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
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.
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**

These are the FNST Core for IFE & MFE

The nuclear environment also affects

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

Exhaust Processing

- PFC & Blanket
- DT plasma
- PFCs Blanket

T storage & management

- Fueling system
- Exhaust Processing
- Impurity separation, isotope separation
- T waste treatment

Design dependent optics
Fusion nuclear environment: multi-field, harsh, unique

<table>
<thead>
<tr>
<th>Neutrons <em>(fluence, spectrum, gradients)</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>- Radiation Effects</td>
</tr>
<tr>
<td>- Tritium Production</td>
</tr>
<tr>
<td>- Bulk Heating</td>
</tr>
<tr>
<td>- Activation and Decay Heat</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Heat Sources <em>(thermal gradients)</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>- Bulk (neutrons)</td>
</tr>
<tr>
<td>- Surface (particles, radiation)</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Magnetic Fields <em>(3-components, gradients)</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>- Steady and Time-Varying Field</td>
</tr>
<tr>
<td>Limited import for IFE</td>
</tr>
</tbody>
</table>

**Mechanical Forces**
- Steady, Cyclic, Transient/Pulsed, Failure-caused
## Fusion nuclear environment: complex effects, interactions, and science

**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

**Combined Loads, Multiple Environmental Effects**
- Thermal-Chemical-mechanical-electrical-magnetic-nuclear interactions and synergistic effects
- Interactions among physical elements of 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 **highly integrated predictive capabilities** for many cross-cutting scientific & engineering disciplines.

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

1. Introduction
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MFE & IFE share many common interests and R&D needs inFNST.

Many common interests

− 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

List is incorporated in FNST Critical Issues (next)

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

*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*.

![Diagram showing the fuel cycle components](image)

- **T storage & management**
- **Fueling system**
- **DT plasma**
- **Impurity separation, Isotope separation**
- **Exhaust Processing**
- **T waste treatment**
- **PFC & Blanket T processing design dependent**
- **PFCs Blanket**

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

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

Tritium Self Sufficiency

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

T waste treatment

Impurity separation, Isotope separation

Fueling system

Exhaust Processing

PFC & Blanket T processing design dependent

PFCs Blanket

DT plasma

new plants

T storage & management

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


release/disposal

startup
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

<table>
<thead>
<tr>
<th>Component</th>
<th>#</th>
<th>Failure rate (1/hr)</th>
<th>MTBF (yrs)</th>
<th>MTTR Major (hrs)</th>
<th>MTTR Minor (hrs)</th>
<th>Fraction Failures Major</th>
<th>Outage Risk</th>
<th>Component Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toroidal</td>
<td>16</td>
<td>5 x10^-6</td>
<td>23</td>
<td>10^4</td>
<td>240</td>
<td>0.1</td>
<td>0.098</td>
<td>0.91</td>
</tr>
<tr>
<td>Poloidal Coils</td>
<td>8</td>
<td>5 x10^-6</td>
<td>23</td>
<td>5 x10^-3</td>
<td>240</td>
<td>0.1</td>
<td>0.025</td>
<td>0.97</td>
</tr>
<tr>
<td>Magnet supplies</td>
<td>4</td>
<td>1 x10^-4</td>
<td>1.14</td>
<td>72</td>
<td>10</td>
<td>0.1</td>
<td>0.007</td>
<td>0.99</td>
</tr>
<tr>
<td>Cryogenics</td>
<td>2</td>
<td>2 x10^-4</td>
<td>0.57</td>
<td>300</td>
<td>24</td>
<td>0.1</td>
<td>0.022</td>
<td>0.978</td>
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<tr>
<td>Blanket</td>
<td>100</td>
<td>1 x10^-5</td>
<td>11.4</td>
<td>800</td>
<td>100</td>
<td>0.05</td>
<td>0.135</td>
<td>0.881</td>
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<tr>
<td>Divertor</td>
<td>32</td>
<td>2 x10^-5</td>
<td>5.7</td>
<td>500</td>
<td>200</td>
<td>0.1</td>
<td>0.147</td>
<td>0.871</td>
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<tr>
<td>Htg/CD</td>
<td>4</td>
<td>2 x10^-4</td>
<td>5.7</td>
<td>500</td>
<td>20</td>
<td>0.1</td>
<td>0.131</td>
<td>0.884</td>
</tr>
<tr>
<td>Fueling</td>
<td>1</td>
<td>3 x10^-5</td>
<td>3.8</td>
<td>72</td>
<td>--</td>
<td>--</td>
<td>0.002</td>
<td>0.998</td>
</tr>
<tr>
<td>Tritium System</td>
<td>1</td>
<td>1 x10^-4</td>
<td>1.14</td>
<td>180</td>
<td>24</td>
<td>0.1</td>
<td>0.005</td>
<td>0.995</td>
</tr>
<tr>
<td>Vacuum</td>
<td>3</td>
<td>5 x10^-5</td>
<td>2.28</td>
<td>72</td>
<td>6</td>
<td>0.1</td>
<td>0.002</td>
<td>0.998</td>
</tr>
<tr>
<td>Conventional</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.952</td>
</tr>
<tr>
<td>Equipment</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL SYSTEM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.624</td>
<td>0.615</td>
</tr>
</tbody>
</table>

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**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

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Practical and Reliable Systems

*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**

Tritium retention and permeation barriers

Waste Minimization and Recycling
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FNST has a science-based framework for R&D.
(as developed by FNST community, supported by ReNeW)

Theory/Modeling/Database → Design Codes, Predictive Cap.

- Basic
- Separate Effects
- Multiple Interactions
- Partially Integrated
- Integrated
- Component

Non-Fusion Facilities
- non-neutron test stands, plasma physics devices
- fission reactors, accelerator-based neutron sources

Measure Properties → Explore Phenomena

Explore Fusion Environment
- Screen Concepts
- Verify Performance
- Verify Design
- Reliability Data

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 -

<table>
<thead>
<tr>
<th>Non-Neutron Test Stands [PFC/HHF, PSI, LMMHD, Safety]</th>
<th>Neutron Effects*</th>
<th>Nuclear Heating</th>
<th>Thermal-Mechanical-Magnetic-Electrical-Chemical-Interactions</th>
<th>Integrated Synergistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Fission Reactors</td>
<td>partial</td>
<td>partial</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Acceleator-Based Neutron Sources</td>
<td>partial</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>

* 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.

Nygren, Abdou, Sharpe - Fusion Nuclear Science & Technology – 9 Dec 2009 OFES
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 cm²)
- 20 MW/m² on target, 10^{23-24} /m²s under high recycling conditions

*ORNL*
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.
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
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 worldwide in blankets using ceramic breeders or Pb-Li based blankets)

*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)

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

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

Nygren, Abdou, Sharpe - *Fusion Nuclear Science & Technology* – 9 Dec 2009 OFES
Integrated testing in a fusion environment will proceed in three stages.

Stage 1: ~ 0.3 MW-y/m²
- Fusion Break-in & Scientific Exploration

Stage 2: 1-3 MW-y/m²
- Engineering Feasibility – Verify Performance –

Stage 3: 4-6 MW-y/m²
- Component Development & Reliability Growth

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

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**FNSF/FDF GA Design**

- high elongation & triangularity
- Demountable TF coils, double null for high gain

\[ P_{\text{fusion}} = 125 \text{ MW at } P_{\text{NW}} \text{ of } 1 \text{ MW/m}^2 \]

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**FNSF/ST ORNL design**

- Cu center post & TF coils

\[ P_{\text{fusion}} = 76\text{MW at } P_{\text{NW}} \text{ of } 1 \text{ MW/m}^2 \]

**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*
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   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 science, engineering, technology and materials 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 enabling technology 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.*
END