Fusion Nuclear Science and Technology (FNST) Challenges and Facilities on the Pathway to Fusion Energy

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

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Over the past 3 decades we have done much planning and defining ambitious goals for the long term (power reactors) based on what we "perceive" the technical challenges are, and what may be attractive.

- This planning has suffered from lack of fundamental knowledge on FNST

- **NOW it is time to focus on "actions" to perform substantial FNST R&D in the immediate and near-term futures: this will give us real scientific and engineering data with which we can:**
  - **evaluate our long-term goals (too ambitious? Realistic?)**
  - **define a practical and credible pathway**

<u>The Major Challenges NOW are in FNST</u>

The major FNST challenges are not only the difficulty and complexity of the technical issues

➢ But also how and where (facilities) we can do experiments to resolve these issues.

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.

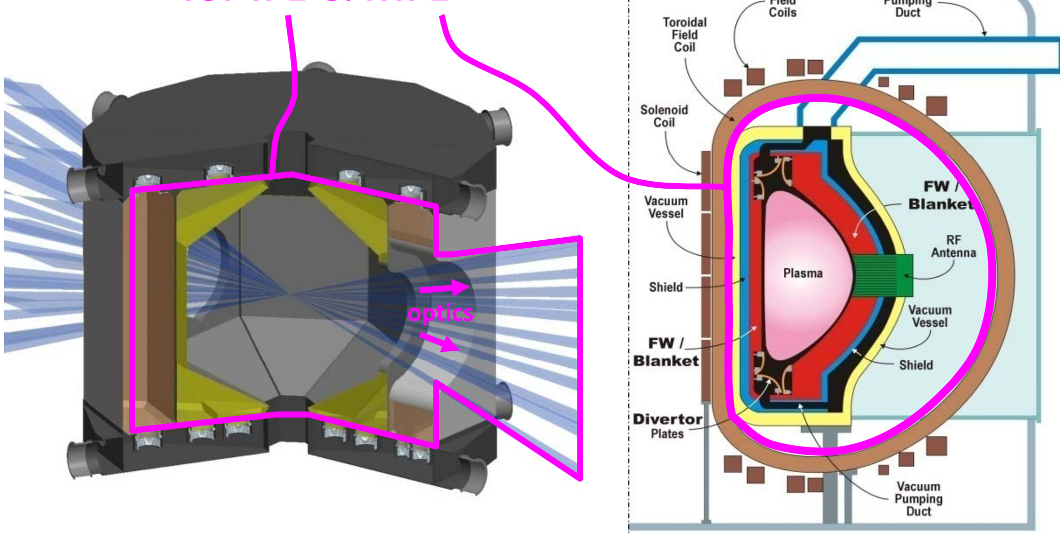
In-vessel Components

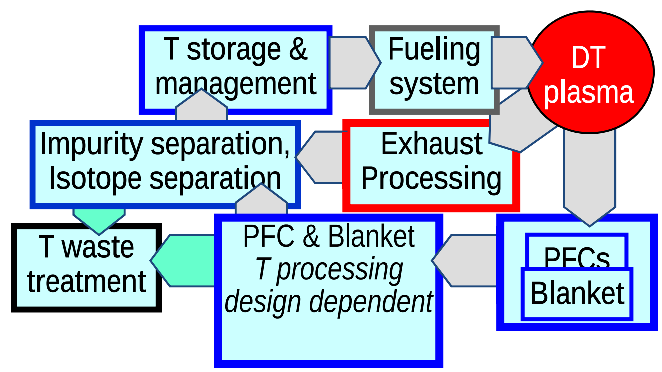
- **Plasma Facing Components**
  divertor, limiter, heating/fueling and final optics, etc.
- **Blanket** and **Integral First Wall**
- **Vacuum Vessel** and **Shield**

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 Science and Technology (FNST) must be the Central element of any Roadmapping for fusion

ITER (and KSTAR, EAST, JT-60SU, etc) will show the Scientific and Engineering Feasibility of:

- **Plasma (**Confinement/Burn, CD/Steady State, Disruption control, edge control)
- **Plasma Support Systems** (e.g. Superconducting Magnets)

- **ITER does not address FNST (all components inside the vacuum vessel are NOT DEMO relevant - not materials, not design, not temperature)**

  (TBM provides very important information, but limited scope)

- **FNST is the major missing Pillar of Fusion Development**

FNST will Pace Fusion Development Toward a DEMO.

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 DT-plasma based facility.*

Challenging Consequences

- Non-fusion facilities (laboratory experiments) need to be substantial to simulate multiple fields, multiple effects
  - ***We must "invest" in new substantial laboratory-scale facilities.***
- Results from non-fusion facilities will be limited and will not fully resolve key technical issues. A DT-plasma based facility is required to perform "multiple effects" and "integrated" fusion nuclear science experiments. So, the first phase of FNSF is for "scientific feasibility".
- But we have not yet built DT facility – so, the first FNSF is a challenge.

Fusion Nuclear Environment is Complex & Unique

Neutrons ***(flux, 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

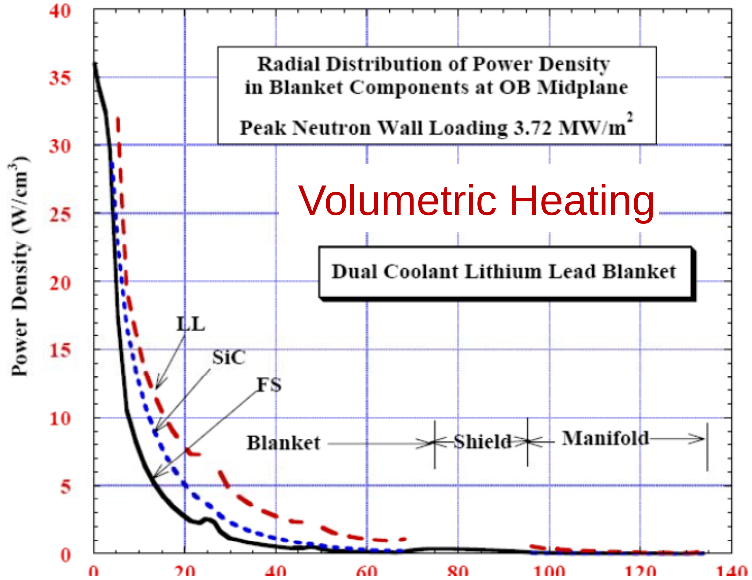
Mechanical Forces
- Normal *(steady, cyclic)* and Off-Normal *(pulsed)*

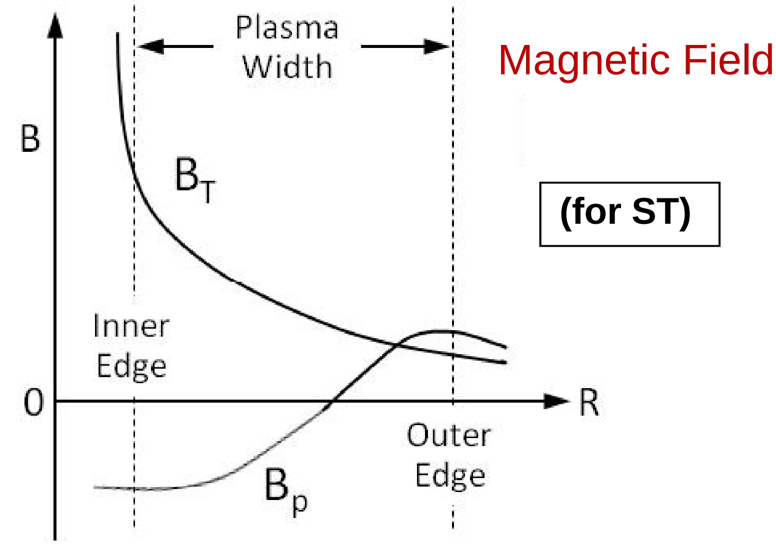
Multiple functions, materials, and many interfaces in highly constrained system

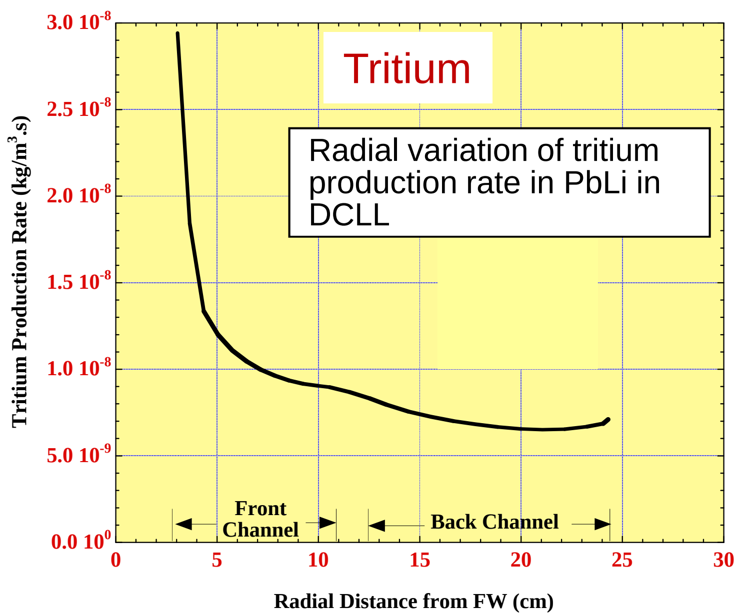
Combined Loads, Multiple Environmental Effects
- Thermal-chemical-mechanical-electrical-magnetic-nuclear interactions and synergistic effects
- Interactions among physical elements of components

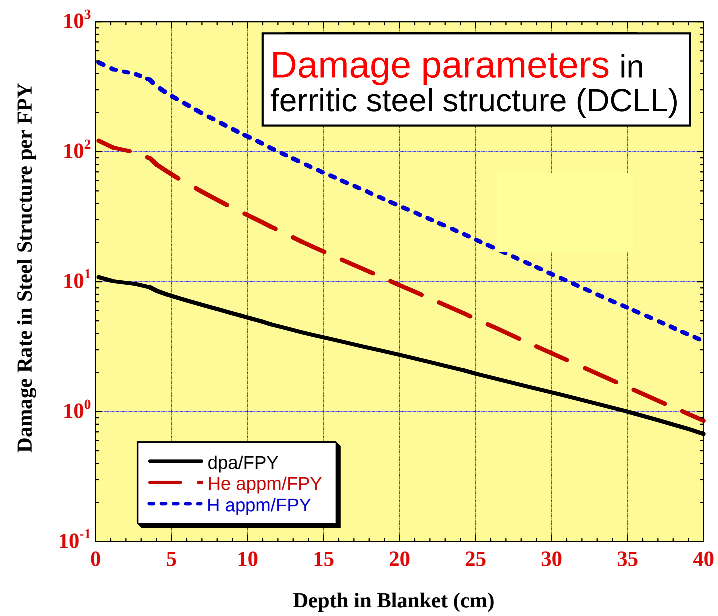
Non-fusion facilities (Laboratory experiments) need to be substantial to simulate multiple effects
Simulating nuclear **bulk heating in a large volume** is the most difficult and is most needed
Most phenomena are temperature (and neutron-spectrum) dependent– it needs DT fusion facility
The full fusion 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.

Importance of Bulk Heating and Gradients of 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 (very limited testing volume, wrong spectrum, wrong gradient)

Conclusions:

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

Reliability/Availability/Maintainability/Inspectability (RAMI) is a Serious Issue for Fusion Development

(table from Sheffield et al)

Availability required for each component needs to be high

Component	#	failure rate (1/hr)	MTBF (yrs)	MTTR/type Major (hrs)	Minor (hrs)	Fraction Failures Major	Outage Risk	Component Availability
Toroidal C	16	5×10^{-6}	23	10^4	240	0.1	0.098	0.91
P 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							0.884
Fueling	1							0.998
Tritium System	1							0.995
Vacuum	3							0.998
Conventional equi								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

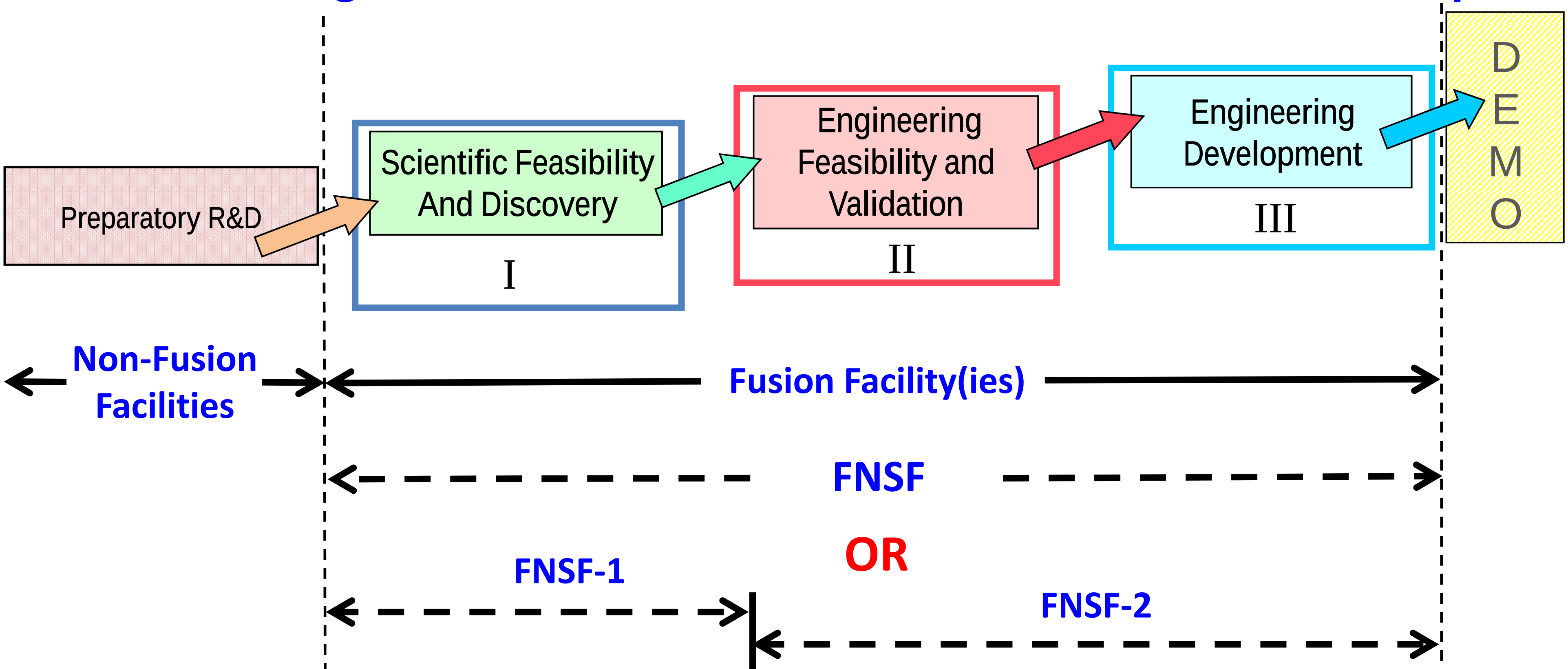
DEMO availability of 50% requires:

- **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!!

Carefully studying these FNST challenges lead to suggesting that we should plan on FNSF as the “Now + 1” (or “0+1”) facility. Not as “DEMO-1” facility.

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.

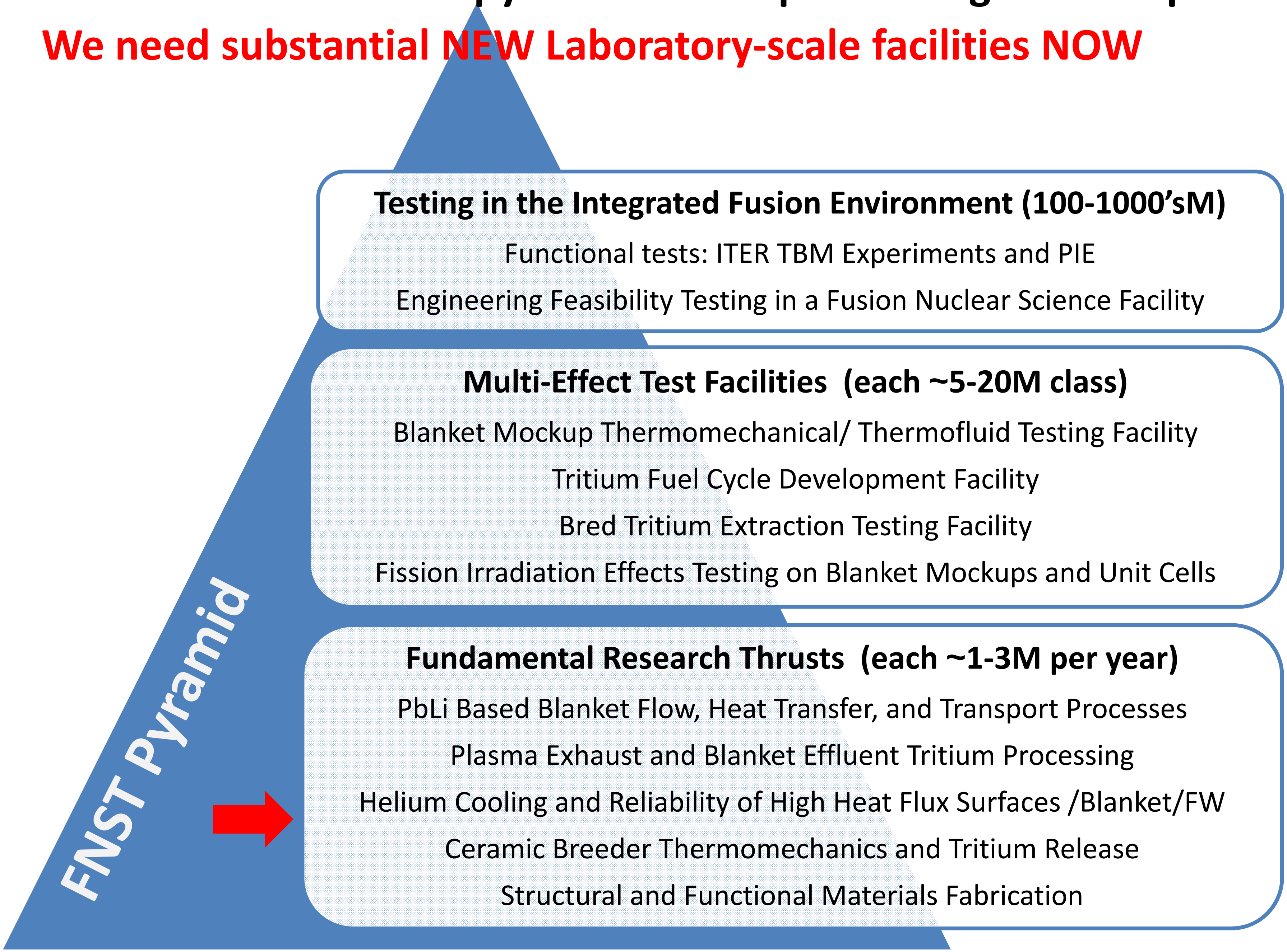
  May be multiple FNSF in parallel?!

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)

Establish the base of the pyramid Before proceeding to the top

We need substantial NEW Laboratory-scale facilities NOW



Concluding Remarks

- **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.