Fusion Nuclear Science and Technology (FNST)
Strategic Issues, challenges, and Facilities
on the Pathway to Fusion DEMO

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With input from the FNST Community

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**

The Major Challenges NOW are in FNST

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.

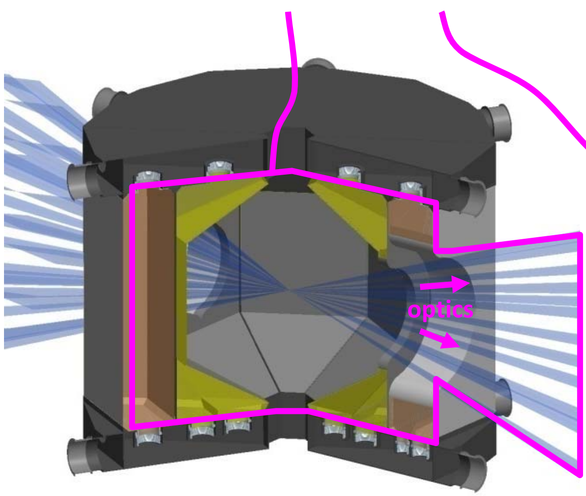
In-vessel Components

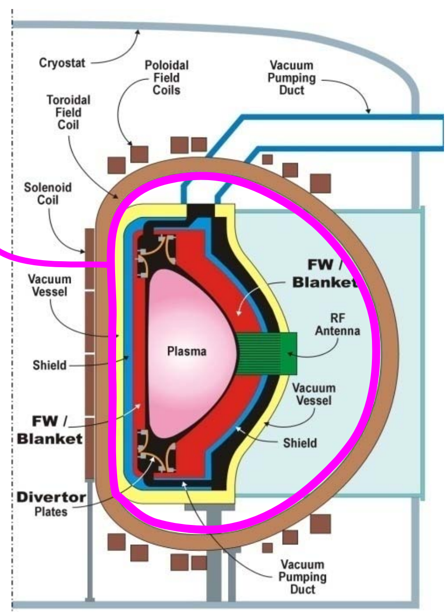
- **Plasma Facing Components**
  divertor, limiter, heating/fueling and final optics, etc.
- **Blanket** and **Integral First Wall**
- **Vacuum Vessel** and **Shield**

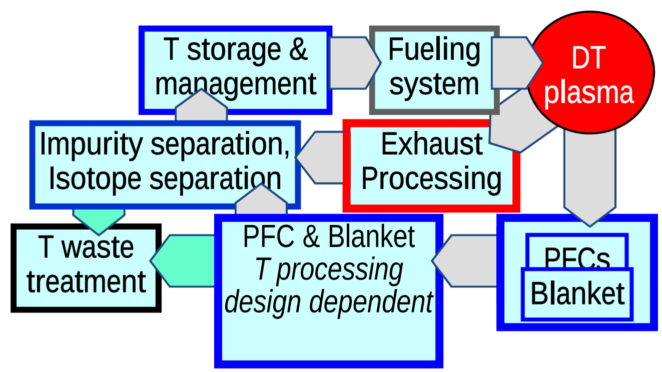
The nuclear environment also affects

- **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.*

- Complex configuration with FW/Blanket/Divertor inside the vacuum vessel.

What are the Principal Challenges in the development of FNST? (cont'd)

Challenging Consequences for the 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. **So, the first phase of FNSF is for "scientific feasibility".**
- Major consequences of FW/Blanket/Divertor inside the vacuum vessel:

  a- many failures (e.g. coolant leak) require immediate shutdown

  Low fault tolerance, short MTBF

  b- repair/replacement take a long time

  Attaining high Device "Availability" is a Challenge!!
- 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

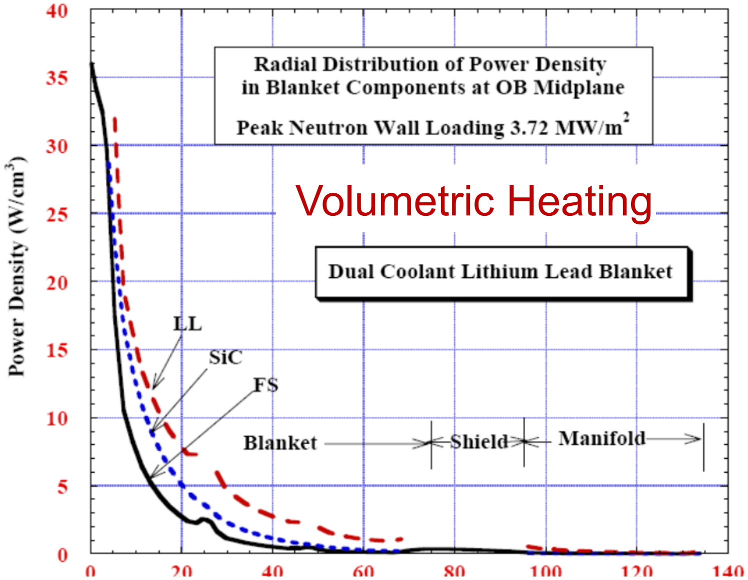
Mechanical Forces
- Normal *(steady, cyclic)* and Off-Normal *(pulsed)*

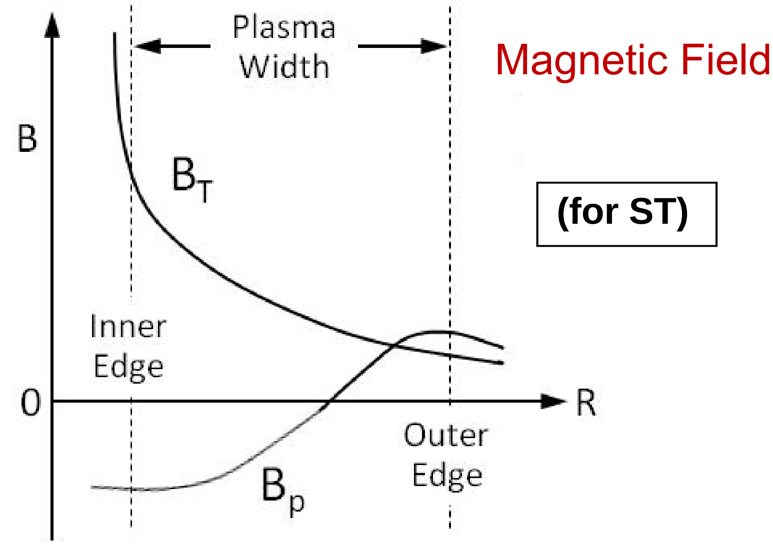
Multiple functions, materials, and many interfaces in highly constrained system

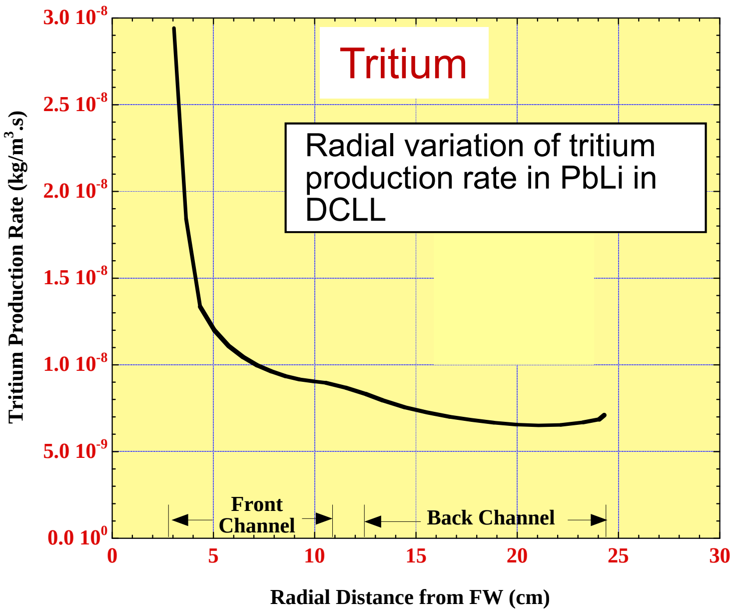
Combined Loads, Multiple Environmental Effects
- Thermal-chemical-mechanical-electrical-magnetic-nuclear interactions and synergistic effects
- Interactions among physical elements of components

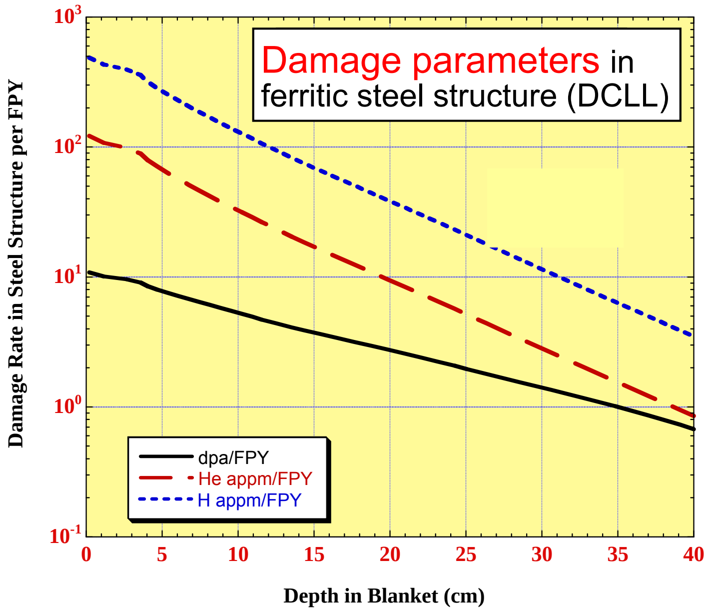
Non-fusion facilities (Laboratory experiments) need to be substantial to simulate multiple effects
Simulating nuclear **bulk heating in a large volume** is the most difficult and is most needed
Most phenomena are temperature (and neutron-spectrum) dependent– it needs DT fusion facility
The full fusion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

Steady State and Transient Heat and EM Loads and DESIGN of Divertor and integrated First Wall/Blanket

– First Wall must be **integrated** with the blanket. **Separate** first wall not viable because of reduction in TBR and difficulties in attachment design, reliability, and maintenance. ITER has separate thick FW (70mm SS/water). Reactor studies have much thinner integrated first wall ~10mm (~25mm with 60% helium)

– Current Situation: Large uncertainties exist in Steady State and Transient Heat and EM Loads on Divertor and First Wall. Reactor studies so far do not incorporate transients into design considerations. Design solutions are yet to be discovered for the higher loadings and transients (disruptions, ELMS, etc)

– Roadmap must emphasize:

* Strong coupling between physics and engineering, determining with better accuracy a narrower range of heat loads and ability to control transients, and determining the engineering limits of capabilities to handle heat and EM loads

* Parallel R&D in this area, e.g Solid Wall (W) AND Liquid Walls/Surfaces (Li, Sn-Li,..)

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)	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]								
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							0.884
Fueling	1							0.998
Tritium System	1							0.995
Vacuum	3							0.998
Conventional equi[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

GRAND Challenge: Huge difference between Required and Expected!!

RAMI for nuclear components, is one of the most challenging issues on the Development Pathway to DEMO - Key consideration for FNSF

- **A primary goal of the next step fusion nuclear facility, FNSF, is to solve the RAMI issue for DEMO** by:

  1- understanding and acquiring data on failure modes, rates and effects

  2- acquiring maintenance experience and data to Quantify MTTR

  3- providing for "reliability growth" testing

- **But achieving modest Availability in the FNSF device is by itself a challenge**
  - **We must think of ways to gain some information on RAMI before FNSF:**

    e.g. What if we build blanket modules and ran them for long time and loaded them by applying FW heat flux and cycling the temperature of the coolants or using some internal heaters, and subjecting it to vibrations, etc.?

    e.g. Can we gain information on MTTR from non-neutron configuration/maintenance facility with vacuum vessel?

- **RAMI has a MAJOR impact on:**
  - Defining the FNST Testing Requirements on FNSF to achieve given goals for DEMO. This directly defines FNSF major parameters e.g. Fluence, number of test modules , test area, availability, and testing strategy in FNSF
  - Design and Testing Strategy on FNSF and R&D required Prior to FNSF

    e.g. Material and Blanket Development and Testing Strategy

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.

Stages of FNST R&D

Classification is in analogy with other technologies. Used extensively in technically-based planning studies, e.g. FINESSE. Used almost always in external high-level review panels.

- **Stage 0 : Exploratory R&D**
  - Understand issues through basic modeling and experiments
- **Stage I : Scientific Feasibility and Discovery**
  - Discover and Understand new phenomena
  - Establish scientific feasibility of basic functions (e.g. tritium breeding/extraction/control) under prompt responses (e.g. temperature, stress, flow distribution) and under the impact of rapid property changes in early life
- **Stage II : Engineering Feasibility and Validation**
  - Establish engineering feasibility: satisfy basic functions & performance, up to 10 to 20% of MTBF and 10 to 20% of lifetime
  - Show Maintainability with MTBF > MTTR
  - Validate models, codes, and data
- **Stage III: Engineering Development and Reliability Growth**
  - Investigate RAMI: Failure modes, effects, and rates and mean time to replace/fix components and reliability growth.
  - Show MTBF >> MTTR
  - Verify design and predict availability of components in DEMO

Fusion Nuclear Science Facility (FNSF)

- The idea of FNSF (also called VNS, CTF) is to build a small size, low fusion power DT plasma-based device in which Fusion Nuclear Science and Technology (FNST) experiments can be performed and tritium self sufficiency can be demonstrated in the relevant fusion environment:

  1- at the smallest possible scale, cost, and risk, and

  2- with practical strategy for solving the tritium consumption and supply issues for FNST development.

In MFE: small-size, low fusion power can be obtained in a low-Q (driven) plasma device, with normal conducting Cu magnets.

The DD Phase of FNSF also has a key role in providing integrated testing without neutrons prior to the DT Phase.

Why FNSF should be low fusion power, small size

- **To reduce risks associated with external T supply and internal breeding shortfall**
- **Reduce cost (note Blanket/FW/ Divertor will fail and get replaced many times)**
- **FNST key requirement 1-2 MW/m^2 on 10-30 m^2 test area**
- **Cost/risk/benefit analysis lead to the conclusion that FNSF fusion power <150 MW**
- **For Tokamak (standard A & ST) this led to recommendation of:**
  - **Low Q plasma (2-3) - and encourage minimum extrapolation in physics**
  - **Normal conducting TF coil (to reduce inboard B/S thickness, also increase maintainability e.g. demountable coils).**

FNST Requirements for Major Parameters for Testing in Fusion Facilities (e.g. FNSF) with Emphasis on Testing Needs to Construct DEMO Blanket

- These requirements have been extensively studied over the past 20 years, and they have been agreed to internationally (FINESSE, ITER Testing Blanket Working Group, IEA-VNS, etc.)
- Many Journal Papers published (>35), e.g. IEA-VNS Study Paper (Fusion Technology, Vol. 29, Jan 1996)

Parameter	Value
Neutron wall load[a] (MW/m^2)	**1 to 2**
Plasma mode of operation	**Steady State[b]**
Minimum COT (periods with 100% availability) (weeks)	**1 to 2**
Neutron fluence at test module ($MW\cdot y/m^2$)	
Stage I[C]: scientific feasibility (less demanding requirements than II & III)	**~0.1- 0.3**
Stage II: engineering feasibility	**1 to 3**
Stage III[d]: engineering development (and reliability growth)	**4 to 6[d]**
Total "cumulative" neutron fluence experience ($MW\cdot y/m^2$)	**>6**
Total test area (m^2)	**>10**
Total test volume (m^3)	**>5**
Magnetic field strength (T)	**>4**

a - Prototypical surface heat flux (exposure of first wall to plasma is critical)
b - For stages II & III. If steady state is unattainable, the alternative is long plasma burn with plasma duty cycle >80%
c - Initial fusion break-in has less demanding requirements than stages II & III
d - Note that the fluence is not an accumulated fluence on "the same test article"; rather it is derived from testing "time" on "successive" test articles dictated by "reliability growth" requirements

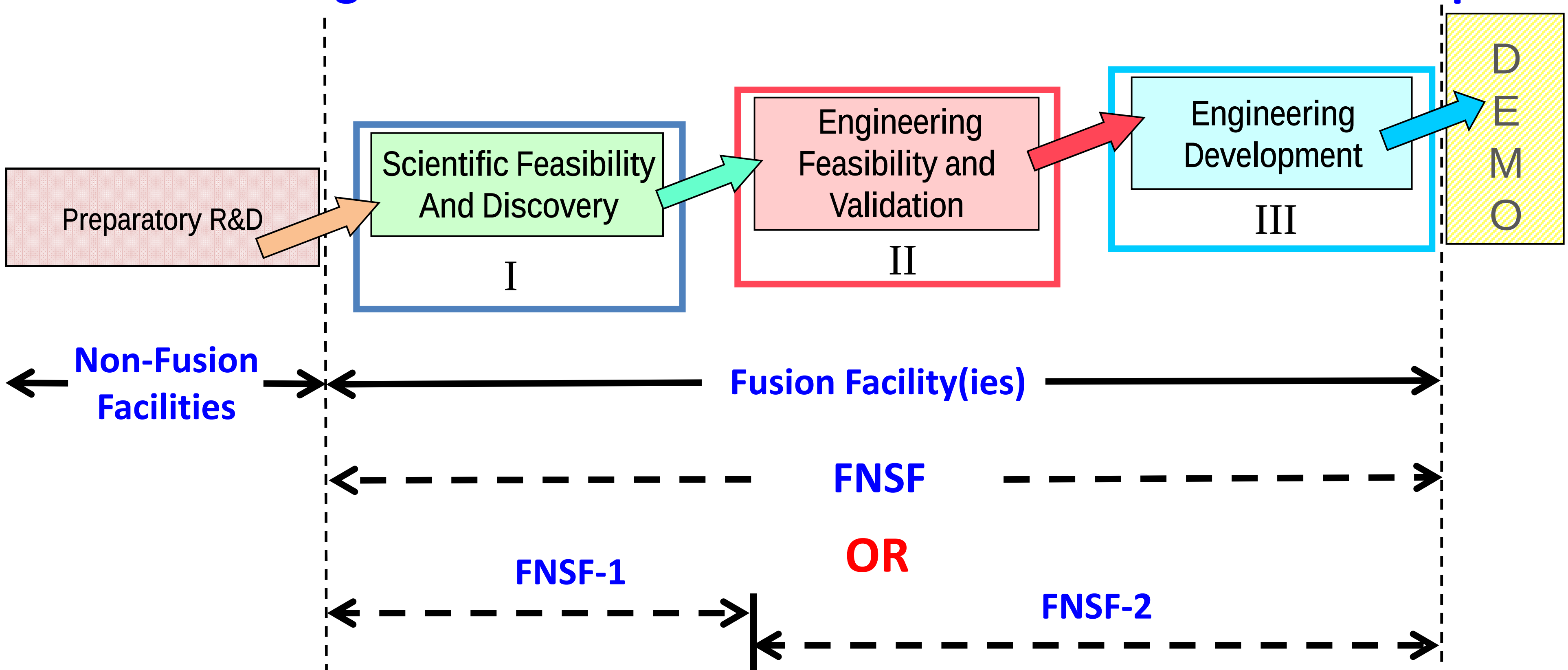
A **rollback** approach, used in FNST studies over the past 25 years, was very useful in defining the experimental testing conditions and types of facilities required for FNST to reach DEMO

A **roll-forward** approach has become necessary to explore FNSF options and the issues associated with the facility itself

Findings from roll-forward approach studies over the past 2 years

- **Rolling forward reveals practical problems we must face today** like
  -- Vac Vessel -- MTBF/MTTR -- standard A, ST, other configuration?
  -- level of advanced physics -- level of flexibility in device configuration -- Licensing!
- **Sensitivity to exact details of the DEMO becomes less important** – Instead: we find out we must confront the practical issue of how to do things for the first time – nuclear components never before built, never before tested in the fusion nuclear environment.
- **Debate about "how ambitious FNSF should be" becomes less important** because WE DO NOT KNOW what we will find in the fusion nuclear environment
  -- How many stages FNSF can do? Maybe one FNSF can do all 3 stages. Or, we may need 2 or 3 consecutive FNSF facilities. May be multiple FNSFs in parallel?!
  -- What Critical flaws may be found in initial operation of FNSF? Maybe we cannot get past stage 1? e.g. MTBF too short, MTTR too long, cannot contain tritium?
  -- Maybe we will get an early answer to "is tokamak a feasible option for power plant?"

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)

Conclusions on Tritium Self Sufficiency

We have identified a **"phase space" of physics and technology conditions in which tritium self sufficiency can be attained**. Our R & D in plasma physics, blanket technology, and fuel cycle must aim at ensuring tritium self sufficiency. In particular, our R & D Goals should:

Minimize Tritium Inventories and Reduce Required TBR

- T burnup fraction x fueling efficiency > 5% (not less than 2%)
- Tritium processing time (in plasma exhaust/fueling cycle) < 6 hours
- Minimize Tritium Inventories in Blanket, PFC, other components
- Minimize tritium processing time in breeder and coolants cycles

Ensure Achievable TBR is not significantly below the currently calculated value of 1.15

- Avoid Design choices that necessitate use of large neutron absorbing materials in blanket and divertor regions (challenges: thickness of first wall and divertors and blankets structure to handle plasma off-normal conditions such as disruptions, and ELMS; passive coils inside the blanket region for plasma stabilization and attaining advanced plasma physics mode)
- Aim the R & D for subsystems that involve penetrations such as impurity control/exhaust and plasma auxiliary heating to focus on design options that result in minimum impact on TBR

Where, How, and When Can We Accurately Predict , Verify, and Validate Achievable TBR?

Validation of achievable TBR requires:

1. Detailed, accurate, and validated definition of a practical design of the in-vessel components (PFC, FW/Blanket, penetrations, etc.)
   - Possible only after experiments in DT-plasma-based facility
2. Prototypical accurate integral neutronics experiments:
   - **This can be achieved only in DT-plasma-based facility**
   - Current integral experiments are limited to point neutron source with $S < 5 \times 10^{12}$ n/s. Does not allow a) accurate simulation of angular neutron flux, b) complex geometry with subsystem details and heterogeneity. (Efforts on such experiments showed that calculations differ from experiments by ~10%)
   - *Analysis has shown that at least a "full sector" testing in fusion facility is required for accurate measurement of achievable TBR. (Uncertainties in extrapolation in the poloidal direction from module is larger than the required accuracy.)*

- **ITER TBM will provide very important information on achievable TBR (initial verification of codes, models, and data).**
- **FNSF is essential in providing more definitive validation of codes, models, and data and the predictability of achievable TBR. (Total tritium production will be measured directly in addition to local measurements). FNSF is essential to validating the design of blanket, divertor, and other in-vessel components.**

DEMO Availability and First Wall Lifetime and Fluence

- US and other countries studies set DEMO availability goal as 50%.
- The IEA-HVPNS study concluded that after 6MW • y/m^2 testing in FNSF the first phase of DEMO will only achieve 30% availability
- **Lifetime of the first wall is not as critical as random failures because first wall replacement can be "scheduled" to coincide with plant annual "scheduled outage".**
  - ***FOR DEMO: First wall "Needed" lifetime: 2-4 years***
    ("Needed" to ensure "scheduled" replacement does not significantly affect availability)
- For Demo, fusion power will be smaller than for power plants to save capital cost. Hence, the wall load in DEMO will be smaller.
  - ***FOR DEMO Fusion Power ~1500 – 2000 MW: Neutron wall load ~2-2.5 MW/m^2***

First wall "Needed" lifetime dose =

(2-2.5 MW/m^2) (available 0.3-0.5) (2-4 yr)

= 1.2 – 5 MW • y/m^2

= 12 – 50 dpa

Base Breeding Blanket and Testing Strategy in FNSF

- **A Breeding Blanket should be installed as the "Base" Blanket on FNSF from the beginning**
  - Needed to breed tritium.
  - Switching from non-breeding to breeding blanket involves complexity and long downtime. <u>There is no non-breeding blanket for which there is more confidence than a breeding blanket</u>.
  - Using base breeding blanket will provide the large area essential to "reliability growth". This makes full utilization of the "expensive" neutrons.

- **The primary concepts for DEMO should be used for both "testing ports" and "Base" Breeding Blanket in FNSF**

- **Both "port-based" and "base" blanket will have "testing missions"**
  - Base blanket operating in a more conservative mode (run initially at reduced parameters/performance)
  - Port-based blankets are more highly instrumented, specialized for experimental missions, and are operated near their high performance levels; and more readily replaceable

Reduced activation Ferritic/Martensitic Steel (FS) is the reference structural material option for DEMO

- **FS is used for TBMs in ITER and for mockup tests prior to ITER**
- **FS should be the structural materials for both base and testing breeding blankets on FNSF.**
- **FS irradiation data base from fission reactors extends to ~80 dpa, but it generally lacks He (only limited simulation of He in some experiments).**
  - ✓ **There is confidence in He data in fusion typical neutron energy spectrum up to at least 100 appm He (~10 dpa).**
    - – **Note: Many material experts state confidence that FS will work fine up to at least 300 appm He at irradiation temperature > 350°C.**

FNSF Strategy/Design for Breeding Blankets, Structural Materials, PFC & Vacuum Vessel

- DD phase role : All in-vessel components, e.g. divertor, FW/Blanket performance verification without neutrons before proceeding to the DT Phase

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 for in-vessel components
- 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, higher performance blanket experiments (also special test module for testing of materials specimens)**

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

Key Summary Points (1 of 3)

- The fusion nuclear environment is complex and unique with multiple fields and strong gradients. The nuclear components exposed to this environment have multiple functions, materials, and interfaces.
  - New Phenomena, important multiple and synergetic effects

- Simulating **nuclear bulk heating in a large volume with gradients** is **essential** to observe key phenomena.
  - But this simulation can be achieved only in DT-plasma-based facility.
  - Therefore, the goal of the first phase of FNSF operation is to provide the environment for fusion nuclear science experiments – Discovery and Exploration of new phenomena.

- There are **3 stages** for FNST development in DT fusion facility(ies):
  1. Scientific Feasibility and Discovery
  2. Engineering Feasibility and Validation
  3. Engineering Development and Reliability Growth

  These **3** stages may be fulfilled in one FNSF OR may require one or more parallel and consecutive FNSFs. **We will not know until we build one**.

Key Summary Points (2 of 3)

- There are serious Reliability/Availability/Maintainability (RAMI) issues. For the nuclear components, the difference between "expected" and "required" is huge for both MTBF, MTTR.
  - RAMI must be explicitly addressed in the strategy for FNSF design and operation.
  - RAMI can be a Deciding Factor in evaluating different options for FNSF mission and designs. Note : first phase of first FNSF will experience "infant mortality".
  - "Reliability growth", increasing MTBF, and decreasing MTTR must be part of the FNSF mission.
  - Fusion programs must find a way to engage experts in RAMI.
  - RAMI can be the "Achilles Heel" for fusion.

- Most of the external tritium supply will be exhausted by ITER.
  - FNSF and other DT facilities must breed their own tritium.

- We identified a "phase space" of physics and technology conditions in which tritium self sufficiency can be attained. This "phase space" provides clear goals for design and performance of plasma, blanket, PFC, tritium processing, and other subsystems.

Validation of achievable and required TBR, and ultimately T self-sufficiency can be realized only from experiments and operation of DT fusion facility(ies).

Key Summary Points (3 of 3)

- Material development must be "component-based", **not** an "abstract stand-alone" objective. Many performance parameters of FW/Blanket/Divertor determine the objectives and strategy of material development. If we must refer to "dpa" for DEMO, the goal is ≤ 50 dpa
- At least in the first phase of FNSF, all components inside the vacuum vessel are "experimental".

- **Blanket Development Strategy in FNSF**
  - A "Base" breeding blanket from the beginning operating initially at reduced parameters/performance
  - "Port-based" blankets – highly instrumented, operated near their high performance levels, more readily replaceable

  Both have "testing missions".

- **Material Development Strategy in FNSF**
  - Initial first wall / blanket / divertor for 10 dpa, 100 appm He in FS
  - Extrapolate a factor of 2 to 20 dpa, 200 appm He, etc. (Bootstrap approach)
  - Conclusive results from FNSF with "real" environment, "real" components

Establish the base of the pyramid Before proceeding to the top

We need substantial NEW Laboratory-scale facilities NOW

FNST Pyramid

Testing in the Integrated Fusion Environment (100-1000'sM)

Functional tests: ITER TBM Experiments and PIE

Engineering Feasibility Testing in a Fusion Nuclear Science Facility

Multi-Effect Test Facilities (each ~5-20M class)

Blanket Mockup Thermomechanical/ Thermofluid Testing Facility

Tritium Fuel Cycle Development Facility

Bred Tritium Extraction Testing Facility

Fission Irradiation Effects Testing on Blanket Mockups and Unit Cells

Fundamental Research Thrusts (each ~1-3M per year)

PbLi Based Blanket Flow, Heat Transfer, and Transport Processes

Plasma Exhaust and Blanket Effluent Tritium Processing

Helium Cooling and Reliability of High Heat Flux Surfaces /Blanket/FW

Ceramic Breeder Thermomechanics and Tritium Release

Structural and Functional Materials Fabrication

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.
3. **Utilize international collaboration (only when it is "effective").**

Thank You!

Backup Slides

The Issue of External Tritium Supply is Serious and Has Major Implications on FNST (and Fusion) Development Pathway

Tritium Consumption in Fusion is HUGE! Unprecedented!

55.6 kg per 1000 MW fusion power per year

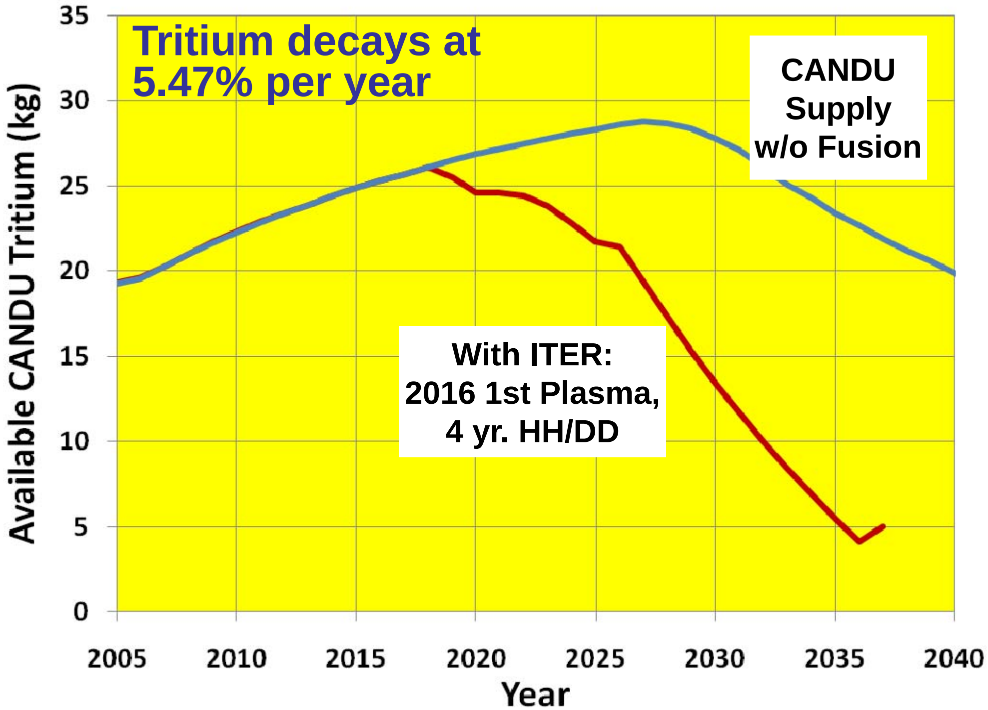
Production in fission is much smaller & Cost is very high:

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 DT fusion devices other than ITER can be operated without a breeding blanket**
- **Development of breeding blanket technology must be done in small fusion power devices.**

Two Issues In Building A DEMO:

1 – Need Initial (startup) inventory of >10 Kg per DEMO

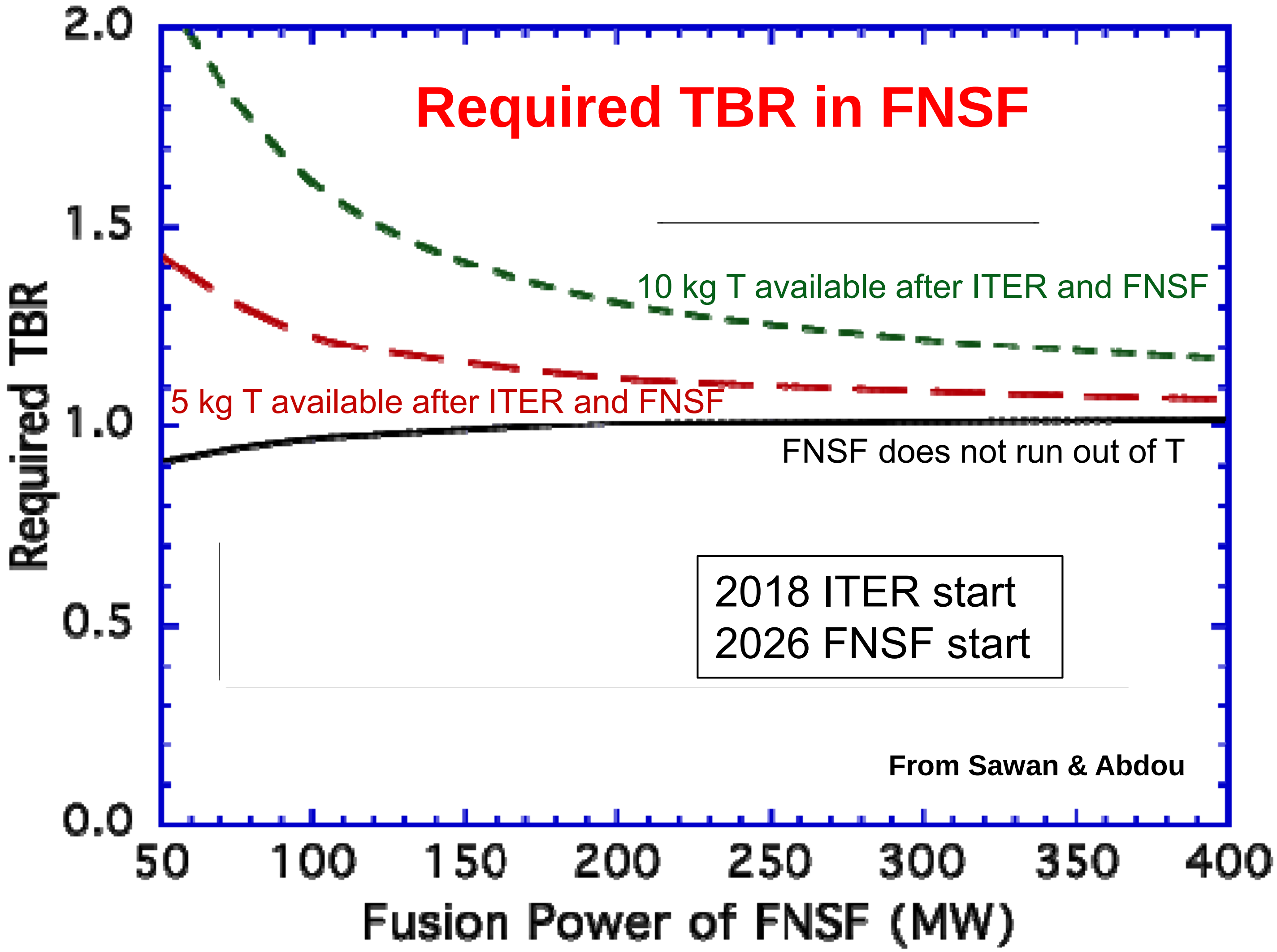
(How many DEMOS will the world build? And where will startup tritium come from?)

2 – Need Verified Breeding Blanket Technology to install on DEMO

FNSF has to breed tritium to:

a- supply most or all of its consumption

b- accumulate excess tritium sufficient to provide the tritium inventory required for startup of DEMO



Situation we are running into with breeding blankets: What we want to test (the breeding blanket) is by itself An ENABLING Technology

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Reliability/Availability/Maintainability/Inspectability (RAMI)

- RAMI is a complex topic for which the fusion field does not have an R&D program or dedicated experts.
- A number of fusion engineers tried over the past 3 decades to study it and derive important guidelines for FNST and Fusion development

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.

Inside the Vacuum Vessel "Reactor Core":

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

RAMI is particularly challenging for FNST

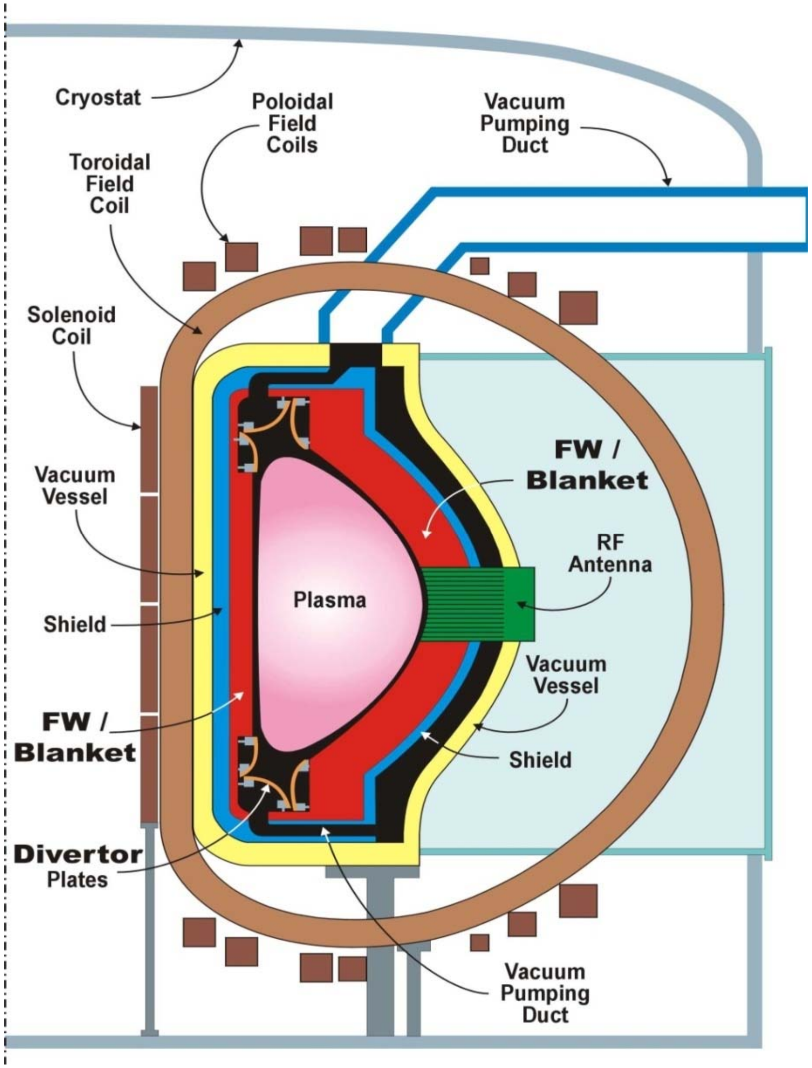
The location of the Blanket / Divertor inside the vacuum vessel is necessary but has major consequences:

a- many failures (e.g. coolant leak) require immediate shutdown

Low fault tolerance, short MTBF

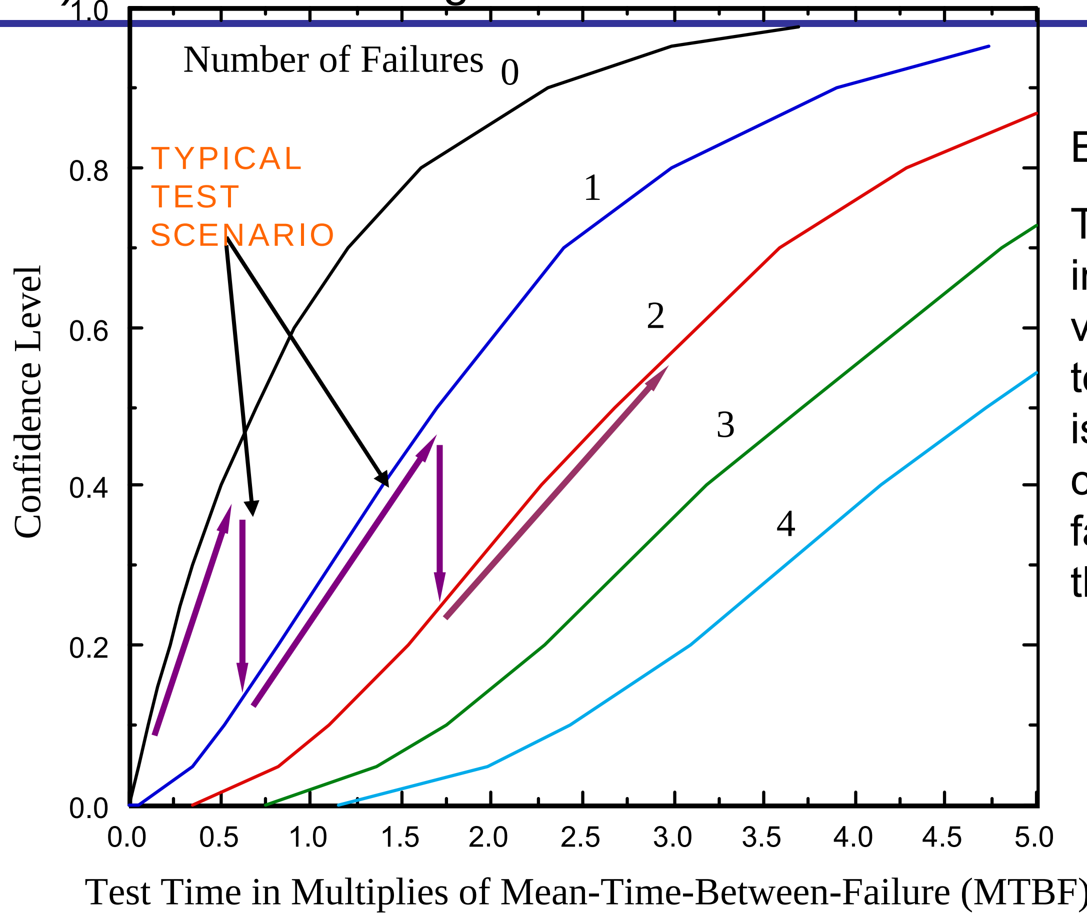
b- repair/replacement take a long time

Attaining high Device "Availability" is a Challenge!!



"Reliability Growth"

Upper statistical confidence level as a function of test time in multiples of MTBF for time terminated reliability tests (Poisson distribution). Results are given for different numbers of failures.



Example,

To get 80% confidence in achieving a particular value for MTBF, the total test time needed is about 3 MTBF (for case with only one failure occurring during the test).

Reference: **M. Abdou et. al., "FINESSE: A Study of the Issues, Experiments and Facilities for Fusion Nuclear Technology Research & Development, Chapter 15 (Figure 15.2-2.) Reliability Development Testing Impact on Fusion Reactor Availability", Interim Report, Vol. IV, PPG-821, UCLA,1984. It originated from A. Coppola, "Bayesian Reliability Tests are Practical", RADC-TR-81-106, July 1981.**

FNSF (CTF/VNS) MISSION (as developed in FNST Studies)

The mission of FNSF is to test, develop, and qualify Fusion Nuclear Components (fusion power and fuel cycle technologies) in prototypical fusion power conditions.

The FNSF facility will provide the necessary integrated testing environment of high neutron and surface fluxes, steady state plasma (or long pulse with short dwell time), electromagnetic fields, large test area and volume, and high “cumulative" neutron fluence.

The experimental program on FNSF and the FNSF device operation will demonstrate in consecutive phases the scientific feasibility, engineering feasibility, provide data on reliability / maintainability / availability, and enable a “reliability growth” development program sufficient to design, construct, and operate blankets, plasma facing and other FNST components for DEMO.

These phases may be achievable in one FNSF, or may require a number of parallel and consecutive FNSFs – this can be determined only after obtaining fusion nuclear experiments results from the first FNSF – i.e. after we build a next step FNSF

FNSF will solve the serious tritium supply problem for fusion development by a- not consuming large amounts of tritium, b- breeding much of its own tritium, c- accumulating excess tritium (in later years) sufficient to provide the tritium inventory required for startup of DEMO, and d- developing the blanket technology necessary to ensure DEMO tritium self sufficiency

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

- our base to design, understand and interpret integrated testing in fusion facilities

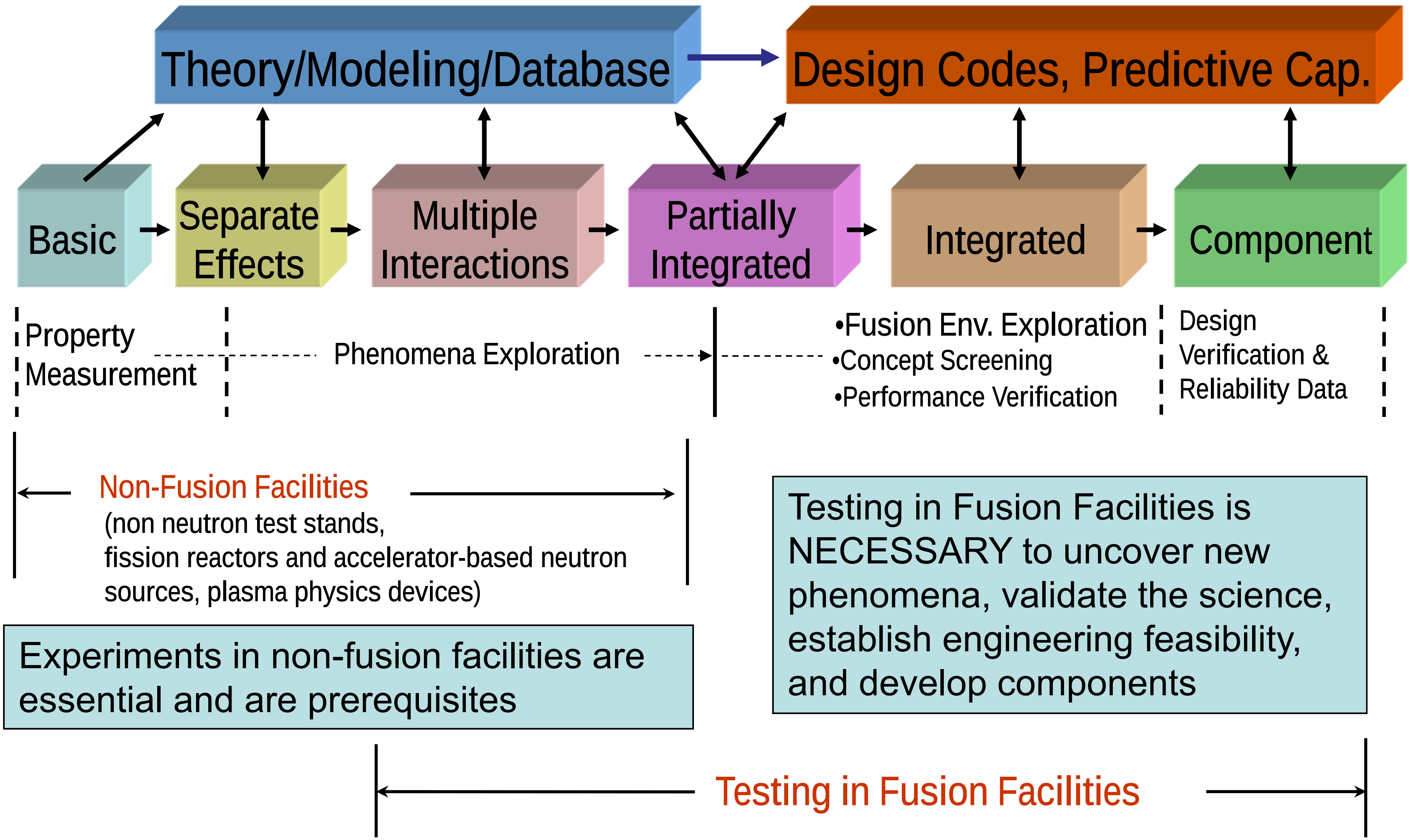
	Neutron Effects*	Nuclear Heating	Thermal-Mechanical-Magnetic-Electrical-Chemical-Interactions	Integrated Synergistic
Non-Neutron Test Stands [PFC/HHF, PSI, LMMHD, Safety]	**no**	**no**	**partial**	**no**
Fission Reactors	**partial**	**partial**	**no**	**no**
Accelerator-Based Neutron Sources	**partial**	**no**	**no**	**no**

*** radiation damage, tritium and helium production, transmutations**

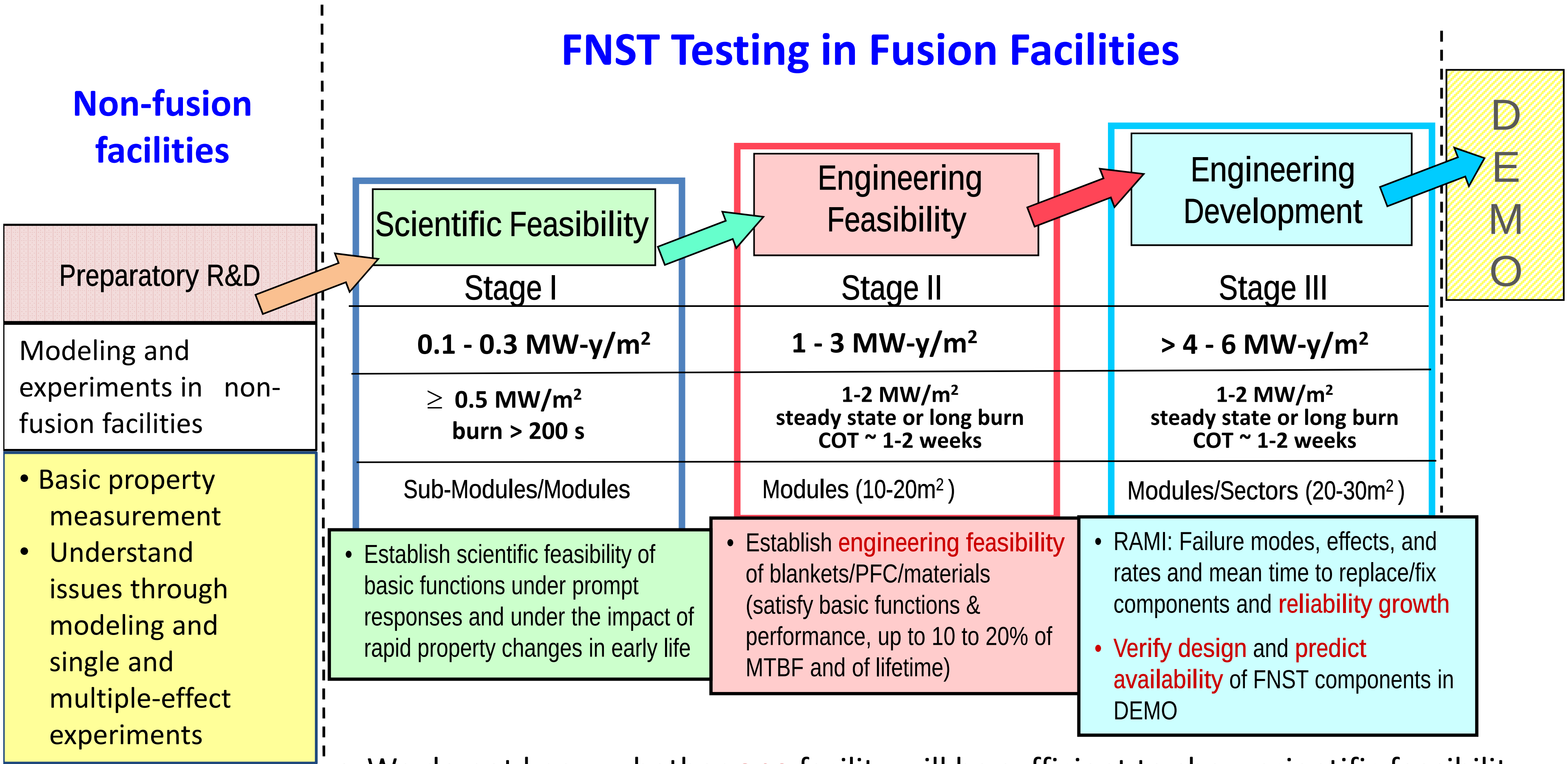
We urgently need multiple lab-scale test stands in thermofluids, thermo-mechanics, tritium, chemistry, etc.

We need extensive modeling activities strongly coordinated with experiments

Science-Based Framework for FNST R&D involves modeling and experiments in non-fusion and fusion facilities



FNST Studies Science-Based FNST Pathway to DEMO



None of the top level technical issues can be resolved before testing in the fusion environment

- 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.

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)