

Role and Challenges of Fusion Nuclear Science and Technology (FNST) toward DEMO

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What is fusion?

- **Fusion powers the Sun and Stars.** Two light nuclei combine to form a heavier nuclei (the opposite of nuclear fission).

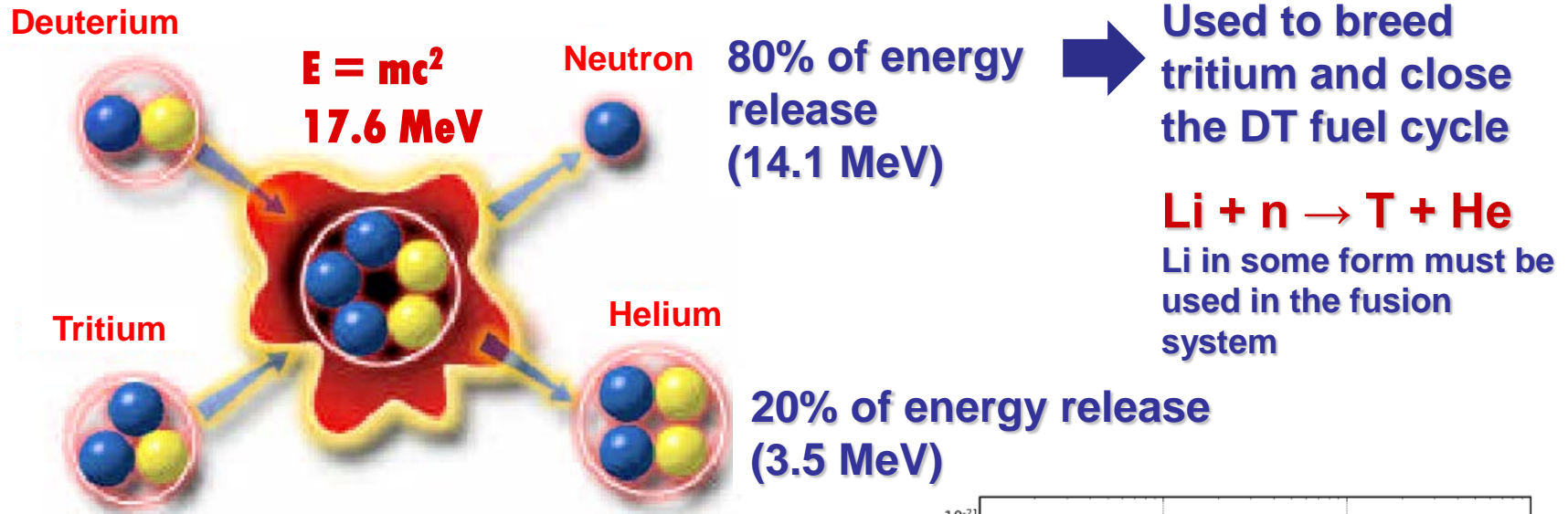
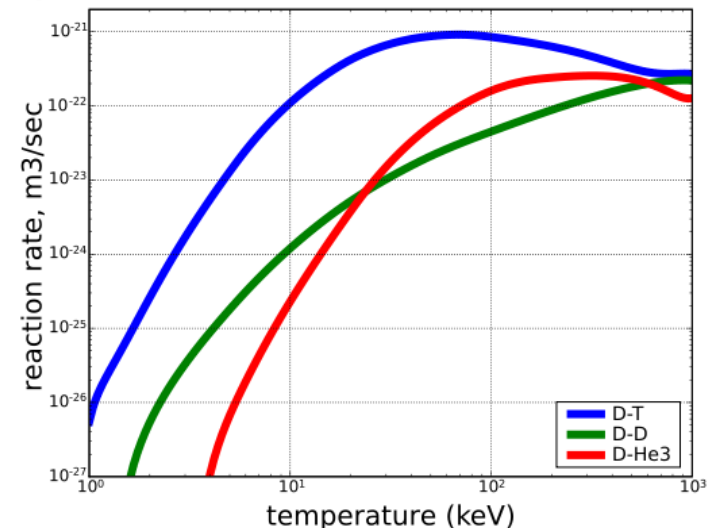
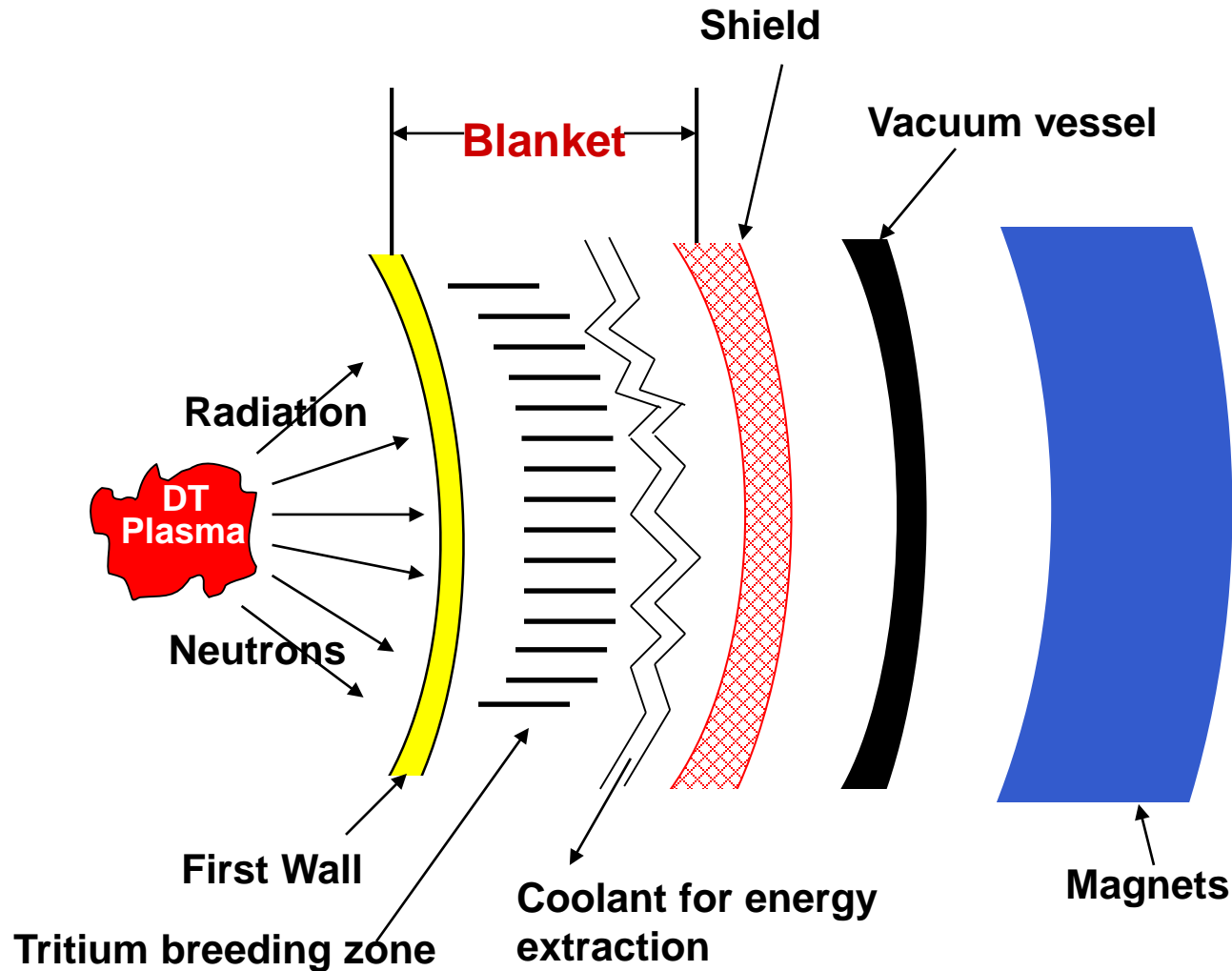


Illustration from DOE brochure

- Deuterium and tritium is the easiest, attainable at lower plasma temperature, because it has the largest reaction rate and high Q value.
- The World Program is focused on the D-T Cycle



A blanket surrounding the plasma provides for: Power Extraction & Tritium Breeding



Lithium-containing Liquid metals (Li, PbLi) are strong candidates as breeder/coolant. He-cooled Li ceramics are also candidates.

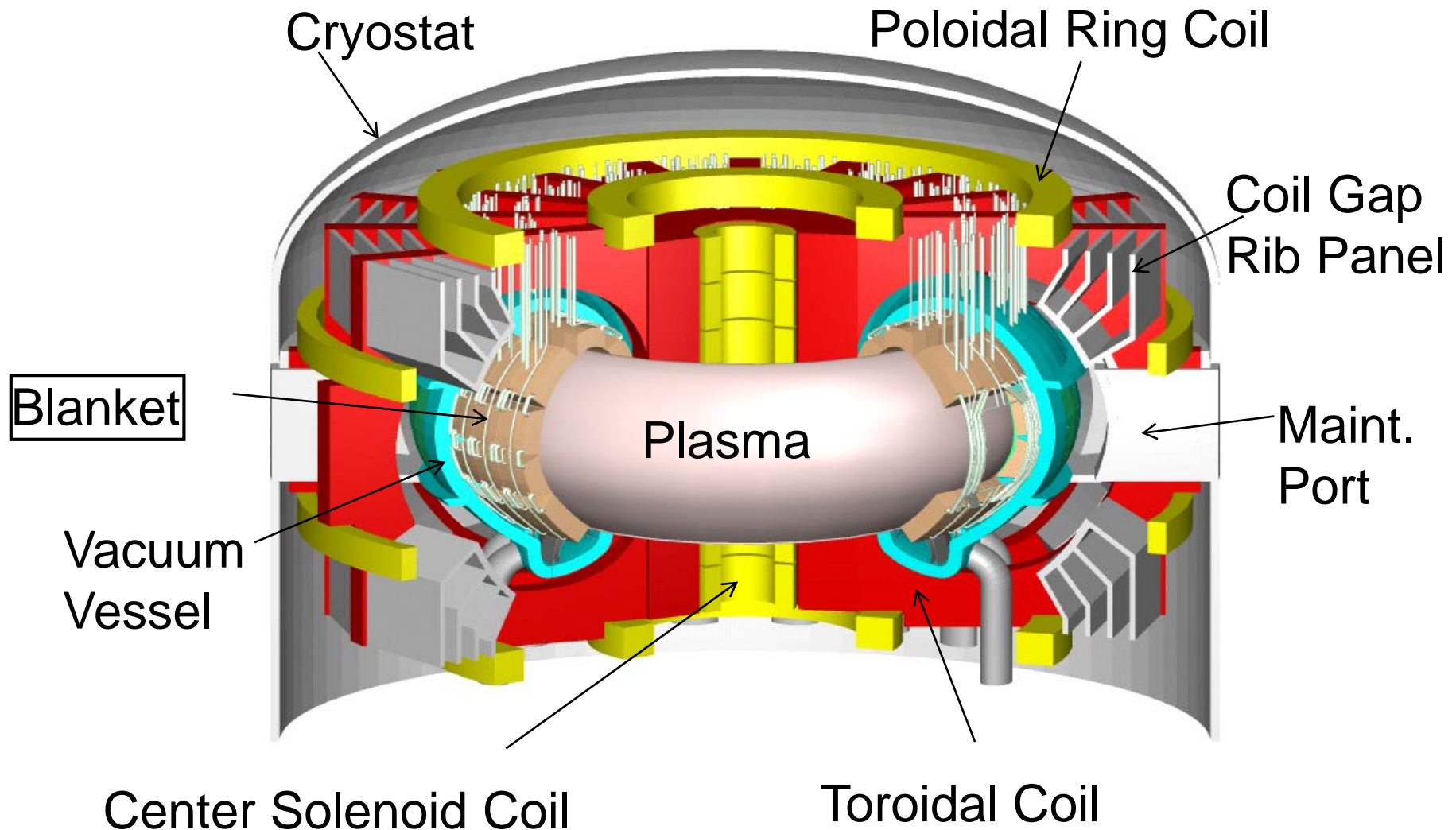
Incentives for Developing Fusion

- Sustainable energy source
(for DT cycle: provided that Breeding Blankets are successfully developed and tritium self-sufficiency conditions are satisfied)
- No emission of Greenhouse or other polluting gases
- No risk of a severe accident
- No long-lived radioactive waste

Fusion energy can be used to produce electricity and hydrogen, and for desalination.

The World Fusion Program has a Goal for a Demonstration Power Plant (DEMO) by ~2050(?)

Plans for DEMO are based on Tokamaks



(Illustration is from JAEA DEMO Design)

Fusion Nuclear Science & Technology (FNST)

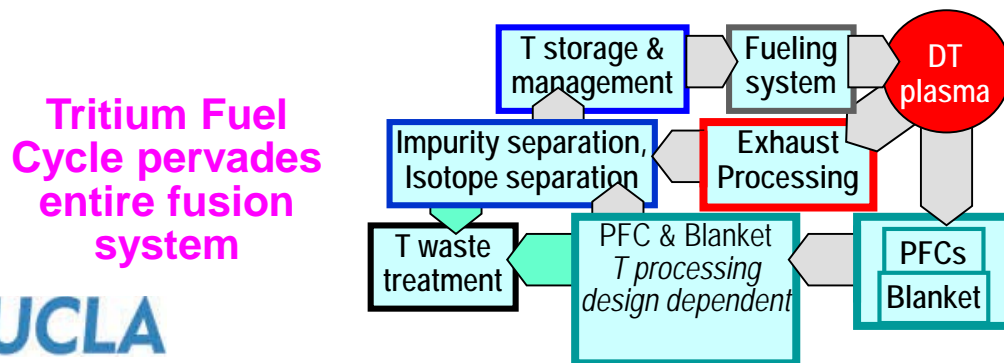
FNST is the science, engineering, technology and materials for the fusion nuclear components that generate, control and utilize neutrons, energetic particles & tritium.

In-vessel Components (Core)

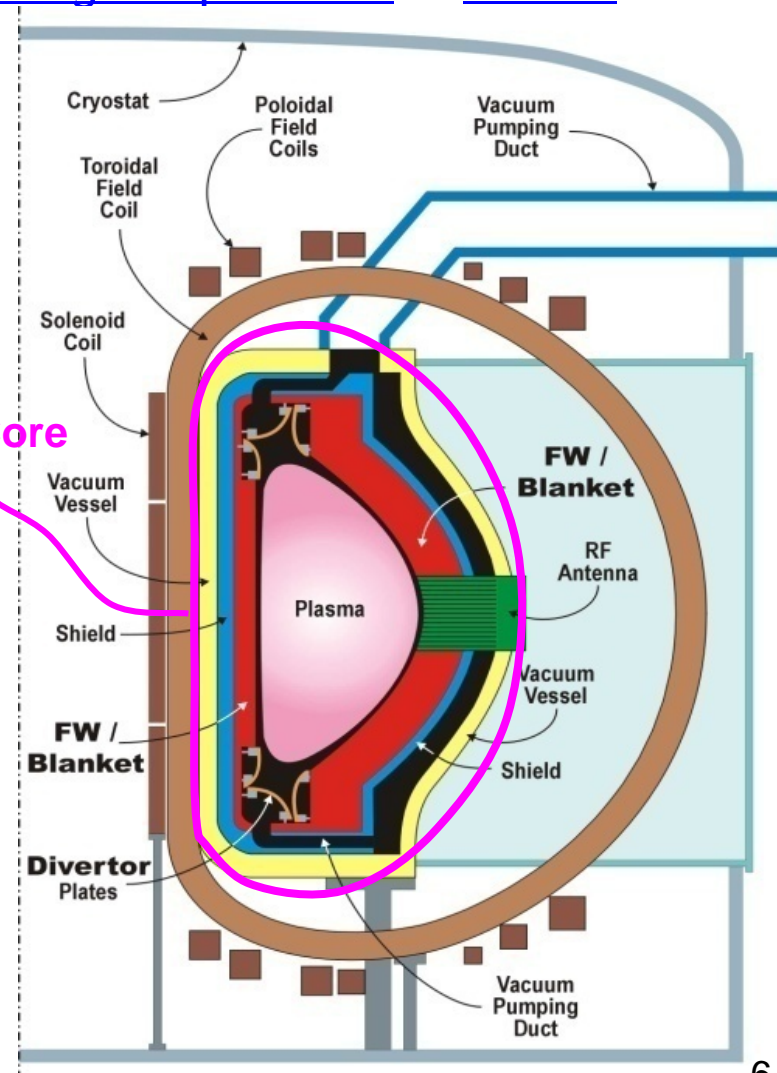
- **Blanket and Integral First Wall**
- **Divertor/PFC**
- **Vacuum Vessel and Shield**

Key Supporting Systems

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

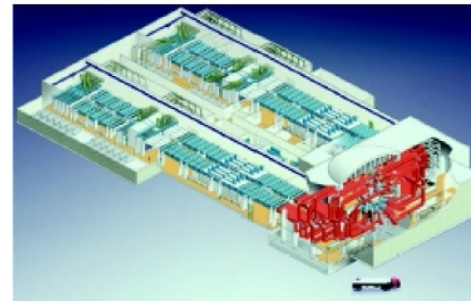


FNST Core

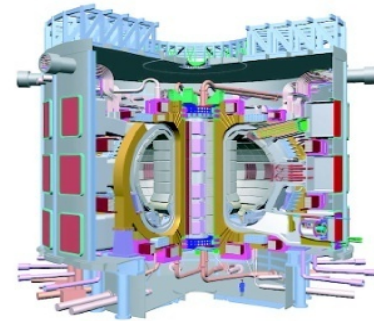


Fusion Research is about to transition from Plasma Physics to Fusion Nuclear Science and Technology

- 1950-2015
 - The Physics of Plasmas
- 2015-2035
 - The Physics of Fusion
 - Fusion Plasmas-heated and sustained
 - $Q = (E_f / E_{\text{input}}) \sim 10$
 - ITER (MFE) and NIF (inertial fusion)
- ITER is a major step forward for fusion research. It will demonstrate:
 1. Reactor-grade plasma
 2. Plasma-support systems (S.C. magnets, fueling, heating)



National Ignition Facility



ITER

**But the most challenging phase of fusion development still lies ahead:
The Development of Fusion Nuclear Science and Technology**

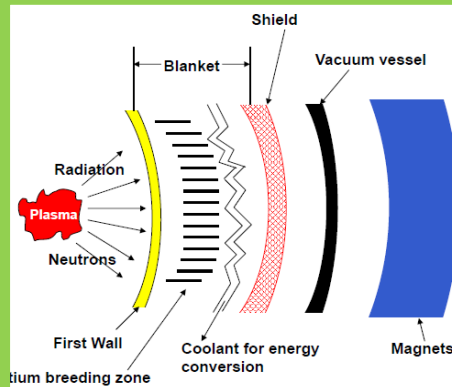
The cost of R&D and the time to DEMO and commercialization of fusion energy will be determined largely by FNST.

Key Technical Challenges beyond ITER

FNST: Fusion Nuclear Components (In-Vessel Components: Blanket/FW, Exhaust/Divertor) and associated technical disciplines (Materials, RAMI, Tritium)

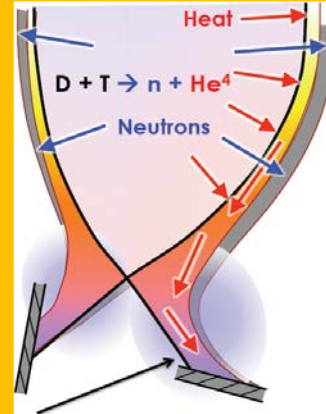
Blanket / FW

- Most important/challenging part of DEMO
- Strict conditions for T self-sufficiency with many physics & technology requirements
- Multiple field environment, multiple functions, many interfaces
- Serious challenges in defining facilities and pathway for R&D



Exhaust / Divertor

- High heat and particle fluxes and technological limits: challenge to define a practical solution
- Both solid and liquid walls have issues
- Huge T inventory in Exhaust for low T burn fraction



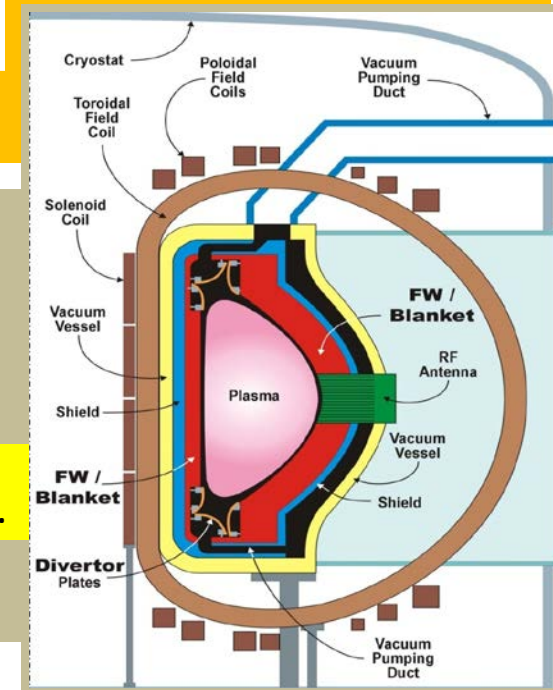
Materials

- Structural, breeding, multiplier, coolant, insulator, T barrier
- Exposed to steep gradients of heating, temperature, stresses
- Many material interfaces e.g. liquid/structure
- Many joints, welds where failures occur, irradiation

Reliability / Availability / Maintainability / Inspect. (RAMI)

- FNCs inside vacuum vessel in complex configuration lead to fault intolerance and complex lengthy remote maintenance
- Estimated MTBF << required MTBF
- Estimated MTTR >> required MTTR
- No practical solutions yet
- How to do RAMI R&D?

Low avail.



- **Serious Challenges that require aggressive FNST R&D and a well thought out technically Credible Pathway to DEMO**

What are the Principal Challenges in the development of FNST/Blanket/FW

- **The Fusion Nuclear Environment**: Multiple field environment (neutrons, heat/particle fluxes, magnetic field, etc.) with high magnitude and steep gradients.
 - *lead to yet undiscovered new phenomena due to multiple interactions and synergistic effects*
 - *can not simulate in laboratory facilities or fission reactors*
- **Nuclear heating** in a large volume with steep gradients
 - *drives temperatures and most FNST phenomena.*
 - *very difficult to simulate in laboratory facilities*
- **Complex configuration** with FW/Blanket/Divertor inside the vacuum vessel.

What are the Principal Challenges in the development of FNST/Blanket/FW (cont'd)

Consequences for the Fusion Development Pathway

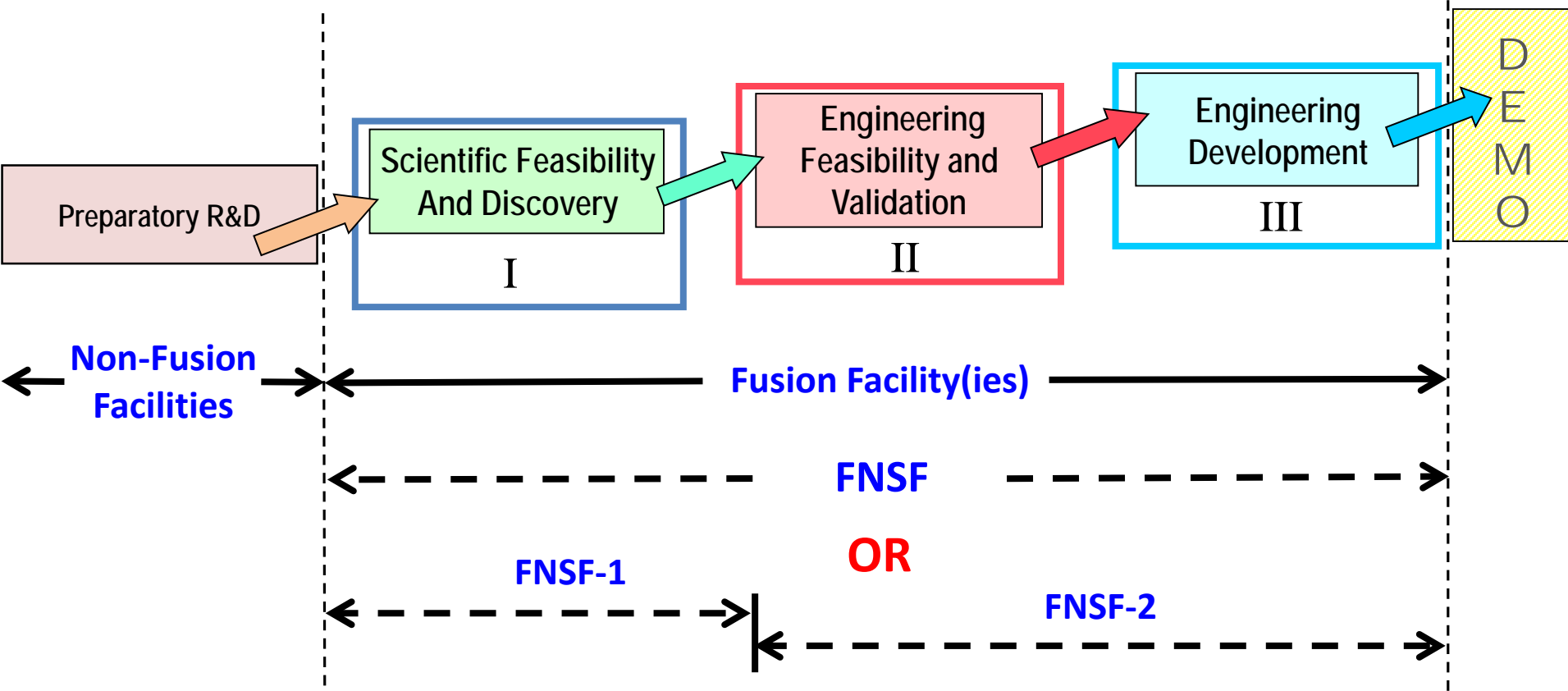
- Non-fusion facilities (laboratory experiments) need to be substantial to simulate multiple fields, multiple effects
 - *We must “invest” in new substantial laboratory-scale facilities.*
- Results from non-fusion facilities will be limited and will not fully resolve key technical issues. A DT-plasma based facility is required to perform “multiple effects” and “integrated” fusion nuclear science experiments. **This facility is called Fusion Nuclear Science Facility (FNSF). FNSF should be constructed parallel to ITER to ensure timely development of fusion.**
- The US and China fusion development plans call for construction of FNSF-type facility prior to construction of DEMO.

In US: called FNSF

In China: called CFETR

- We have not yet built DT facility – so, the first FNSF is a challenge.

Necessary R&D Stages of Testing FNST components in the fusion nuclear environment prior to DEMO



- We need to build one (or more) Fusion Nuclear Science Facility (FNSF) as an experimental DT fusion facility in which we do the necessary experiments (Stages I, II, III) of FNST components development in the fusion nuclear environment prior to DEMO

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, processing and control
- 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

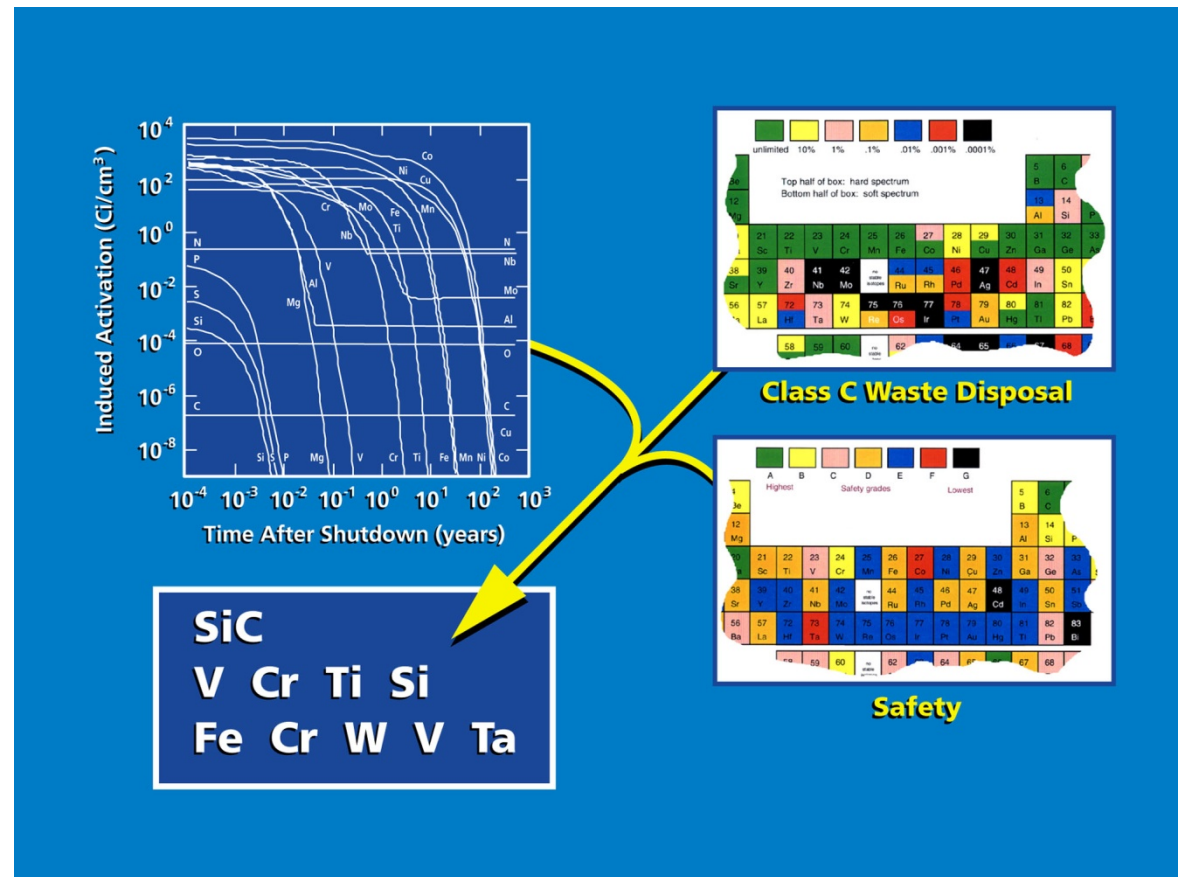
Resolving the challenging FNST issues will require “ingenuity” and “time”. FNST needs to attract and train bright young scientists and engineers in many technical disciplines .

Thank You

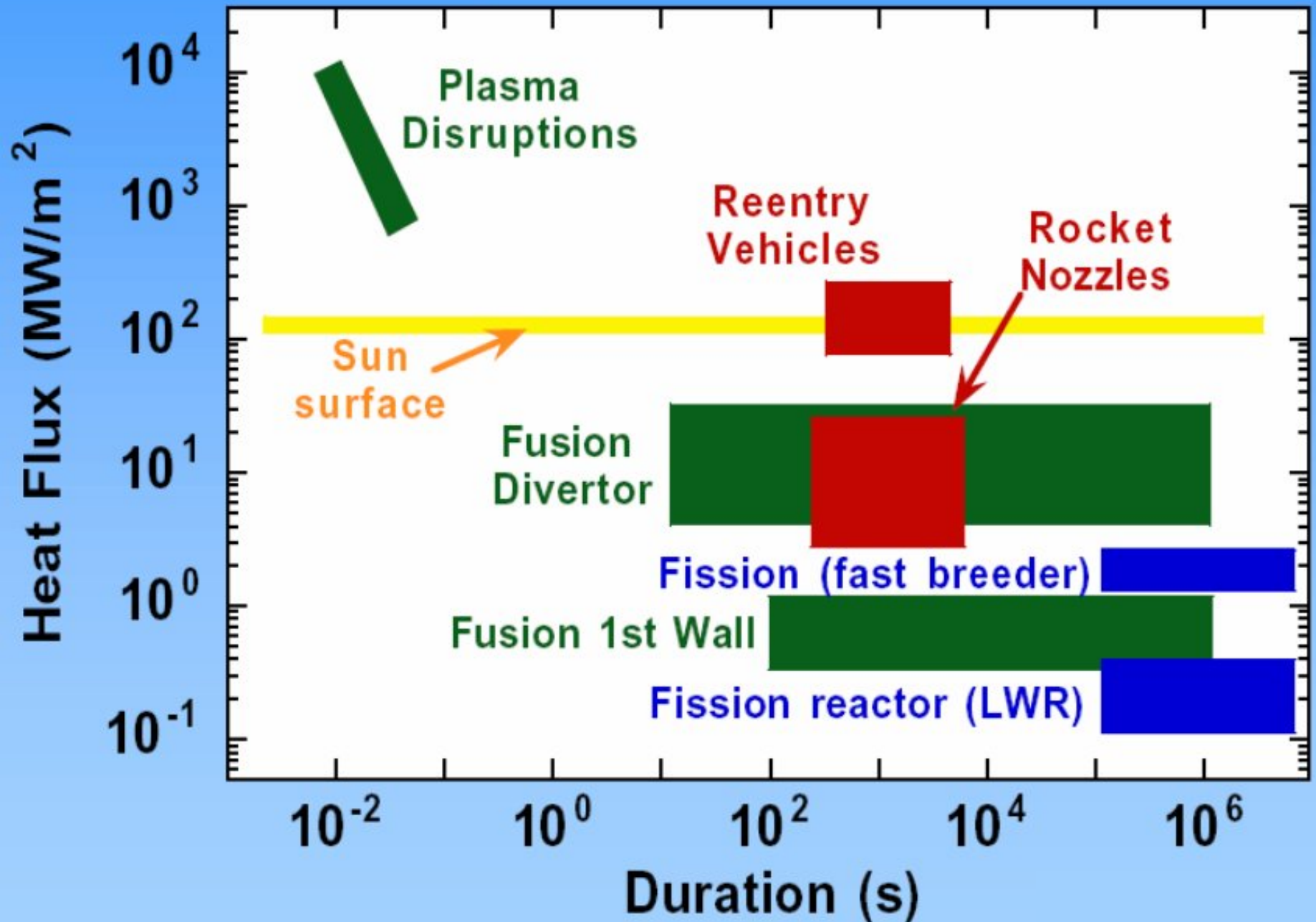
Backup slides

In fusion, the fusion process does not produce radioactive products. Long-term radioactivity and waste disposal issues can be minimized by careful **SELECTION** of **MATERIALS**

- This is in contrast to fission, where long term radioactivity and waste disposal issues are “intrinsic” because the products of fission are radioactive.
- Based on safety, waste disposal and performance considerations, the three leading candidates are:
 - RA FM and NFA steels
 - SiC composites
 - Tungsten alloys (for PFC)



Comparison of Heat Fluxes



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*)

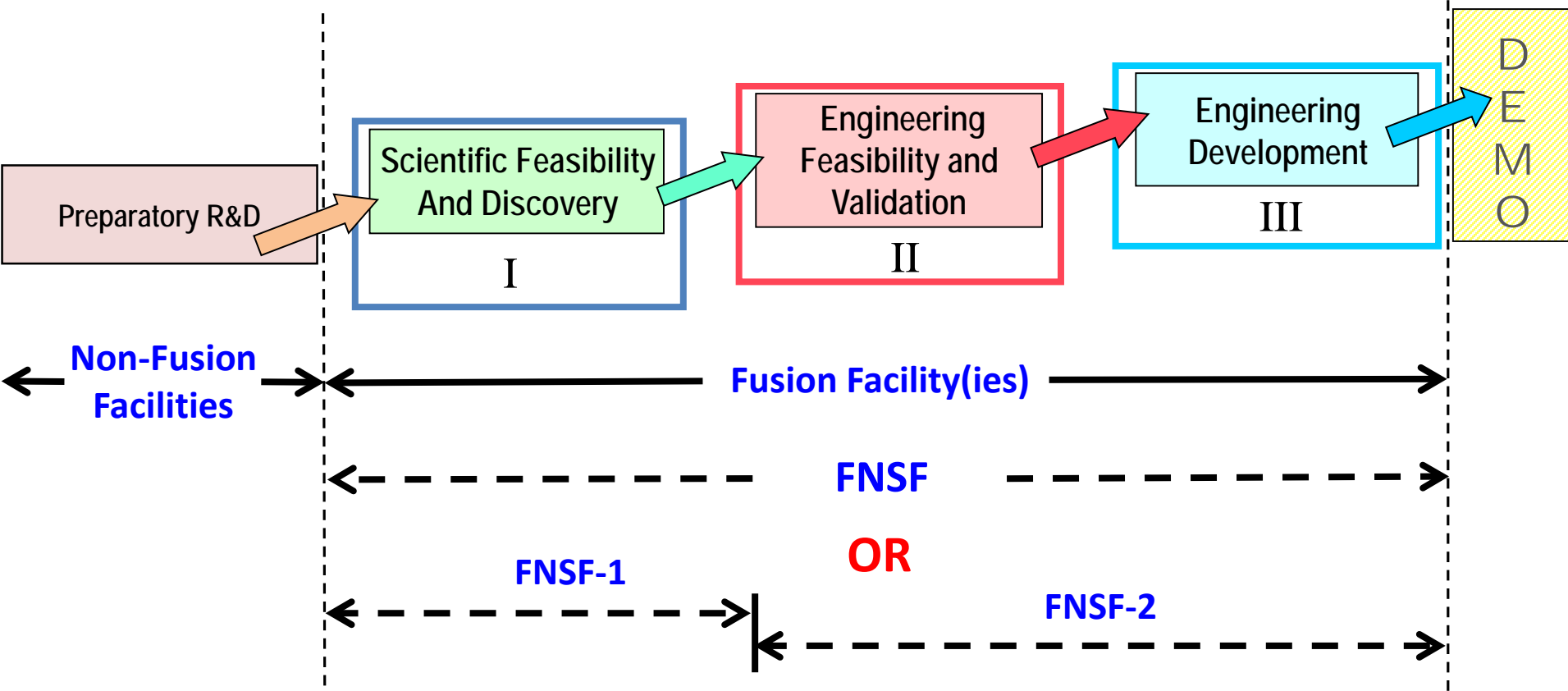
Multiple functions, materials,
and many interfaces in highly
constrained system

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
- Simulating multiple effect/multiple interactions in Experiments & Models is necessary
- Laboratory experiments need to be substantial to simulate multi loads and interactions

Necessary R&D Stages of Testing FNST components in the fusion nuclear environment prior to DEMO



- 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.

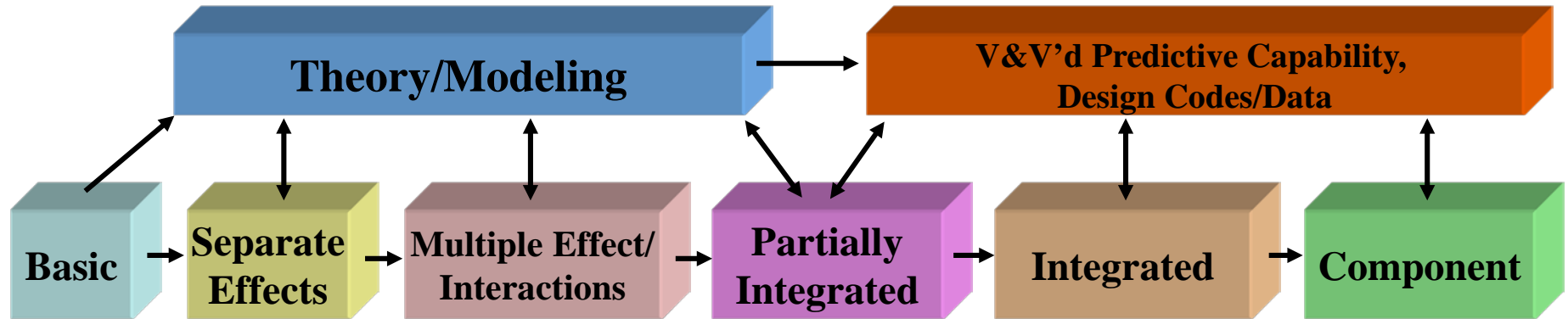
May be multiple FNSF in parallel?! (2 or 3 around the world)

We will not know until we build one!!

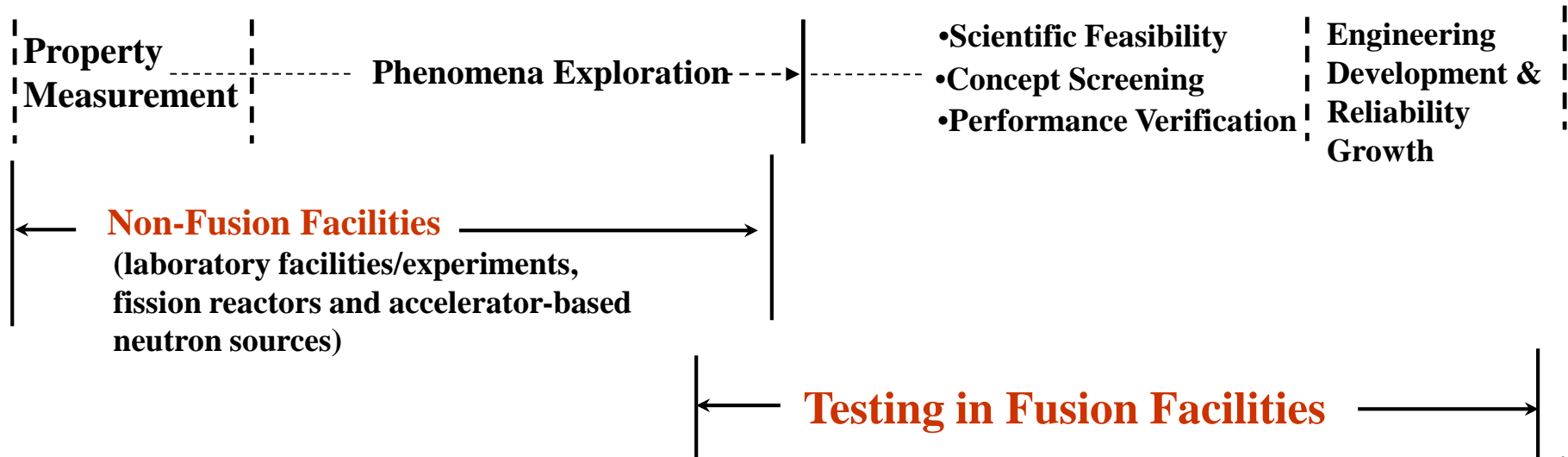
- Only Laws of nature will tell us regardless of how creative we are. We may even find we must change “direction” (e.g. New Confinement Scheme)

Science-Based Framework for Blanket/FW R&D involves modeling & experiments in non-fusion and fusion facilities.

It should be utilized to identify and prioritize R&D Tasks



For each step, detailed performance parameters can be defined to quantify requirements of experiments and modeling and measure progress



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

