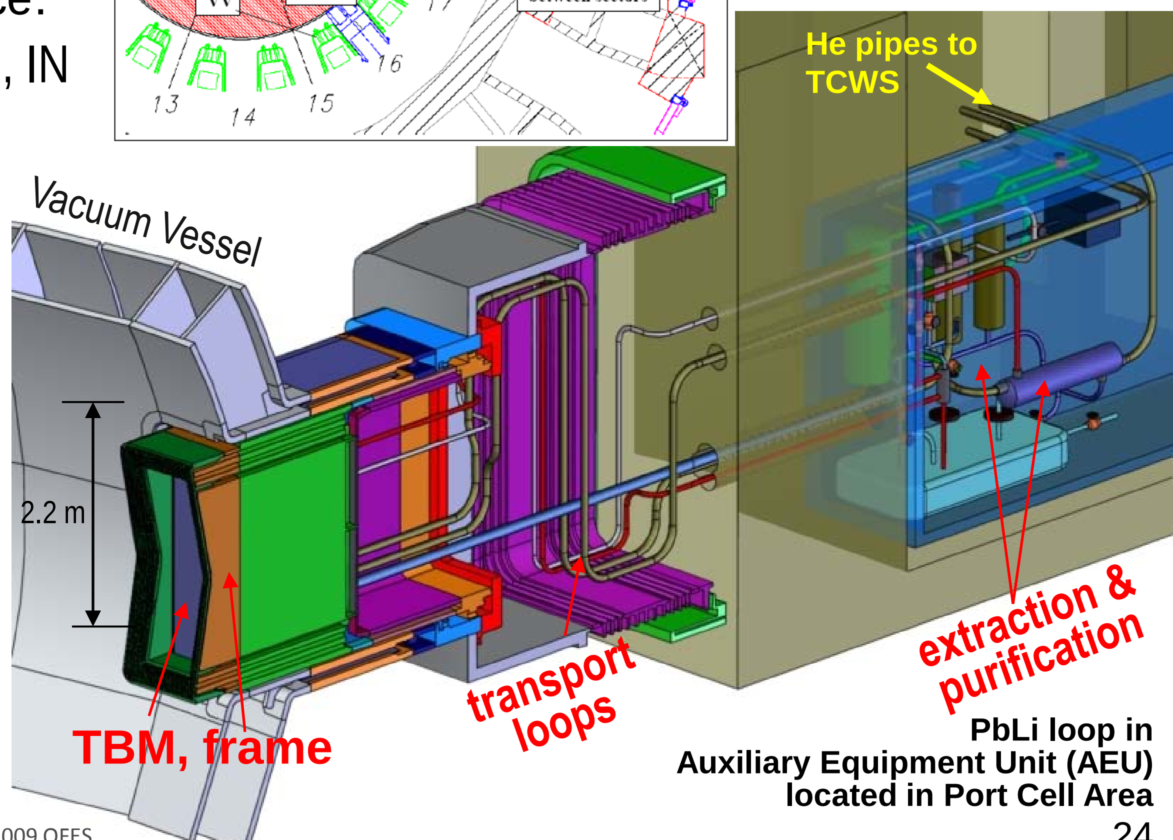
Test Blanket Module (TBM) Program is now an integral part of ITER

ITER provides substantial hardware for testing FW/Blanket Systems.

- Other parties have large programs to utilize this valuable test space:
  2 half ports EU; 1 each for JA, CH, IN
- The US has been asked to be **test space coordinator** for the unassigned 6th half-port due to international interest in the US DCLL concept.
  This is an innovative, niche area for US



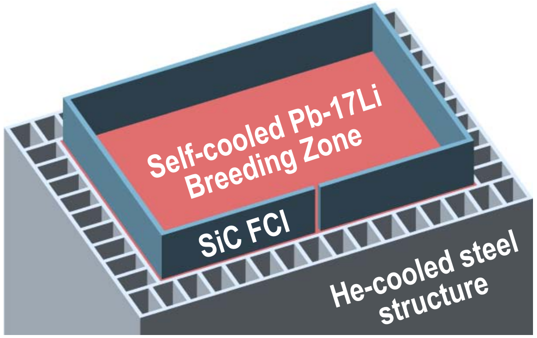
- **3 equatorial ports allocated, each can have 2 modules. (6 TBMs max. at one time)**
- **Neutrons, heat sinks, hot cells, etc. already paid for**



US Planning for ITER-TBM experiments

FNST community spent 2 years formulating a TBM technical plan and cost estimate****.**

- Focus tests on 2 concepts (1. LM, 2. ceramic breeder) with substantially different feasibility issues
- Capitalize on international collaboration with other ITER parties (strong interest world-wide in blankets using ceramic breeders or Pb-Li based blankets)



LM Option - DCLL Typical Unit Cell with SiC flow channel insert

The plan was reviewed twice**.

Technical Review -- found the planning "complete and credible."

- "The committee believes that the TBM effort is essential for the overall development of fusion in the U.S. and strongly recommends that this effort continue." - *review committee headed by M. Hechler, August 2006*

Programmatic Review -- FNST program needs to be strongly strengthened.

- "...the fusion technology program must be strengthened if US participation is to be successful. A strong well-funded scientifically based FNT program is necessary... the US needs to make these investments today..,"
  -- *review committee headed by D. Petti, June 2007*

We (FNST community) **continue to explore collaboration with EU, JA, KO and others to provide input to OFES on TBM options for US participation.**

***Complete reports available for technical plan, cost estimate, and reviews*

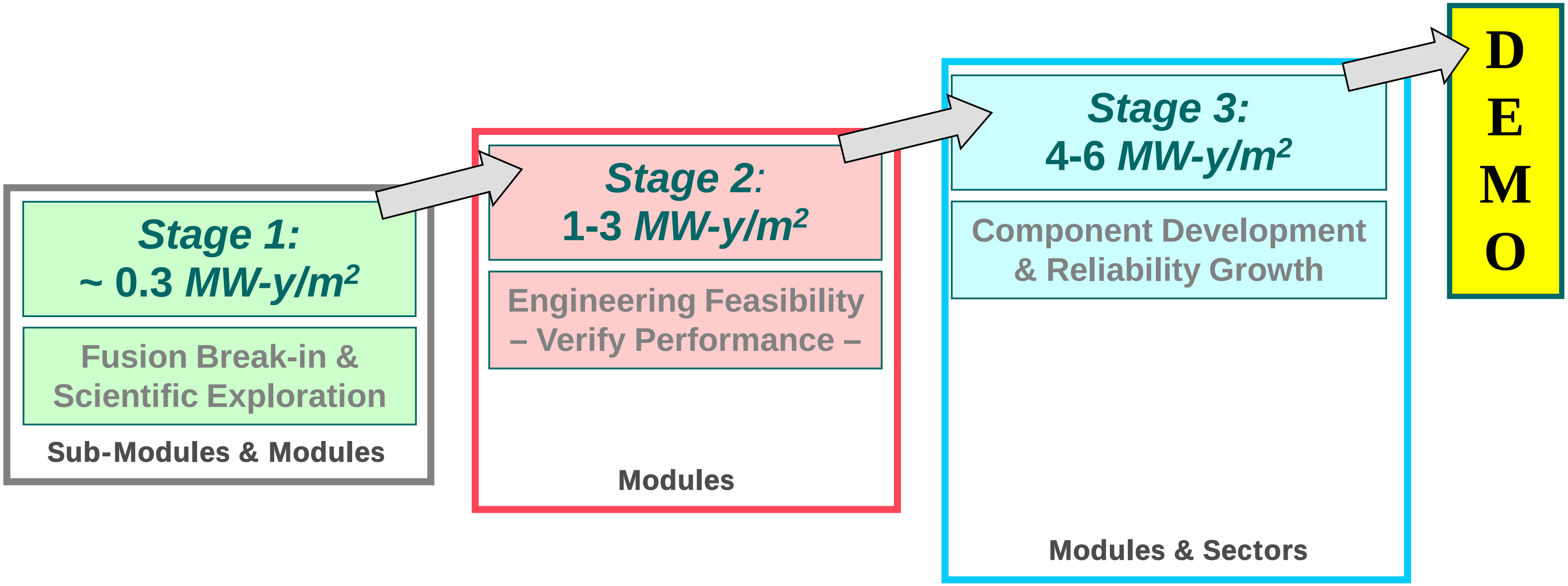
Breakdown of ITER TBM Cost Estimate over 10 years

(from FNST Community Study)

Category	Examples of Activities	Reference Case Cost*	Comment
Basic R&D	• Joining technologies for RAFS • SiC FCI development • LM MHD flow behavior experiments • Solid breeder thermomechanics • Tritium control and extraction • Advanced predictive capabilities	**$41M**	**Basic & applied R&D needed before ANY tests in an integrated environment** **(ITER-TBM, FNSF, etc.)**
Design and Development Activities	• TBM design and analysis • Safety analysis and support • Testing scaled mockups in non-fusion facilities	**$40M**	
TBM & Ancillary Equipment Fabrication	• TBM fabrication & acceptance tests • Ancillary coolant loops and support systems fabrication & acceptance tests	**$10M**	(for FNSF multiply equip cost by number of testing ports) **The cost to lead a TBM concept**
“Project” Costs	• Administration & management, US share • Contingency	**$23M**	(for FNSF project costs will also be much larger)
Total Costs (over the next 10 years)		**$114M**	**Including escalation & contingency**

*** Reference Case – Lead DCLL international consortium, support HCCB consortium with US R&D and submodule**

Integrated testing in a fusion environment will proceed in three stages.



These stages set the requirements for FNSF.

-steady state, wall load, energy, fluence goals, etc. –

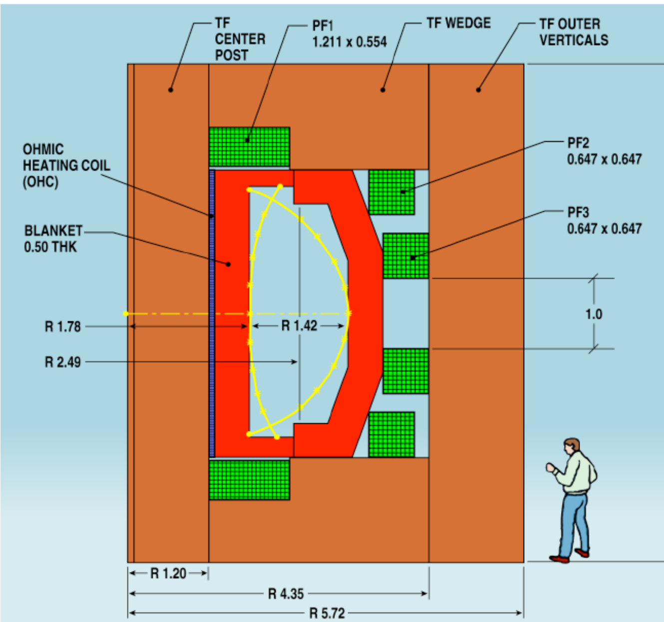
[derived by the FNST Community and used by FNSF Designers]

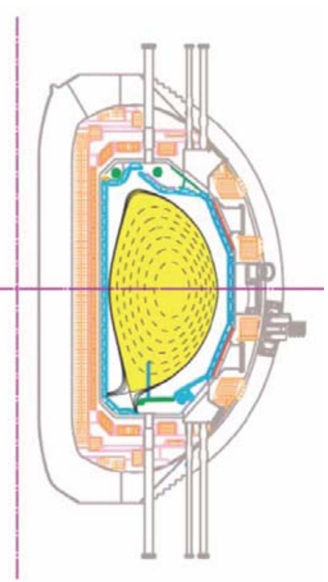
TWO classes of Design Options are proposed for FNSF

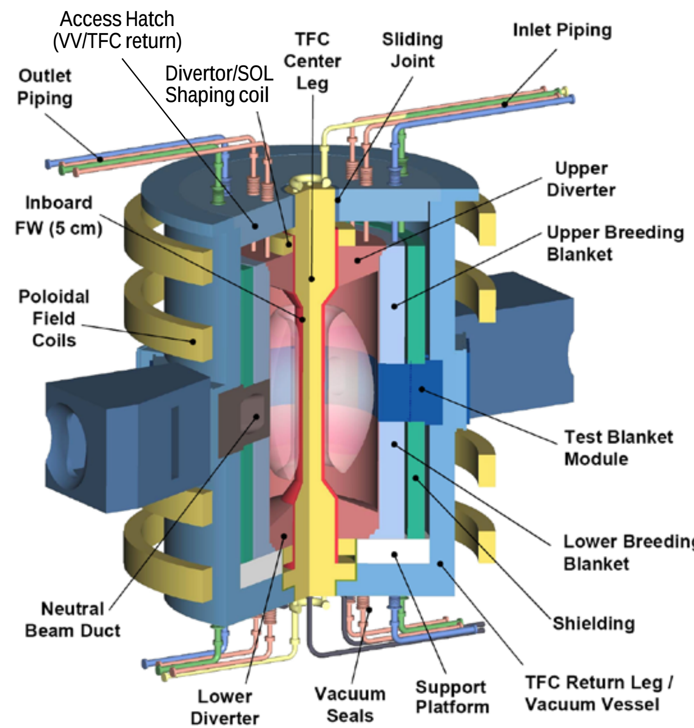
Both options satisfy FNST testing requirements

Standard Aspect Ratio, 2.8-4

Small Aspect Ratio, ~1.5, kappa 3







FNSF/FDF GA Design

high elongation & triangularity

Demountable TF coils, double null for high gain

P_{fusion} 125 MW at P_{NW} of 1 MW/m²

FNSF/ST ORNL design

Cu center post & TF coils

P_{fusion} 76MW at P_{NW} of 1 MW/m²

Differences are in the physics, configuration, and TF Coil resistive power.

The Plasma and FNST communities jointly have explored options and evolved strategies for testing in FNSF.

Strategy / Design for Breeding Blankets & Structural Materials

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
- 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, high performance blanket experiments**

Upgrade Blanket 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 (real environment) for testing structural materials,
  - no uncertainty in spectrum or other environmental effects
  - prototypical response, e.g., gradients, materials interactions, joints, …

There is consensus on the need for FNSF,
but some issues require further studies and deliberations.

FNSF Options now proposed (could be others)

-Tokamak with standard aspect ratio *OR* ST with small aspect ratio
- Minimum extrapolation needed for FNST R&D
  OR include advanced physics mission

FNSF Structural Materials – *strategy for data confirming performance*

1. 10dpa/100ppmHe - Consensus on FS and data for first stage of FNSF
2. Options for obtaining/using higher fluence data
   a. Follow fission reactor strategy; extrapolate FNSF data by a factor of 2
   b. Also obtain high fluence data using IFMIF, or MTS, or other facilities

Blanket & FNSF Strategy & Options

Optimal level of US participation in ITER TBM? Timing of TBM and FNSF?

1. Lead for DCLL and supporting role in other concepts
2. Supporting role only to other lead parties

PFC Test Options

1. Test PFC as the first phase (HH/DD) of FNSF. ("single step")
2. Explore conditions and concepts (e.g., W, "hot" walls, super-X, liquid metal divertors) in a separate facility (e.g. NHTX, Vulcan, other satellites) before FNSF.

What is needed now for FNST?

- **Strengthen FNST: upgrade/add facilities, support R&D.**

  Elements include: modeling and experiments in upgraded and new lab facilities, testing of innovative divertor concepts and helium cooling, and feasibility studies (e.g., joining of materials).

  Also, we must attract and train new people.

- **Define and select options for SATs, PSI-X and FNSF.**

  Preparing for and supporting these decisions are important near term activities crucial to the program.

  The FNST community should be strong participant.

- **Improve the framework for international collaboration.**

  We must take advantage of international collaboration, including US participation in the ITER TBM and active collaboration on PFCs with foreign confinement experiments, e.g., EAST.

  A method and framework for equity exchange for the use of US and foreign facilities would be very helpful.

Collaboration opportunities for synergy within DOE

- Nuclear data – *measurements and evaluation, 0 - 20 MeV, ongoing effort since 1970s.* (NE/BES/Nuclear Physics, OEM)
- PSI multi-charged ion research facility - *sputtering coefficients and molecular dynamics* (BES)
- Neutronics, shielding and activation codes (NE)
- Integrated modeling capabilities – *coupled neutronics, thermofluid, structural response, safety…* (NE/NRC)
- Tritium – *database, permeation and control* (NE/NNSA/BES)

- Fission in-pile experiments– *Blanket submodule experiments (e.g. in ATR), Robust techniques and instrumentation* (NE)
- LM and Molten salt – *chemistry, corrosion and thermofluids* (NE)
- High Temperature Helium – *cooling technology, thermofluids* (NE)
- Licensing – *for nuclear experiments & experimental facilities* (NE/NRC)
- Radiation damage and advanced materials (BES/NE/NRC) *(see materials presentation)*

Other more detailed technical example opportunities are possible as well

FNST Briefing:

Outline

1. Introduction

- Scope of fusion nuclear science and technology (FNST)
- Fusion Environment
- Science Based Framework for FNST

2. FNST Key Issues and Research

- Key Issues Summary - MFE/IFE Synergy
- Issue Examples:
  - PSI, MHD, Tritium Fuel Cycle, Reliability, Safety

3. FNST Development Strategy

- Non-fusion Testing, Fusion Testing – TBM & FNSF

4. Closing Summary

Toward the Credibility of Fusion - FNST
We need to launch a strong program now!

- **FNST is the <u>science</u>, <u>engineering</u>, <u>technology</u> and <u>materials</u> for the fusion nuclear components - a grand challenge every bit as difficult as developing plasma physics.**
- **R&D in FNST cannot be decoupled from an effective fusion plasma physics research program,** e.g., hot walls, disruptions, ELM control and mitigation, field ripple, tritium burn fraction.
- **Progress in FNST is essential**

  a) to evaluate how practical and competitive fusion energy will be,

  b) to proceed with DT devices beyond ITER.

  The breeding blanket is an <u>enabling technology</u> for future DT devices. We have no other supply of tritium beyond ITER/NIF.

  Only a DT facility for FNST R&D can supply the initial startup tritium inventory and verify the breeding blanket for DEMO.
- **FNST development will set the pace for a fusion DEMO.**

Examples of possible near term investments in FNST modeling and lab experiments

- **Upgrade/build test capability**
  upgrade high heat flux test stand; multiple PbLi flow loops to study MHD, tritium transport and extraction, corrosion, chemistry control
- **Test innovative PFC concepts**
  He cooling concepts for FW, Super-X and liquid metal divertors
- **Plan for major multiple-effects tests**
  Facilities/testing - unit cell PbLi, Ceramic breeder mockups test, chamber clearing, blanket sub-modules in fission reactors
- **Enhance key simulation capabilities**
  plasma-surface interactions, thermofluids, liquid metal MHD, tritium cycle and transport, ...
- **Extend integrated modeling capabilities**
  couple data, geometry, multi-physics, visualization,… to simulate complex component behavior in the fusion environment
- **Initiate feasibility studies in key areas**
  Joining, forming, testing for ferritic steel, SiC flow channel inserts, W-based PFCs and coatings, safety studies on failures and impacts

Toward the Credibility of Fusion - FNST

Is a fusion energy system even feasible?

Can we show one that is practical?

There is a growing consensus on the following.

- **The feasibility and attractiveness of fusion depends mostly on issues in FNST.**
- **Visible results from R&D in FNST are key in establishing a credible path forward.**
- **Progress in FNST will pace our realization of a DEMO (and FNSF).**

We must engage and train talented young scientists who can confront this challenge.

E N D