

**Multiple Effects/ Multiple Interactions and the Need for
Fusion Nuclear Science Facility prior to construction of DEMO
Issues, Role, Design Features, and R&D requirements**

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Multiple Effects/ Multiple Interactions and the Need for Fusion Nuclear Science Facility prior to construction of DEMO

Outline

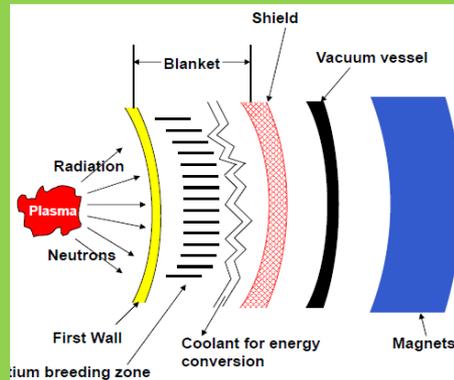
- Summary of Key FNST Technical Challenges beyond ITER
- Science-Based Framework for FNST Development
- **Multiple Effects/Multiple Interactions**
 - Example of Importance
 - Challenges in planning R&D laboratory facilities and experiments
 - Special Challenge: Simulation of Nuclear Heating
- **Three Key facts critical to deciding what the next DT Fusion Facility (Other than ITER) should be**
- Stages of FNST Testing in Fusion Facilities and Need for FNSF
- Comments on strategies for Pathway to DEMO in Major World Programs
- **Key recommended roles/features/parameters for FNSF and why**
 - Fusion power, device size
 - Blanket and Material Testing Strategy
 - Degree of Prototypicality between FNSF and DEMO
- Concluding Remarks

Key Technical Challenges beyond ITER

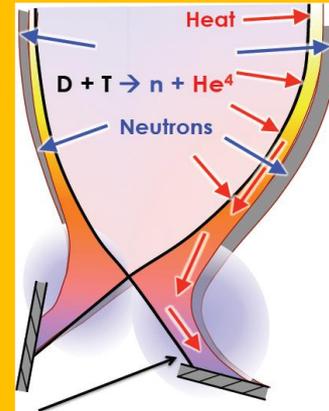
FNST: Fusion Nuclear Components (In-Vessel Components: Blanket/FW, Exhaust/Divertor) and associated technical disciplines (Materials, RAMI, Tritium)

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

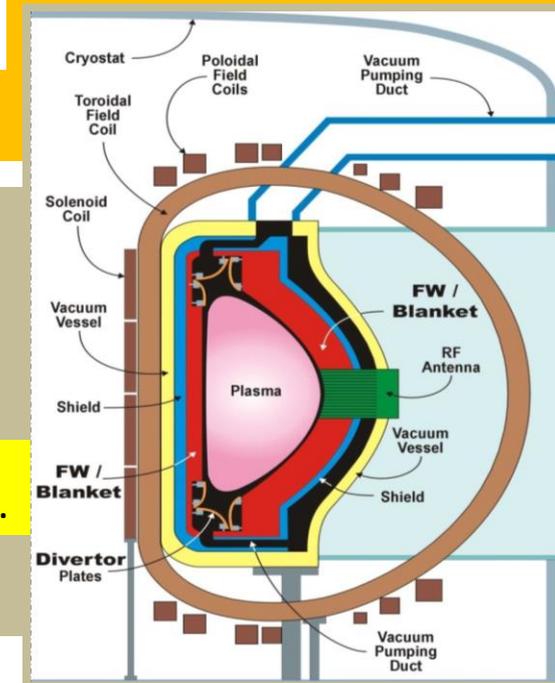
Materials

- 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 \ll required MTBF
- Estimated MTTR \gg required MTTR
- No practical solutions yet
- How to do RAMI R&D?

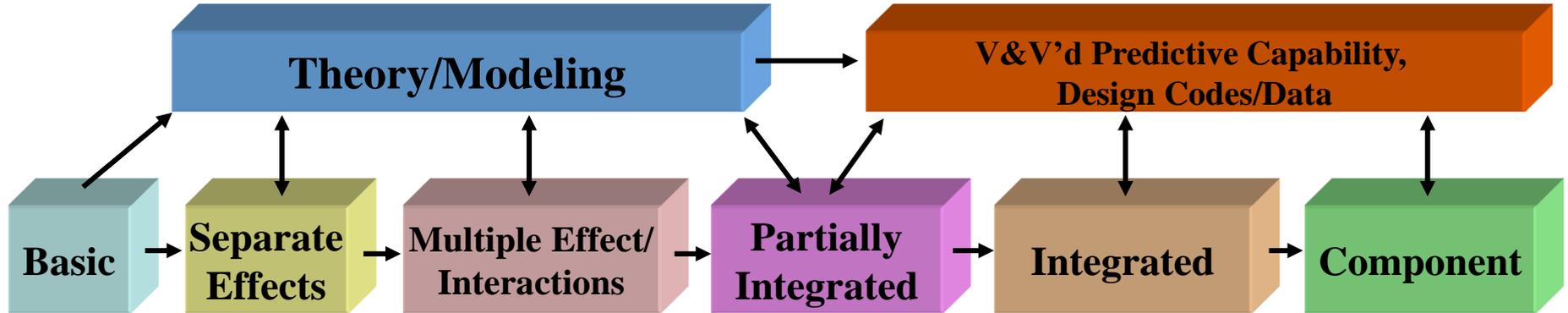
Low avail.



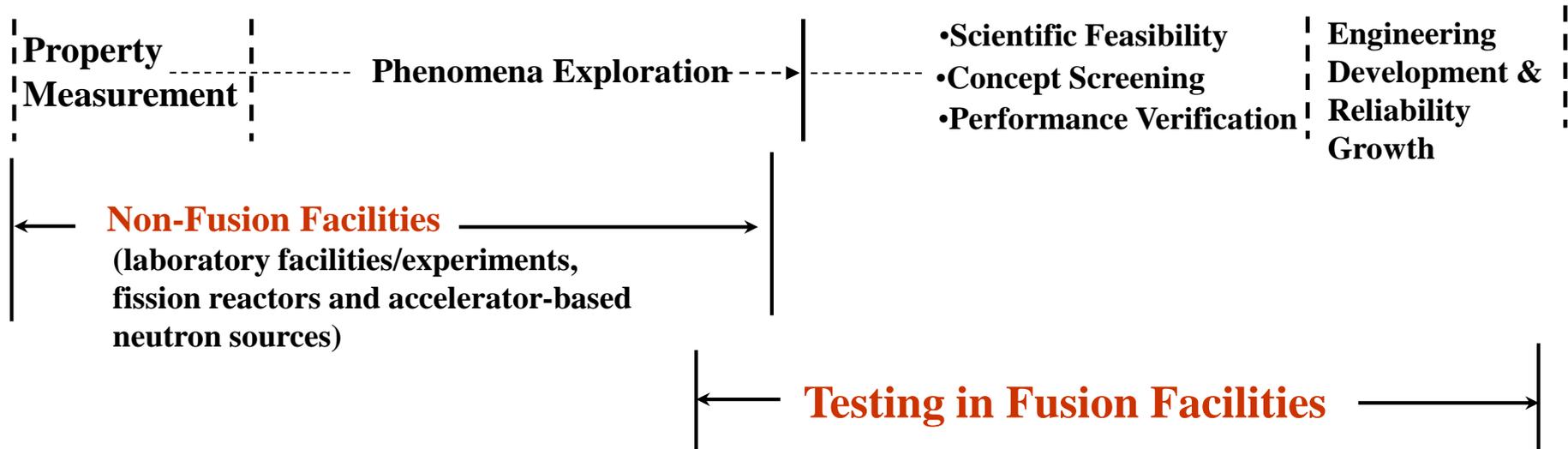
- **Serious Challenges that require aggressive FNST R&D and a well thought out technically Credible Pathway to DEMO**

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

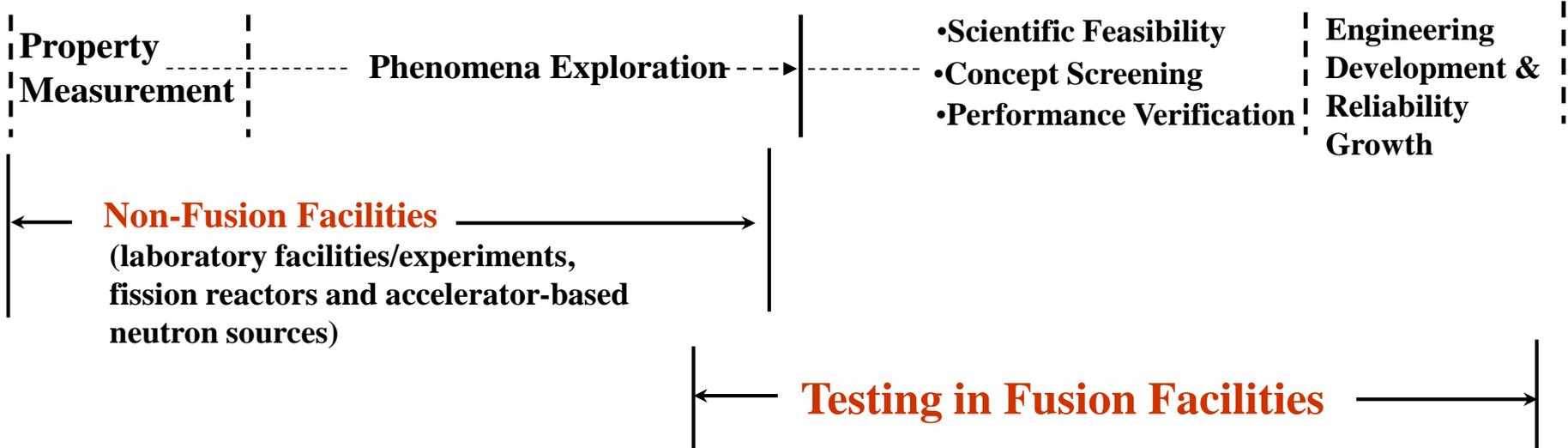
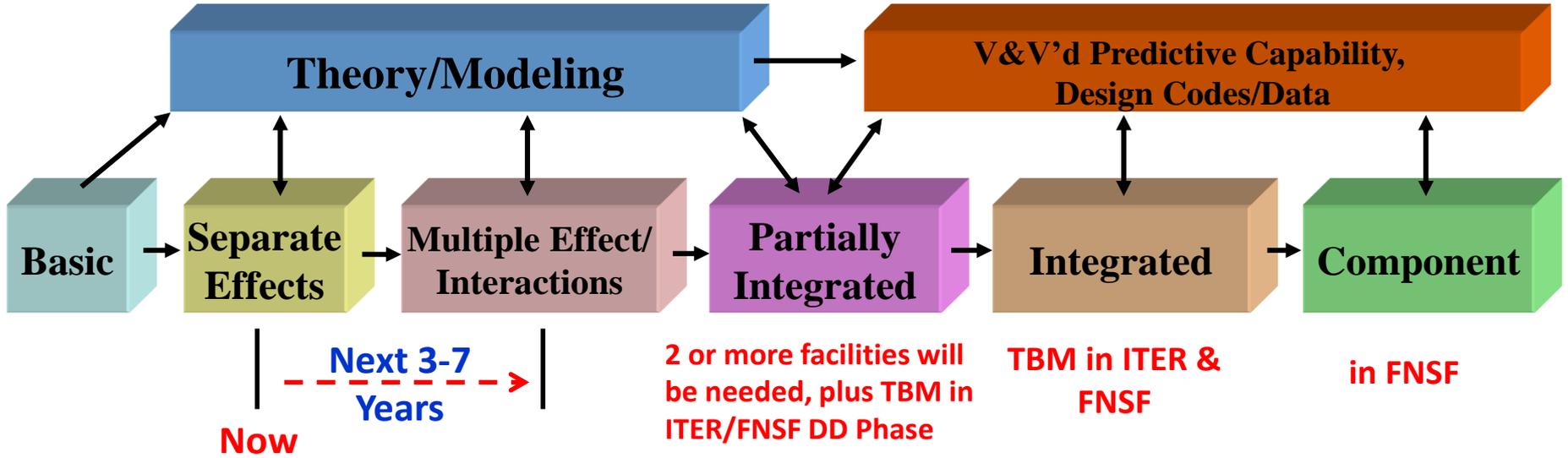
It should be utilized to identify and prioritize R&D Tasks



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



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

- **Complex & Unique 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 caused by multiple effects/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)

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. **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.

Recent Research Results (at UCLA) have shown clearly that the blanket behavior in the fusion nuclear environment cannot be predicted by synthesizing results of separate effects

These results have very serious consequences for the fusion development pathway and the R&D we must do

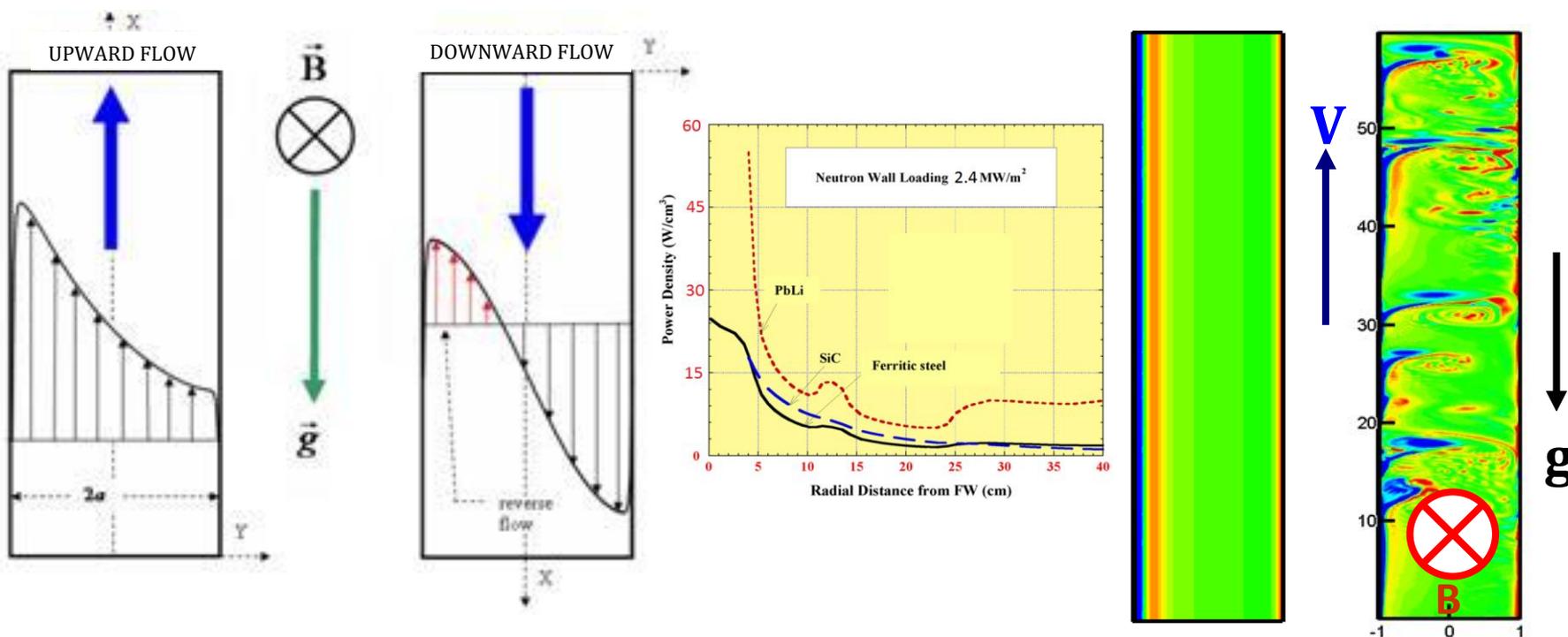
**I will illustrate this by an Example: LM MHD Thermofluids
*(there are other examples for Solid Breeder Blankets and for Divertor/PFC)***

Example: Spatial gradients in nuclear heating & temperature in LM blanket combined with \vec{g} and \vec{B} lead to New Phenomena that fundamentally alter our understanding of the MHD Thermofluid behavior of the blanket in the fusion nuclear environment

Buoyant MHD interactions result in “Mixed Convection” flow regime

Base flow strongly altered leading to velocity gradients, stagnant zones and even “**flow reversal**”

Vorticity Field shows new instabilities that affect transport phenomena (Heat, T, Corrosion)



This result is from modeling at limited parameters in idealized geometry.

- Blankets designed with current knowledge of phenomena and data will not work
- Laboratory Experiments must strive to simulate multiple effects – not separate effects
- FNSF is needed to learn the true behavior of blanket/PFC in the fusion nuclear environment

Summary Points about Multiple Effects/Multiple Interactions and experiments in laboratory facilities

- **Right now, we do not know and cannot predict how the blanket/FW will work in the fusion nuclear environment**

Compelling examples from recent discoveries show that blankets designed with current knowledge of phenomena and data **will not work**

– The sources of this problem are:

1. The fusion nuclear environment has many fields with steep gradients (magnetic, neutrons, nuclear heating), and the blanket has many functions and materials – resulting in many yet undiscovered phenomena caused by multiple and synergistic effects/interactions
2. Simulation of the full fusion nuclear environment in non-fusion facilities is impossible
3. Accurate simulations of volumetric nuclear heating and temperature gradients is not possible
4. The fusion conditions result in very high parameters (e.g. Ha, Gr) not achievable in the lab
5. Phenomena such as MHD thermofluids is non-linear – so we do not know the scaling laws

- **We must build a number of laboratory facilities with strong capabilities to do the best possible simulation of the combined effects of the fusion nuclear environment and representative blanket mockups. A sequence of progressively more powerful facilities is needed (\$5M, \$20M, \$50M).** We also need a multiple of such facilities with different approaches to simulation to be constructed around the world.
- We will also need to do much more serious modeling with high speed computation
- **But even with the aggressive R&D in non-fusion facilities that we must do, we will still have serious uncertainties in predicting the blanket behavior in the fusion nuclear environment. Building FNSF Prior to DEMO is a MUST.**

What should the next DT Fusion Facilities (Other than ITER) be?

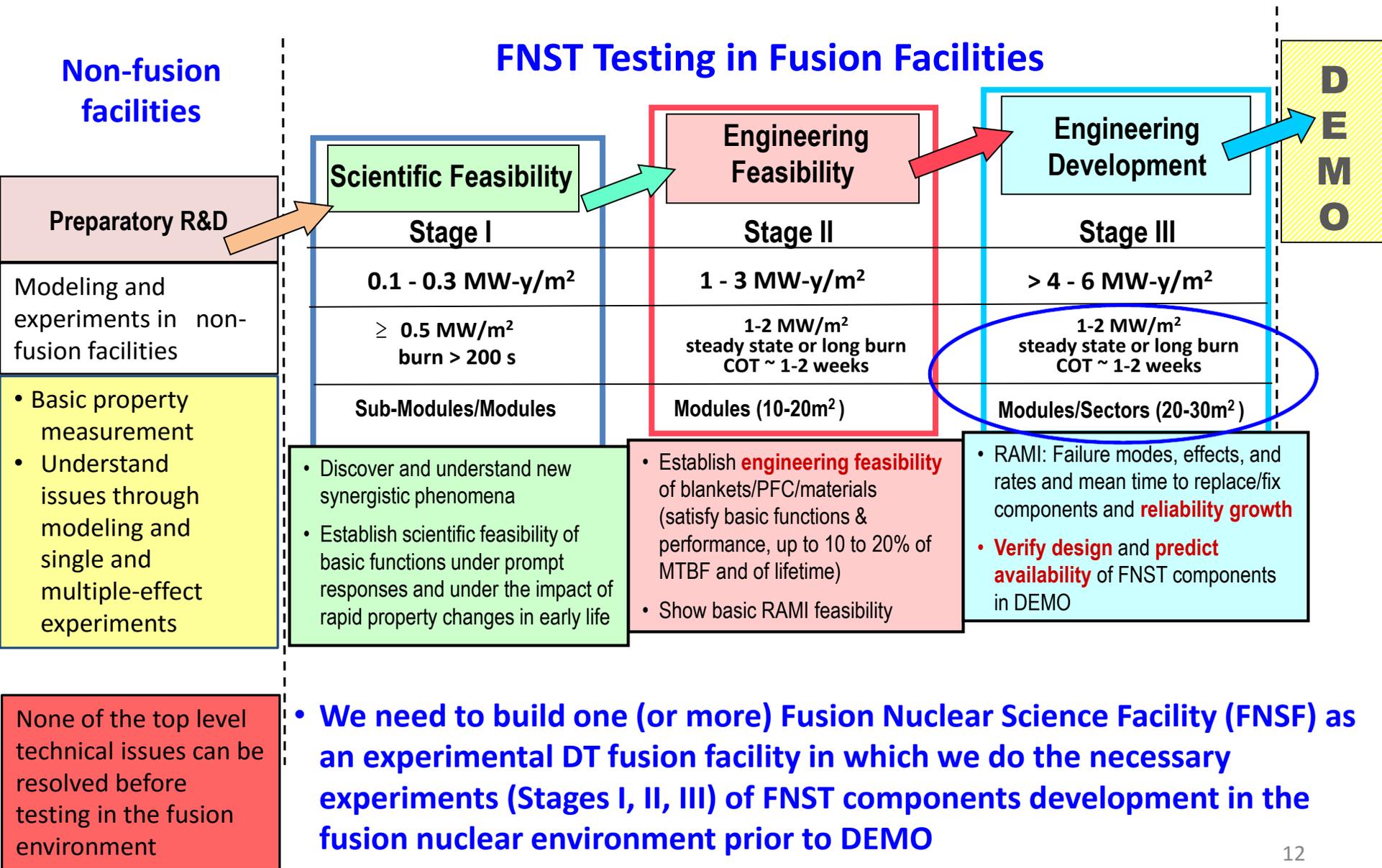
Three key facts must be considered in deliberating on this question

- **Even with the aggressive R&D of computational simulation and experiments in non-fusion facilities that we must do, we will still have serious uncertainties in predicting the blanket behavior in the fusion nuclear environment**

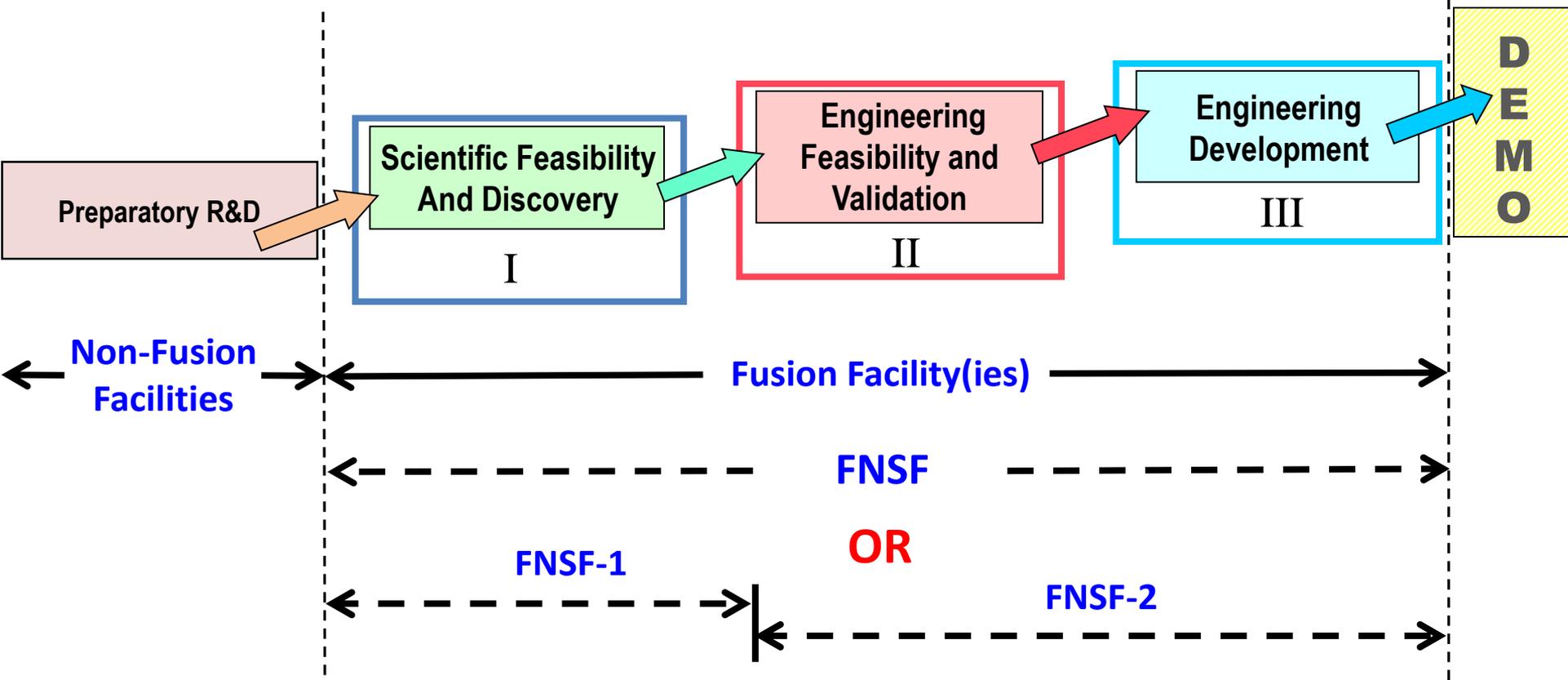
Therefore, the primary goal of the next DT fusion facility (at least the 1st stage) is to perform FNST experiments to discover synergistic effects and learn about blanket/PFC/Materials integrated behavior in the fusion nuclear environment. The next DT fusion facility cannot be for validation or demonstration.

- **RAMI is the “Achilles heel” for fusion. RAMI will be the key issue in determining the feasibility of plasma confinement configurations and blanket concepts**
 - MTBF for Blanket/FW/PFC in any DT fusion Device is estimated to be very short while MTTR is predicted to be too long – leading to very low availability of only a few percent - **DANGER**
 - Very Low Availability (a few percent) will be a dominant issue to be confronted by the next DT fusion device (regardless of its name FNSF, CFETR, DEMO, etc)
 - RAMI must be the most critical factor in any planning we do
- **External Tritium Supply is very limited and expensive AND achieving tritium self-sufficiency in fusion devices has many uncertainties.**

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



Planning the Pathway to DEMO Must Account for Unexpected Negative Results for Current Blanket/PFC and 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?! (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)

Highlights of strategies for Pathway to DEMO in Major World Programs

USA

- **FNSF is required before DEMO**
- (FNSF was first proposed in FINESSE Study in 1984, and in many subsequent studies led by UCLA. IEA Study in 1994-95. Broad community acceptance in 2007. Community Studies by UCLA, GA, and ORNL 2007-2011, also recently a study led by PPPL)
- Two versions for FNSF Device, both with normal conducting magnet: Standard A with $R \sim 2.5$ m, ST with low A and $R \sim 1.2$ m
- Recent study at PPPL: small number of people, tends to push more toward S.C. magnet and large size and prototypically – some choices not widely supported by experts that studied FNSF for years/decades

China

- **FNSF-type facility, called CFETR, required**
- Studies started ~ 4 years ago
- Two versions with two different groups of advocates:
 - Large device the size of ITER, $R \sim 6$ m with SC magnets, but still low fusion power
 - Small size with Normal Magnets, small fusion power

EU

- **No FNSF is planned**
- EuroFusion: Largest Studies in the world on DEMO and R&D

Korea

- **Go directly to DEMO**
- Law to build DEMO by 2040
- Yet, the government recently declined to fund a program on DEMO and its R&D

Japan

- **No FNSF planned**
- Small programs on DEMO studies
- For outsiders, there is concern that Fusion R&D in general, and FNST R&D in particular is shrinking in Japan

FNSF 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 should 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

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:

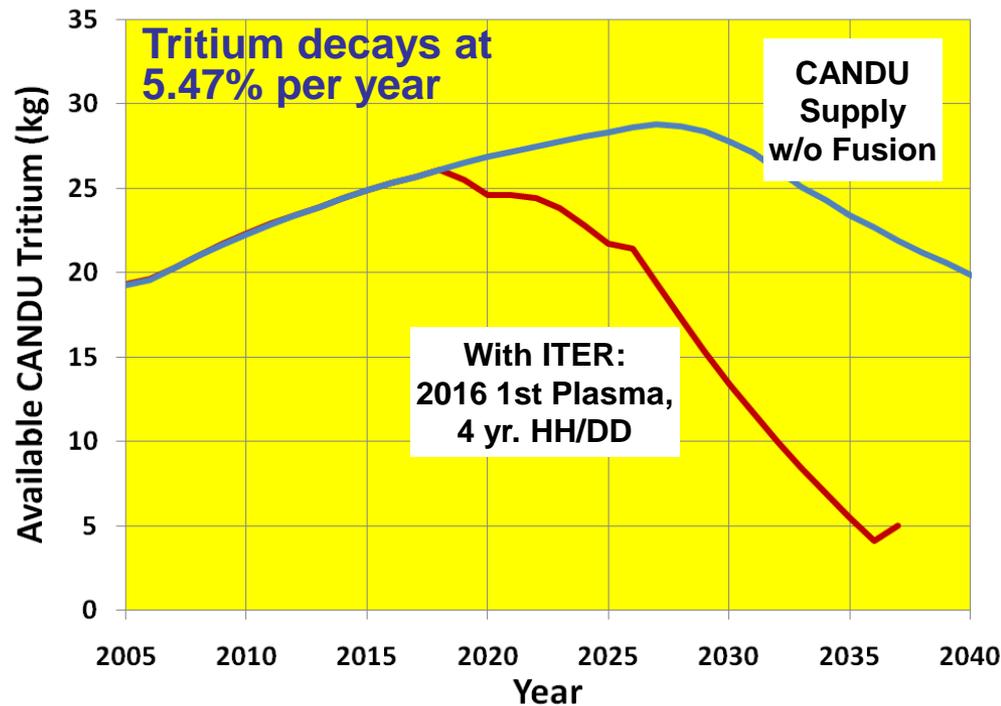
Fission reactors: 2–3 kg/year

\$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:

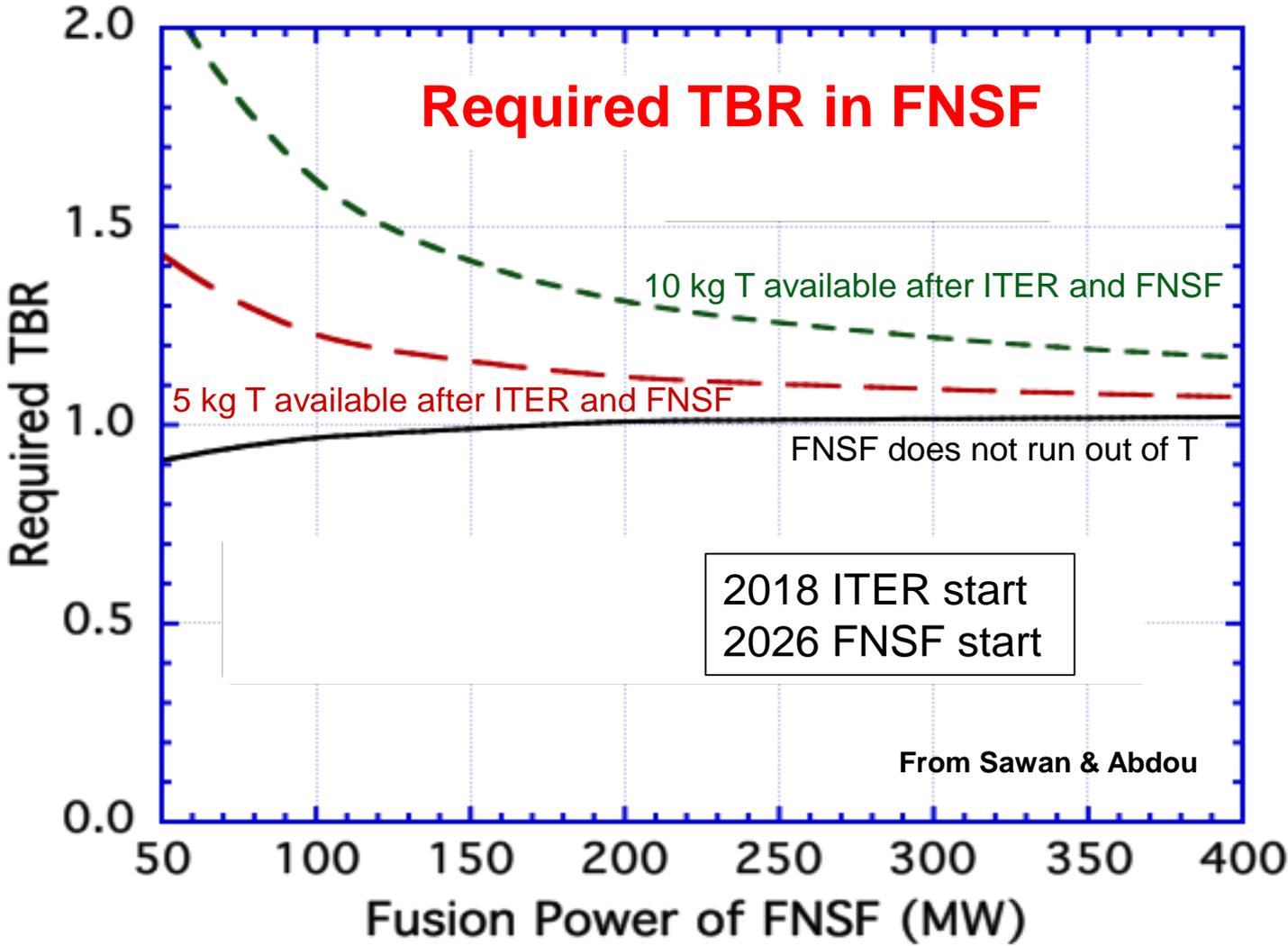
1 – Need Initial (startup) inventory of >10 Kg per DEMO

(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**

Why FNSF should be low fusion power, small size

- To reduce risks associated with external T supply and internal breeding shortfall
- Reduce Capital, operating cost, and replacement time (note Blanket/FW/Divertor will fail and get replaced many times)
- Avoid accumulating “mountains” of Radwaste from failed FNST components
- Satisfy FNST key requirement 1-2 MW/m² on 20-30 m² test area
- Cost/risk/benefit analyses* led to recommendations for Tokamak FNSF:
 - Fusion Power < 150 MW
 - Size comparable to JET (R < 3 m)
 - Low Q plasma (2-3) - and minimize extrapolation in physics from JET
 - Normal conducting TF coils (to reduce inboard B/S thickness, also increase maintainability e.g. by using demountable coils).

Plan FNSF scope, mission, power, and size such that we can build it the soonest (parallel to ITER). Avoid planning FNSF to be very ambitious since this has the risk of ever rising costs and very lengthy schedule delays (learn the lesson of ITER)

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. (for internal use in FNSF and to accumulate the required T inventory for DEMO startup)
 - 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 selected 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
- The DD phase of FNSF should be utilized to optimize the plasma and test divertor and blankets with true materials and design before intensive n in DT

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

- DD phase has important 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)

After first stage, 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 & other materials:
 - no uncertainty in spectrum or other environmental effects
 - prototypical responses, e.g., gradients, materials interactions, joints, ...

Degree of “prototypicality” between FNSF and DEMO?

- Some researchers have recently advocated that FNSF should be as close as possible to DEMO in order to minimize the gap between FNSF and DEMO
 - But our analysis in comprehensive studies over 30 years provides different conclusion
- The major issue in fusion development now is that
 - We don’t know how FNST components will behave in the fusion nuclear environment
 - R&D to test and qualify the FNST components is likely to require long time with success not assured (we do not even have scientific feasibility yet!)
 - The seriousness of the RAMI issue makes the risks very high
- Our concern now should be how to build a practical FNSF with minimum extrapolation of physics and technology (Be technically credible!)
- The focus of FNSF should be on **prototypical “in-vessel” fusion nuclear components** which are missing from ITER
- Components outside the vacuum vessel (e.g. S.C. magnets) are already prototypical and tested in ITER at an almost the same scale as DEMO- no need to be prototypical in FNSF
- An approach that makes FNSF close to DEMO will have:
 - Much larger size than needed for FNSF testing mission
 - Much larger capital and operating costs
 - Longer replacement time and accumulation of much Radwaste
 - Extremely Risky

Think of: “Now + 1” NOT “DEMO – 1”

Trying to skip FNSF is like if we had tried to skip ITER and go directly from a JET plasma to DEMO

- The stated motivation to skip FNSF and proceed to DEMO is to shorten the time for development and commercialization of fusion power
 - DEMO studies are important for the world to provide a vision for a DEMO
 - Trying to shorten the time for development of fusion power is important if a credible pathway is found
- **But any DT device which will be built going forward in which the fusion nuclear components are exposed to the fusion nuclear environment for the first time will serve the function of FNSF regardless of name DEMO or FNSF**
- We should think of a new approach to international collaboration much different from the ITER model. For example:
 - 2 or 3 countries each build its own FNSF and share results and experience
 - Other countries can contribute more to R&D for FNSF and DEMO
 - Each Major Country builds its own DEMO when there is enough data, experience, testing, and qualification of fusion nuclear components in the fusion nuclear environment (from FNSF)

ITER TBM is Important and Must be fully supported

- ITER TBM will provide important information in the fusion nuclear environment
- **But ITER TBM has limitations**
 - Fluence limited to $0.1 \text{ MW} \cdot \text{y}/\text{m}^2$
 - Limitations on replacing failed TBMs
 - One test module per blanket concept
 - Not all blankets will be tested (e.g. DCLL)
- Even with FNSF parallel to ITER, it is still prudent to utilize ITER for TBM testing in addition to testing in FNSF because:
 1. No extra cost for facility: Substantial capital investment infrastructure for TBM testing; and facility operating cost is free for TBM
 2. Big saving on R&D costs because of international collaboration
 - Six parties, each is paying for R&D for one blanket concept
 - Sharing the results of R&D and ITER testing of six blanket concepts among the parties saves the world money and effort
 3. TBM testing in ITER complements FNSF:
ITER has more prototypical magnetic configuration compared to the smaller size FNSF. ITER TBM tests can help benchmark FNSF results in the more prototypical magnetic fields and plasma current/confinement

Urge the world TBM program to devote more effort to: What to measure, how to measure, how results extrapolate, how to deal with early TBM failures

Concluding Remarks (1 of 2)

- Right now, we do not know and cannot predict how the blanket/FW will work in the fusion nuclear environment.
- Blanket R&D is **now in “separate effect” stage**. The World Programs **need to move rapidly toward “multiple effects/multiple interactions” experiments and modeling**. This requires a number of new laboratory facilities. There are many Challenges in planning multiple effects experiments that need to be confronted now.
- RAMI especially is the “Achilles heel” for fusion. RAMI will be the key issue in determining the feasibility of plasma confinement configurations and blanket concepts. RAMI must be the most critical factor in any planning, design and R&D we do.
- Even with the aggressive R&D in non-fusion facilities that we must do, we will still have serious uncertainties in predicting the blanket behavior in the fusion nuclear environment
Therefore, the primary goal of the next DT fusion facility (or at least the first stage) is to perform FNST experiments to discover synergistic effects and learn about blanket/PFC/Materials integrated behavior in the fusion nuclear environment. It can not be for validation or demonstration.

Concluding Remarks (2 of 2)

- We need to build **one (or more) FNSF** as an **“experimental”** DT fusion facility in which we do the necessary experiments of FNST components in the fusion nuclear environment **prior** to DEMO.
- One FNSF or a sequence of FNSFs will be needed to do the 3 necessary stages of R&D: I. Scientific Feasibility and Discovery, II. Engineering Feasibility and Validation, and III. Engineering Development and Reliability Growth
- To be timely, practical and affordable FNSF should be low power (< 150 MW), low tritium consumption, small sized (comparable to JET) facility with neutron wall load $\sim 1 \text{ MW/m}^2$ with a highly driven plasma and minimum extrapolation of JET-type physics
- **Trying to skip FNSF is like if we had tried to skip ITER and go directly from a JET plasma to DEMO. Could we have done this? At what risks?**

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

For more details and for “references” on topics in this presentation, please see the following article:

Mohamed Abdou, Neil B. Morley, Sergey Smolentsev, Alice Ying, Siegfried Malang, Arthur Rowcliffe, Mike Ulrickson. “Blanket/first wall challenges and required R&D on the pathway to DEMO”. Fusion Engineering and Design, 100 (2015) 2–43.

<http://www.sciencedirect.com/science/article/pii/S0920379615302465/pdf?md5=4797a1f8a18a0755dc92d83f35f6f855&pid=1-s2.0-S0920379615302465-main.pdf>

Thank you!