

Fusion Nuclear Science and Technology (FNST)

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With input from the FNST Community

Message:

The world fusion program must immediately launch an aggressive FNST R&D program if fusion energy is to be realized in the 21st century.

– Leadership of such FNST program is an ideal role for the US

Fusion Nuclear Science and Technology (FNST)

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

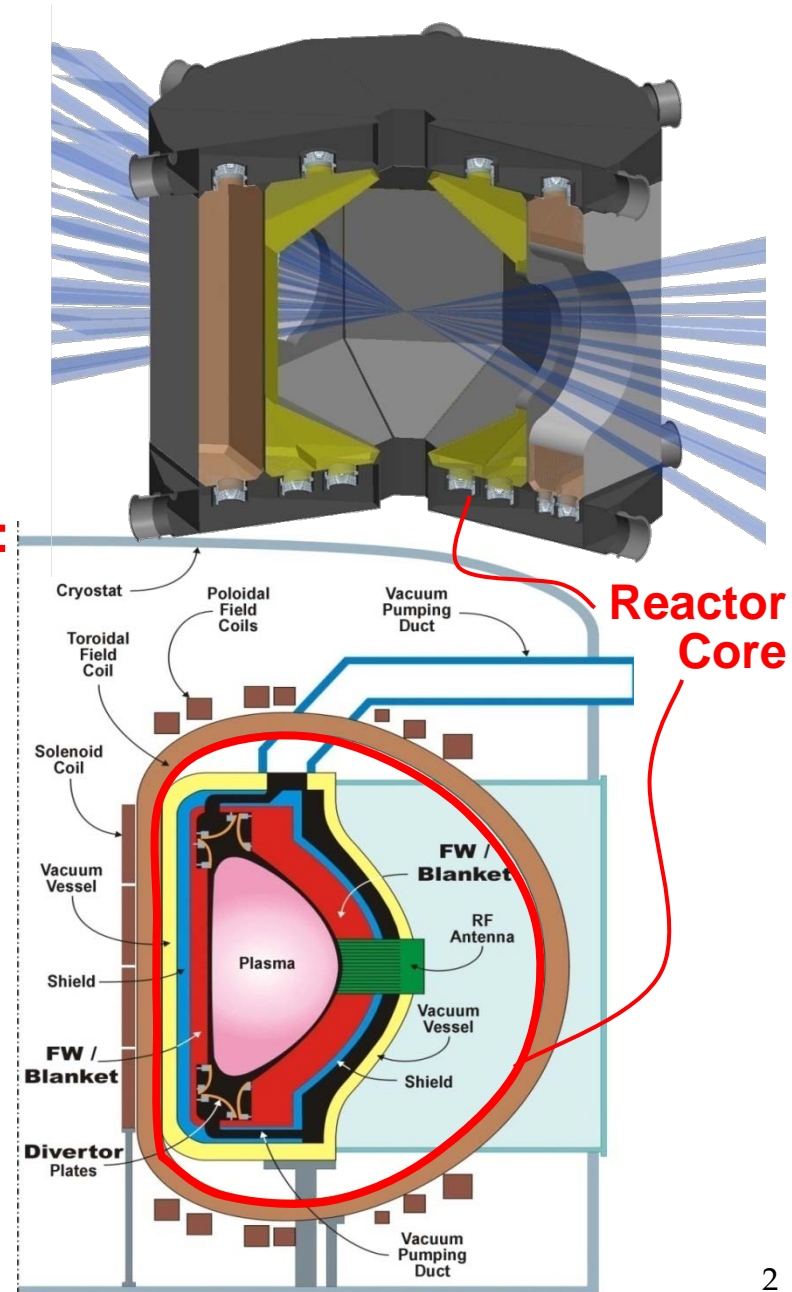
(For both MFE and IFE)

Inside the Vacuum Vessel “Reactor Core”:

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

Other Systems / Components affected by the Nuclear Environment:

- Tritium Processing and Target Factory Systems
- Instrumentation & Control Systems
- Remote Maintenance Components
- Heat Transport & Power Conversion Systems



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

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

These capabilities are needed by any MFE/IFE fusion energy program

Fusion Nuclear Environment is complex & unique

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

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

Highly Constrained
FNST Components

Combined Loads, Multiple Environmental Effects

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

MFE/IFE FNST Issues: Synergy and Uniqueness

Common to MFE/IFE

- **Feasibility and Performance** of a viable PFC/Wall Protection scheme
- **Thermo-mechanical loads & response**
- **Fluid-Materials interactions**
- **Tritium self-sufficiency** in a practical system
- **Tritium generation, extraction & inventory** under actual operating conditions
- **Tritium implantation, permeation & control**
- **Material degradation** by radiation and other damage
- **Fabrication and joining** for reliable components
- **Failure** modes, rates, effects and amelioration
- **Remote maintenance** with acceptable machine downtime

Unique to MFE

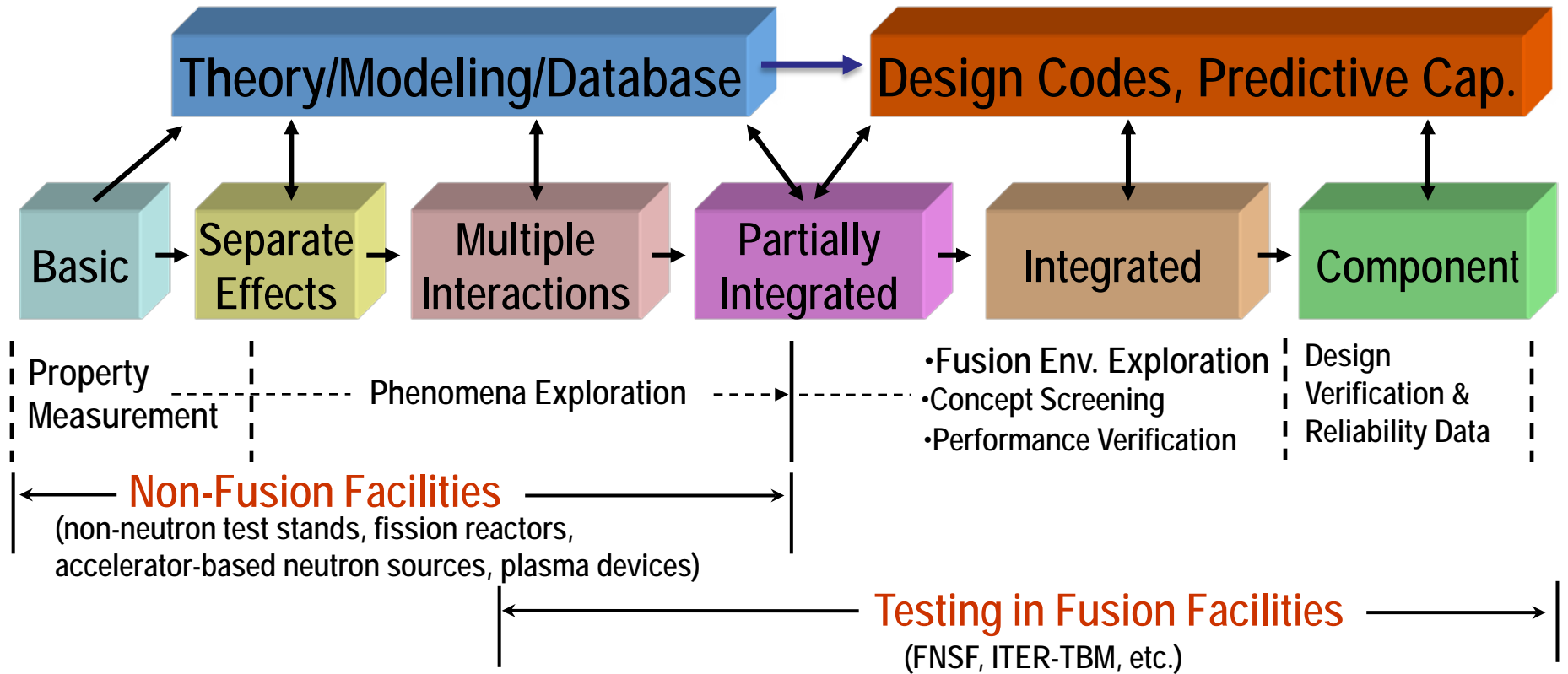
- **Plasma-material interactions** at high temperature for long pulses
- **MHD thermofluid** phenomena, heat transport in electrically-conducting coolants and breeders

Unique to IFE

- **Cavity clearing** at IFE pulse repetition rate
- **Incremental effects of repetitive pulses** (e.g., radiation damage and thermomechanical fatigue)
- **Tritium recovery** from debris
- **Target Injection and Tracking**

Science-Based Framework for FNST R&D

(Developed by FNST community and Supported by ReNeW)



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, develop reliable components

What we need now:

- A strong program of modeling and laboratory experiments in new & existing non-fusion facilities
- Plan for ITER TBM and initiate a study to define and select a DT Fusion Nuclear Science Facility (FNSF) dedicated to FNST R&D in the integrated fusion environment

Why the world needs to launch FNST program now?

- 1. FNST is a grand challenge every bit as difficult as plasma physics development. Progress on FNST is essential to evaluating how practical and how competitive fusion energy systems will be.**
- 2. FNST Research cannot be decoupled from carrying out an effective fusion plasma physics research program.**
- 3. FNST is essential to continued progress of fusion research:**
 - Breeding blanket is an “enabling technology” required for operation of future DT fusion research facilities (No external supply of tritium beyond ITER/NIF).
 - Only a DT fusion facility dedicated to FNST R&D can supply the Initial Startup Tritium Inventory as well as the verified breeding blanket required for DEMO.
- 4. It takes a long time to train talented young scientists who can confront this challenge.**
- 5. FNST R&D will set the pace for fusion development toward a DEMO.**

FNST has some of the most difficult feasibility and attractiveness issues for fusion

Pillars of a Fusion Energy System

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



Fusion Nuclear Science and Technology plays the KEY role

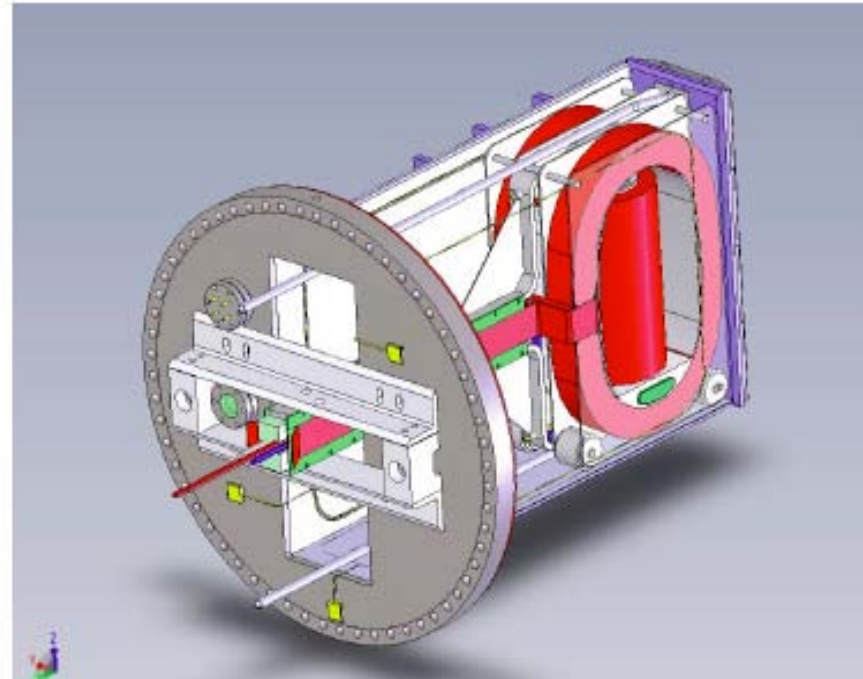
Substantial R&D to understand, quantify and resolve the FNST key issues is necessary to determine if a fusion energy system is practical or even feasible.

FNST Research Is Essential to an Effective Fusion-Plasma Research Program

Many areas that are the **central focus** of much of the plasma physics research today were identified and implemented by interactive FNST/physics research:

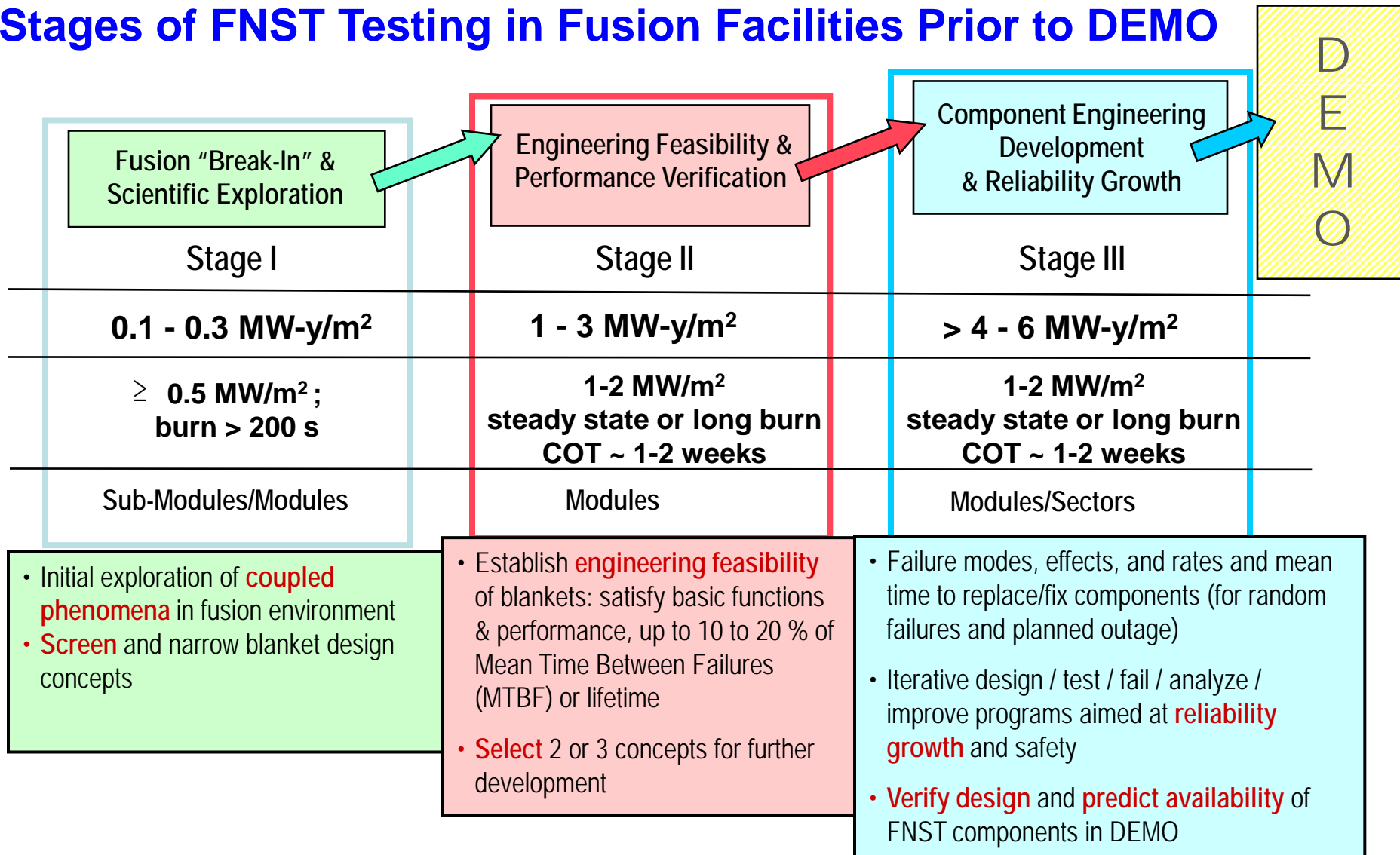
Past and Current Examples of the Power of such Scientific Partnership

- Need for steady state MFE plasma operation (or 5-10 Hz IFE Rep Rate)
- Requirements on non-inductive plasma-current drive, *rf vs NB*
- Intolerable nature of **plasma-disruptions**
- **Tritium burn-up fractions** predicted for ITER are not acceptable for reactors
- Key requirements on plasma edge and DT fueling
- Practical materials and designs for PFCs
- **Field ripple** created by ferritic steel (the only practical structural material identified for any fusion device beyond ITER)
- The blanket inside vacuum vessel. **Can fusion plasmas co-exist with blankets?**
- Intolerable impact of passive Cu coils inside the blanket, Plasma shaping & control?



Ferritic Steel Field Ripple Experiment in DIII-D (M.J. Schaffer)

Stages of FNST Testing in Fusion Facilities Prior to DEMO



- A Fusion Nuclear Science Facility (FNSF) dedicated to FNST R&D in the integrated fusion environment is needed.
- FNST testing requirements and Considerations of cost, risk, and lack of adequate external T supply dictate that FNSF should be a small-size, small-power DT, driven-plasma device with Cu magnets.

The External Tritium Supply issue is serious and has important implications for DT fusion research

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:

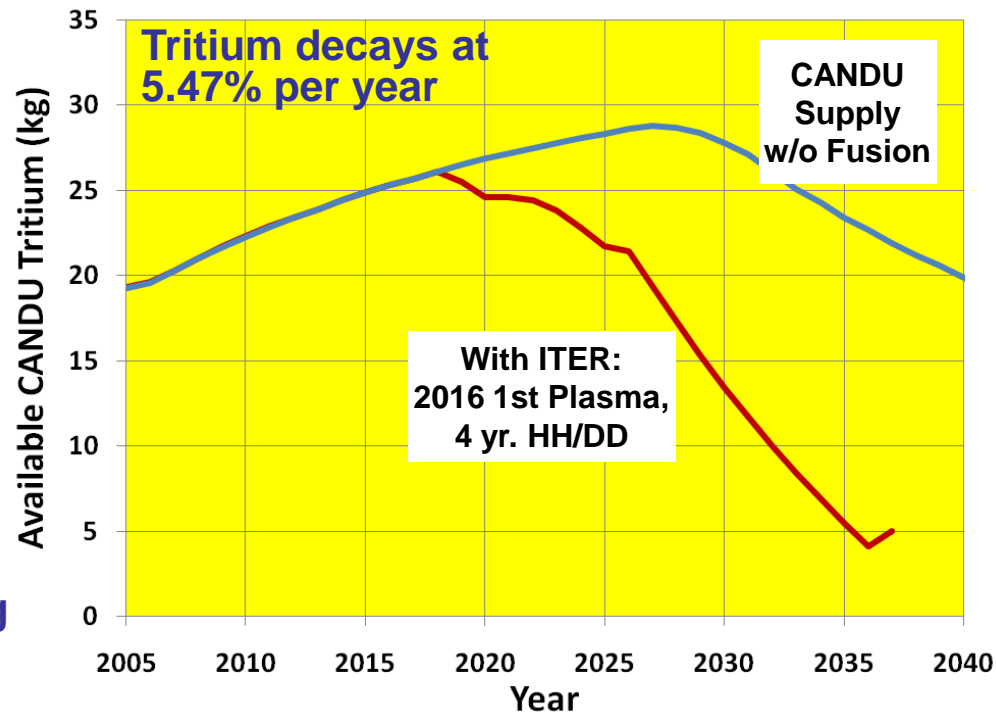
Fission reactors: 2–3 kg/year

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

**www.ig.energy.gov/documents/CalendarYear2003/ig-0632.pdf*

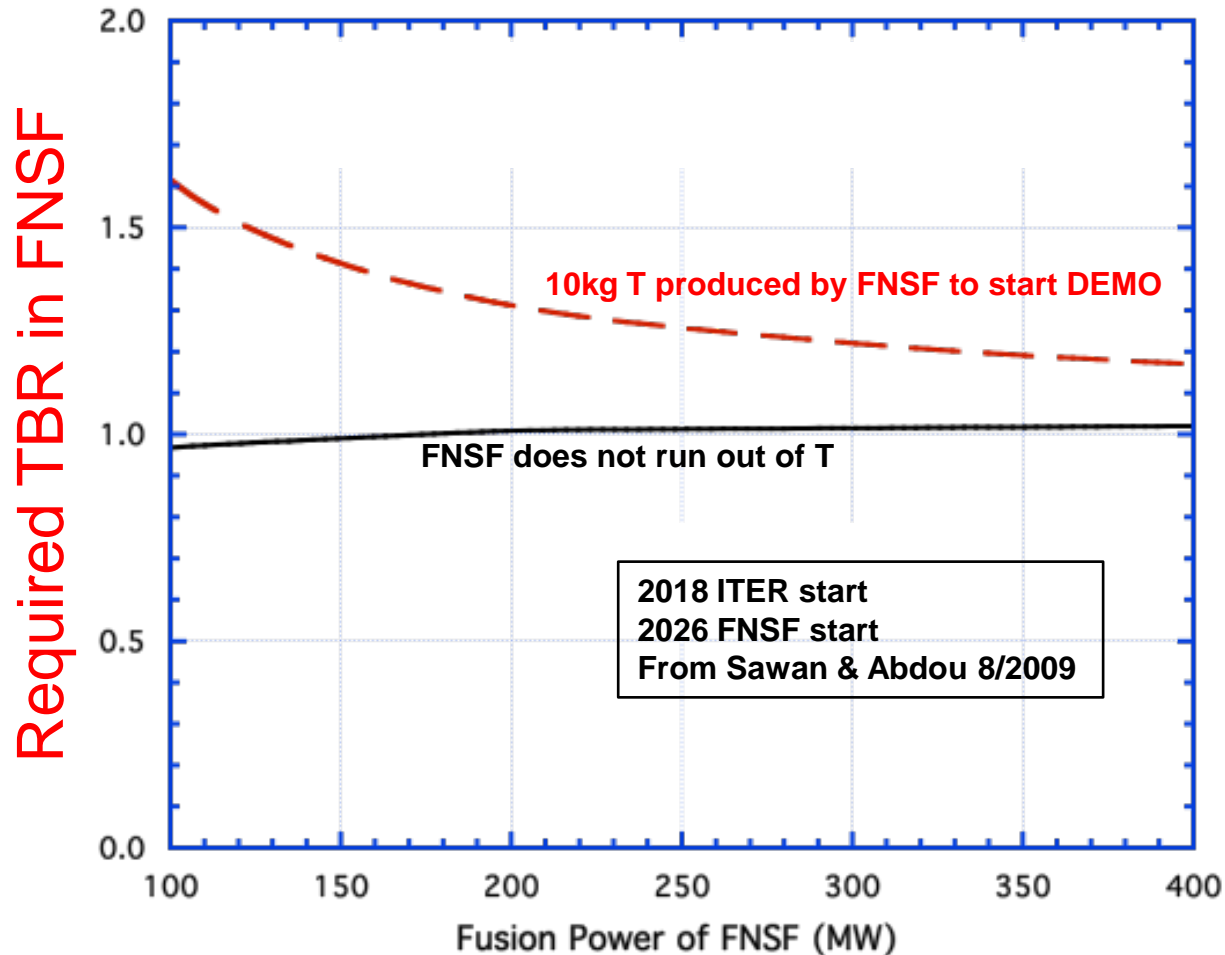
CANDU Reactors: 27 kg from over 40 years, \$30M/kg (current)

- **A Successful ITER will exhaust most of the world supply of tritium**
- **No future DT fusion devices other than ITER, can be operated without a breeding blanket**



FNST R&D is essential to continued progress of fusion research: Breeding blanket is an “enabling technology” for operation of any future DT fusion research facilities including FNSF (No external supply of tritium except for ITER.)

FNSF is also essential to provide the initial start up tritium inventory and providing the verified breeding blanket technology for DEMO (in addition to demonstrating tritium self-sufficiency)



Even FNSF must have a breeding blanket from the beginning of operation. Aggressive FNST R&D is needed NOW.

FNST R&D will set the Pace for Fusion Development

Example: Time required to do R&D for Reliability/Availability/Maintainability (RAMI) for FNST is very long – longer than any other research element.

Summary of RAMI issues

- Many major components, each needs high **AVAILABILITY**
- Blanket/ PFC seem to have **short MTBF** (inside vacuum ,harsh environment) and **long MTTR** (inside the vacuum in complex confinement configuration)
- **Using Standard “Reliability Growth” Methodology, it is predicted that the required cumulative “energy fluence” in the fusion environment (e.g., FNSF) is ~ 6 MW-y/m²**

Development Phases	Duration	Notes
Testing in non-fusion facilities	10-15 years	Essential prior to testing in the fusion env.
Design, Construction, H/DD Phase of FNSF	7-12 years	Can partly overlap with R&D in non-fusion facilities
Testing in DT Phases of FNSF	15-40 years	Depending on FNSF availability & performance
Solve problems encountered	??	Major flaws in blankets, PFC, etc.

An aggressive FNST program must start now to improve the time scale outlook for fusion energy development – “towards fusion’s credibility”.

FNSF provides excellent strategy and real fusion environment for developing and utilizing Structural Materials

- **Reduced activation Ferritic Steel (FS) is the only structural material option for DEMO.**
 - FS should be used in FNSF for both base breeding blanket and specialized and instrumented blanket experiments in “testing ports”.
 - FS irradiation database from fission extends to ~ 80 dpa, but it lacks He.
 - There is confidence in He data up to 100 appm He (~ 10 dpa).
- **Strategy for developing structural material data base on FNSF:**
 - Design initial breeding blanket for FNSF with FS for ~ 10 dpa/100 appm He.
 - Obtain real data on FS performance up to ~ 10 dpa in Stage I testing in FNSF.
 - **Extrapolate by a factor of 2 (standard in fission and other development)** to design next stage blanket in FNSF for 20 dpa/200 appm He. Extrapolate to next stage of 40 dpa.
- **FNSF will provide key information on structural material in 3 ways:**
 - **From base breeding blanket** – large surface area.
 - **From “test port-based” modules** where the performance is pushed toward higher and lower limits (e.g. temperature) and more complete instrumentation.
 - **Thousands of specimens** at different operating conditions (e.g., temperatures).
- **Results of testing structural materials in FNSF will be conclusive.**
 - “Real” fusion environment – no uncertainty in spectrum or other environmental effects.
 - Testing of components with prototypical gradients, materials interactions, joints, and other fusion environmental conditions.

FNST Grand Challenge is an ideal research and development effort for the **US to lead**

- **R&D for Fusion Nuclear Science and Technology is a “Grand Challenge”**
 - multi-function, multi-physics, multi-engineering requirements and
 - complex and unique thermo-magneto-vacu-tritu-nuclear environment of fusion
- **Requires innovation, creativity, cutting edge science, and close coordination between engineering science, technology, and plasma physics research, all areas where the US excels**
- **Prepare the US to design/build/license next DT plasma devices**
- **FNST is of central importance to fusion energy deployment, will US be an importer of fusion nuclear components and materials?**
FNST is where Key IPR will emerge

The current U.S. FNST research program is focused on the most important issues with high scientific content and substantial potential for an improved vision of a fusion energy system – providing excellent foundation for US leadership

Concluding Remarks

- ❑ **There has been significant progress on understanding and resolving many FNST technical issues.** But there are many more critical issues for which there has been little or no progress because: 1- these issues represent major scientific and engineering challenges, and 2- the resources available for FNST R&D have been seriously limited.

- ❑ **The World Fusion Program must immediately launch an aggressive FNST R&D program if fusion energy is to be realized in the 21st century.**

- ❑ **An effective FNST program must include:**
 - Fundamental and integrated modeling of important phenomena and multiple synergistic effects.
 - Experiments in **new** and existing non-fusion facilities.
 - **TBM** in ITER accompanied by both research and development programs.
 - A Fusion Nuclear Science Facility (**FNSF**) dedicated to FNST. FNSF is a small size, small power, DT, driven-plasma device with Cu magnets.

US should lead FNST Research.