Primary considerations for strategy and design of base and test blankets/FW in fusion engineering test facility

Recommendations to enhance the prospects of success and maximize the benefits of CFETR

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With Input from: A. Ying, N. Morley, and many scientists and engineers over many years

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Introductory Remarks

- CFETR is a very important fusion Facility for China and for the World Fusion Program. We need to do our best to make sure that CFETR is prudently designed, and successfully constructed and operated.
- I appreciate the opportunity to participate in this annual CFETR meeting.
- The objective of my talk is to provide suggestions/recommendations on some important topics to enhance the prospects of success and maximize the benefits of CFETR to fusion development.

- **For the purpose of this talk, I often use the name "FNSF" (Fusion Nuclear Science Facility). This refers to any facility that will test fusion nuclear components in the actual fusion nuclear environment. This includes broad spectrum of facilities such as CTF, CFETR, first stage of EU DEMO, and the US versions for FNSF.**

Primary considerations for strategy and design of base and test blankets/FW in fusion engineering test facility

Outline

- Many Blanket Concepts around the world
- Which Concept is better?
- Base Breeding Blanket Requirements
- Strategy for Testing: Two classes of Concepts (LM and Ceramic Breeders) in Specially Designed Test Ports
- Testing Strategy for Operating Parameters of Base Breeding Blanket and Test Ports
- Reliability, Availability, Maintainability, Inspecability (RAMI)
- Framework for FNST Development & Requirements for Fusion Testing
- Staged Approach Strategy for Breeding Blankets, Structural Materials, PFC & Vacuum Vessel in FNSF/CFETR
- Summary

Many Blanket Concepts proposed worldwide

A. Solid Breeder Concepts (HCCB, HCPB, WCCB, HCCR)

- Always separately cooled, always require neutron multiplier
- Solid Breeder: Lithium Ceramic (Li_2O, Li_4SiO_4, Li_2TiO_3, Li_2ZrO_3)
- Coolant: Helium or pressurized water, or supercritical water

B. Liquid Breeder Concepts

Liquid breeder can be:

a) **Liquid metal** (high conductivity, low Pr): Li, or ^{83}Pb ^{17}Li

b) **Molten salt** (low conductivity, high Pr): Flibe $(LiF)_n \cdot (BeF_2)$, Flinabe (LiF-BeF_2-NaF)

B.1. Self-Cooled

- Liquid breeder is circulated at high enough speed to also serve as coolant

B.2. Separately Cooled (HCLL, WCLL)

- A separate coolant is used (e.g., helium or pressurized water)
- The breeder is circulated only at low speed for tritium extraction

B.3. Dual Coolant (DCLL)

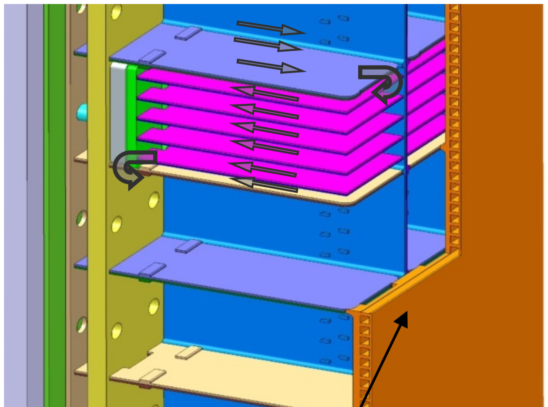
- FW and structure are cooled with separate coolant (He)
- Breeding zone is self-cooled
- Flow Channel Insert (FCI) as electric and thermal insulator

Which Blanket Concept is Better?

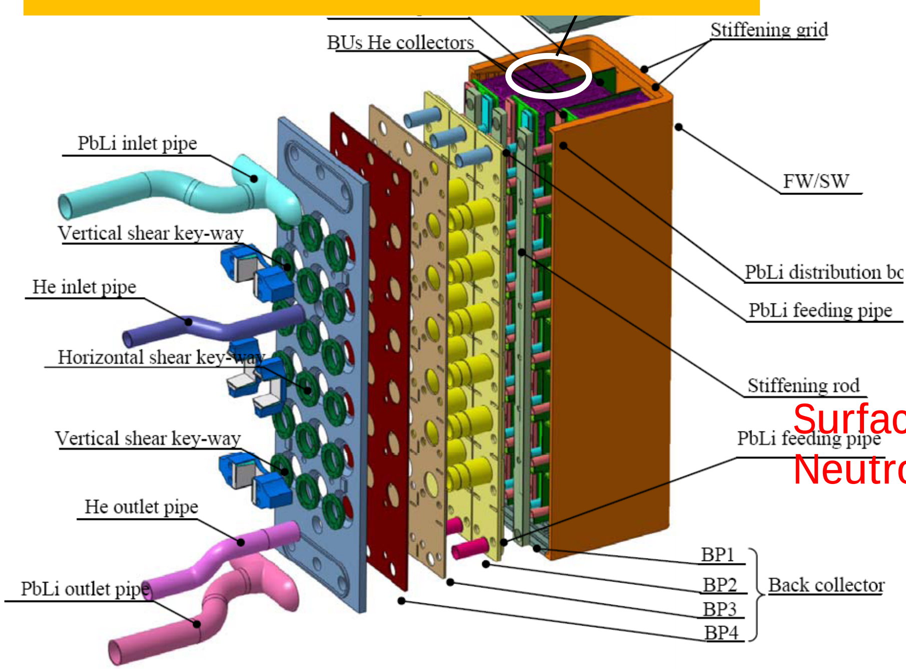
- No experienced expert can definitely answer this question.
- All what we know is that all blanket concepts have feasibility issues and attractiveness issues
- But we do not have real and reliable scientific information to enable evaluation of the feasibility and attractiveness of any of the blanket concepts. Such definitive information will be available only from testing blankets in the true fusion nuclear environment (e.g. CFETR, first stage of EU DEMO, FNSF)
- Some researchers express some preferences for certain concepts. But these preferences differ among the researchers based on each one's past experiences in other fields. These should be considered as "best guess," but it is a "guess."

Blanket/FW systems are complex and have many functional materials, joints, fluids, and interfaces

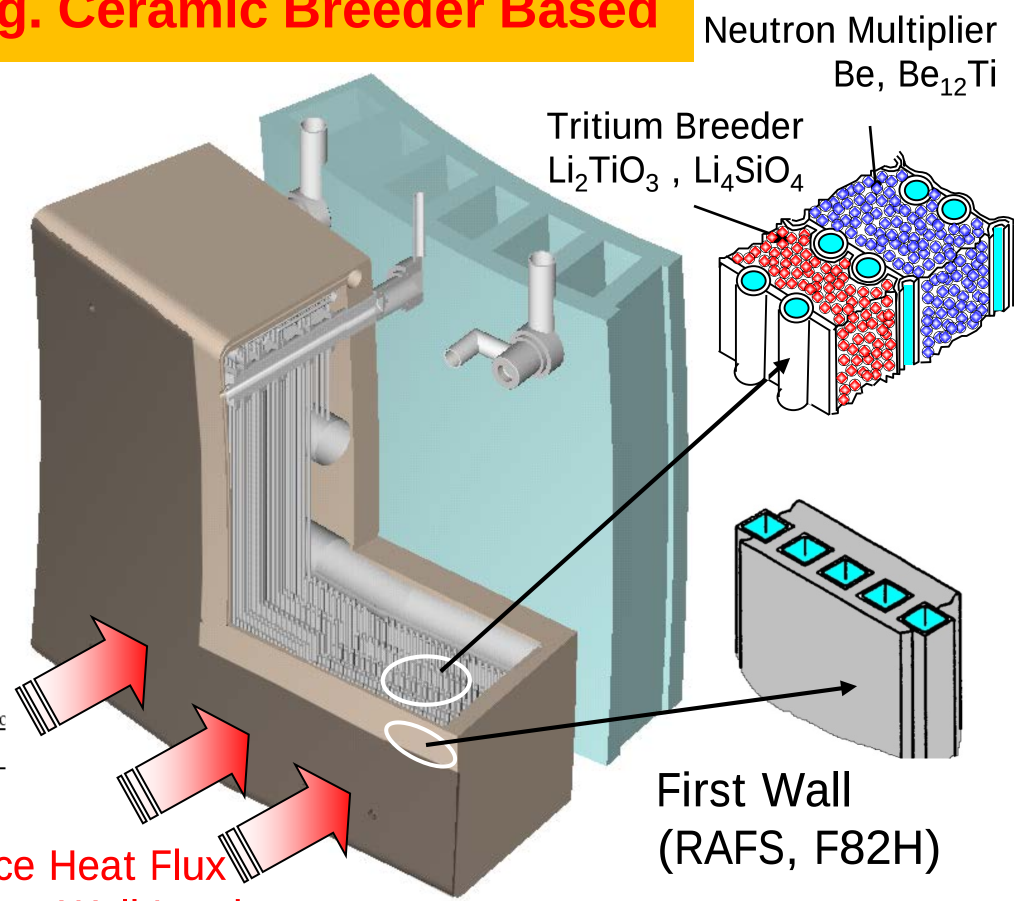
Li, PbLi,
Li-Salt flow



E.g. Liquid Breeder Based



E.g. Ceramic Breeder Based



Coolants: He, H_2O, or liquid metal or salt

International studies on FNST have concluded:

- **Testing in non-fusion facilities is necessary prior to testing in fusion facilities.**
  - Non-fusion facilities (laboratory experiments and fission reactors) and modelling can and should be used to narrow material and design concept options and to reduce the costs and risks of the more costly and complex tests in the fusion environment. Extensive R&D programs on non-fusion facilities should start now.

~10-15 years of R&D, design, analysis, and mockup testing are required to qualify blanket test modules for testing in any nuclear fusion facility

However, non-fusion facilities cannot fully resolve any of the critical issues for blankets.

  - There are critical issues for which no significant information can be obtained from testing in non-fusion facilities (An example is identification and characterization of failure modes, effects and rates). *Many Multiple Effects/Multiple Interactions in the blanket can not be adequately simulated in non-fusion facilities because nuclear heating in a large volume with steep gradients can be simulated only in DT Plasma-based facility*

- **Extensive Testing in Fusion Facilities is necessary prior to DEMO.**

Even the "Feasibility" of Blanket Concepts can NOT be established prior to testing in DT fusion facilities.

Do we need to develop and test all blanket concepts in the Fusion Nuclear Environment?

- No, it is not affordable

- Instead, we should focus on **testing TWO Classes of Concepts**:

  Liquid Metal Blanket Concept
  Ceramic Breeder blanket Concept

- Firm conclusion from prior studies: Both classes have serious feasibility and attractiveness issues that cannot be resolved prior to testing in the fusion nuclear environment

- But for each of the two classes , there are many variations depending on coolants (helium, water), configurations, etc.

- Each Major Program should test liquid metal blanket with at least one coolant, and ceramic breeder blanket with preferably a different coolant

How about Molten Salts?

- UCLA performed R&D program on molten salts for Japanese Universities for many years. Conclusion: No design window available with current structural material
- Molten Salt was selected for the US initial TBM and studied extensively 2003-2006. It was finally abandoned because of need for very expensive chemistry R&D, severe tritium permeation, corrosion, massive use of beryllium, possible need for additional Be to breed, and very narrow or non-existent design window
- But if there are advances in the future (e.g. Higher temperature structural material, or lower m.p. molten salt), then molten salts should be evaluated then to see if they should be reconsidered

“BASE” Breeding Blanket (Also called “Driver” Breeding Blanket)

Due to the lack of adequate external non-fusion supply of tritium, No DT fusion devices other than ITER can be operated without a full breeding blanket

– **Base breeding blanket should be installed on CFETR / FNSF from the beginning**

EXTERNAL T Supply Issue: Tritium Consumption and Production

Tritium Physical Constants

- Half life: 12.32 years; decay rate: 5.47 %/yr - **Relatively short life**
- Some of the T will be lost by radioactive decay during T flow, processing, and storage
- **T available now from non-fusion sources is totally irrelevant to evaluating availability of T for startup of DEMO or FNSF constructed > 20 years from now**

Tritium Consumption in Fusion Systems is Huge

55.8 kg per 1000 MW fusion power per year

Tritium Production in Fission Reactors* is much smaller (and cost is very high)

LWR (with special designs for T production): ~ 0.5-1 kg/year

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

***Typical CANDU produces ~ 130 g per year** (0.2 Kg per GWe per full power year) (T is unintended by product)*

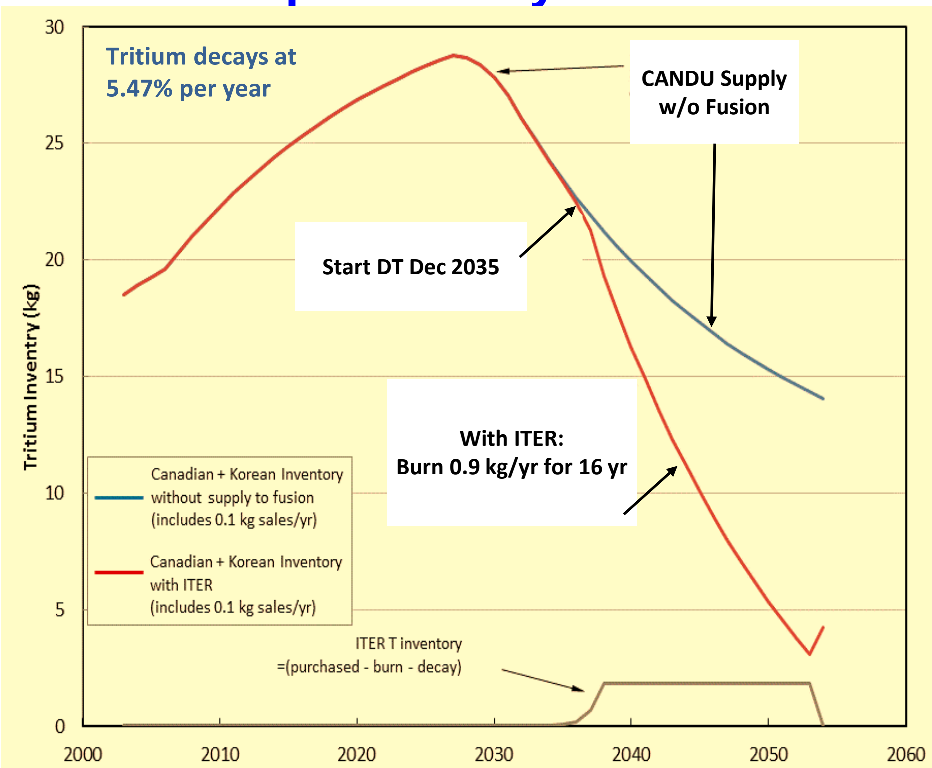
CANDU Ontario: Current supply will be exhausted by ITER DT starting in 2036.
Future Supply from CANDU depends on whether current reactors can be licensed to extend life by 20 years after refurbishment.
There are many political, national policy, and practical issues with both CANDU and LWR

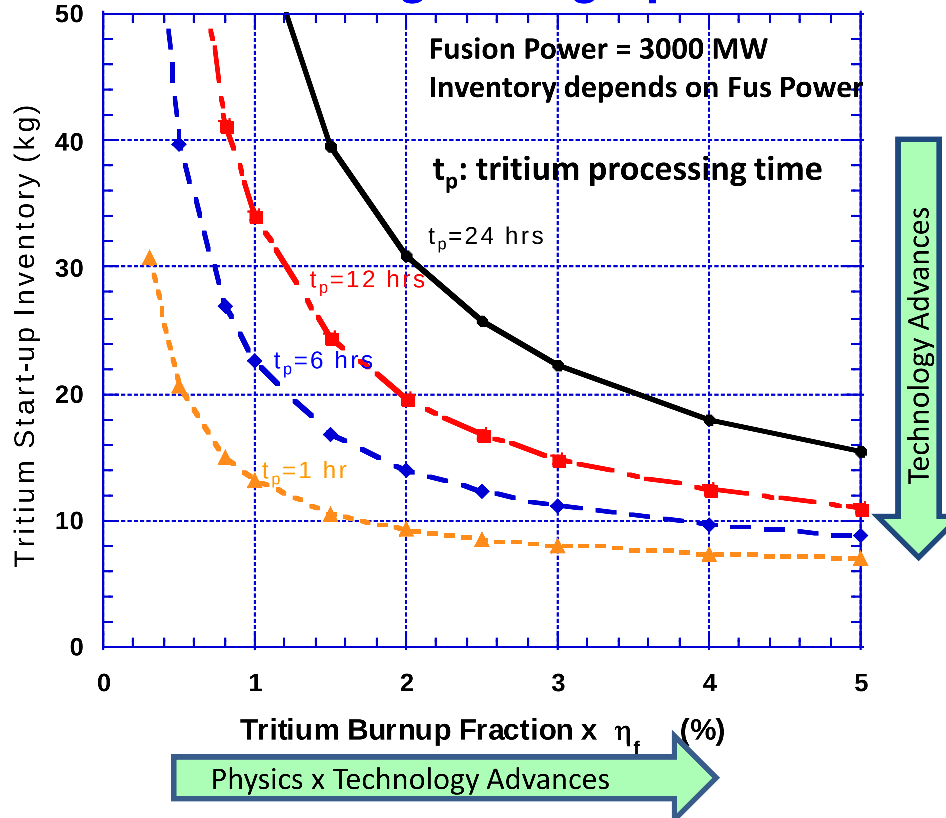
- **Other non-fission sources (e.g. APT (proton-accelerator)) proved totally uneconomical**
- **Start-up with D-D fuel would pose additional tokamak physics and technological problems, and would delay power production by years and is not economically sensible**

** Note: Fission reactor operators do not really want to make tritium because of permeation and safety concerns. They want to minimize tritium production if possible*

Issue: With ITER DT start in 2036, there will be no tritium left to provide "Start up" T inventory for any major DT Fusion facility beyond ITER

Physics and Technology R&D is Required to minimize the required T Startup inventory and avoid short fall in T breeding during operation



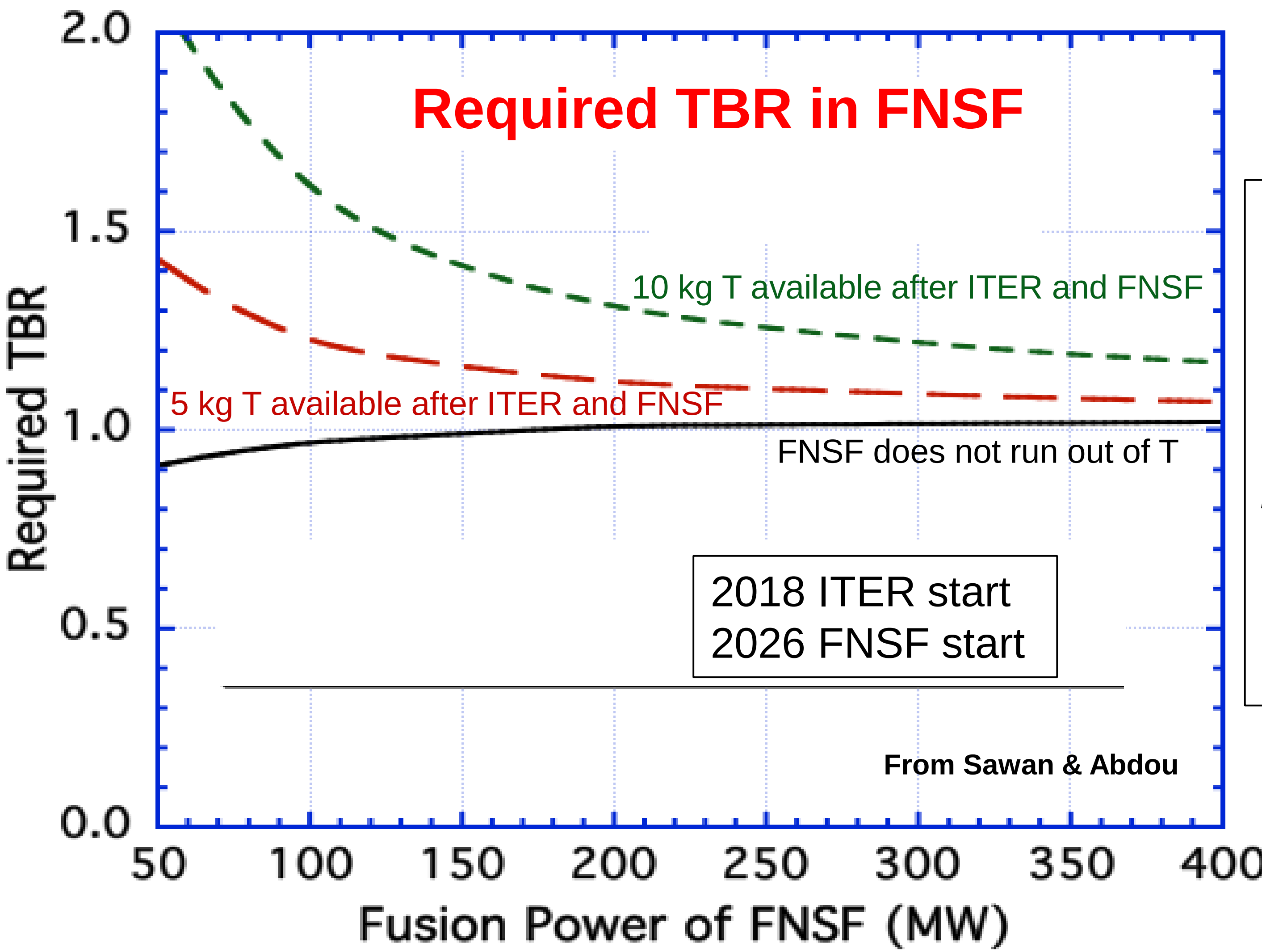


- **Base breeding blanket should be installed on CFETR / FNSF from the beginning**
- **CFETR starting at low fusion power is prudent decision**
- **Required Startup inventory has many uncertainties and can be large-- need to perform Physics and Technology R&D to minimize it:**
  - $f_b \times \eta_f > 5\%$, $t_p < 6$ hours Also minimize T retention inventories in blanket, PFC

FNSF/CFETR should be designed to breed tritium to:

a) Achieve T self sufficiency, **AND**

b) Accumulate excess tritium sufficient to provide the tritium inventory required for startup of DEMO



Impose a new requirement not originally in the mission of FNSF when it was first proposed in 1984 and in subsequent studies in the 1980's and 90's

Situation we are running into with breeding blankets:

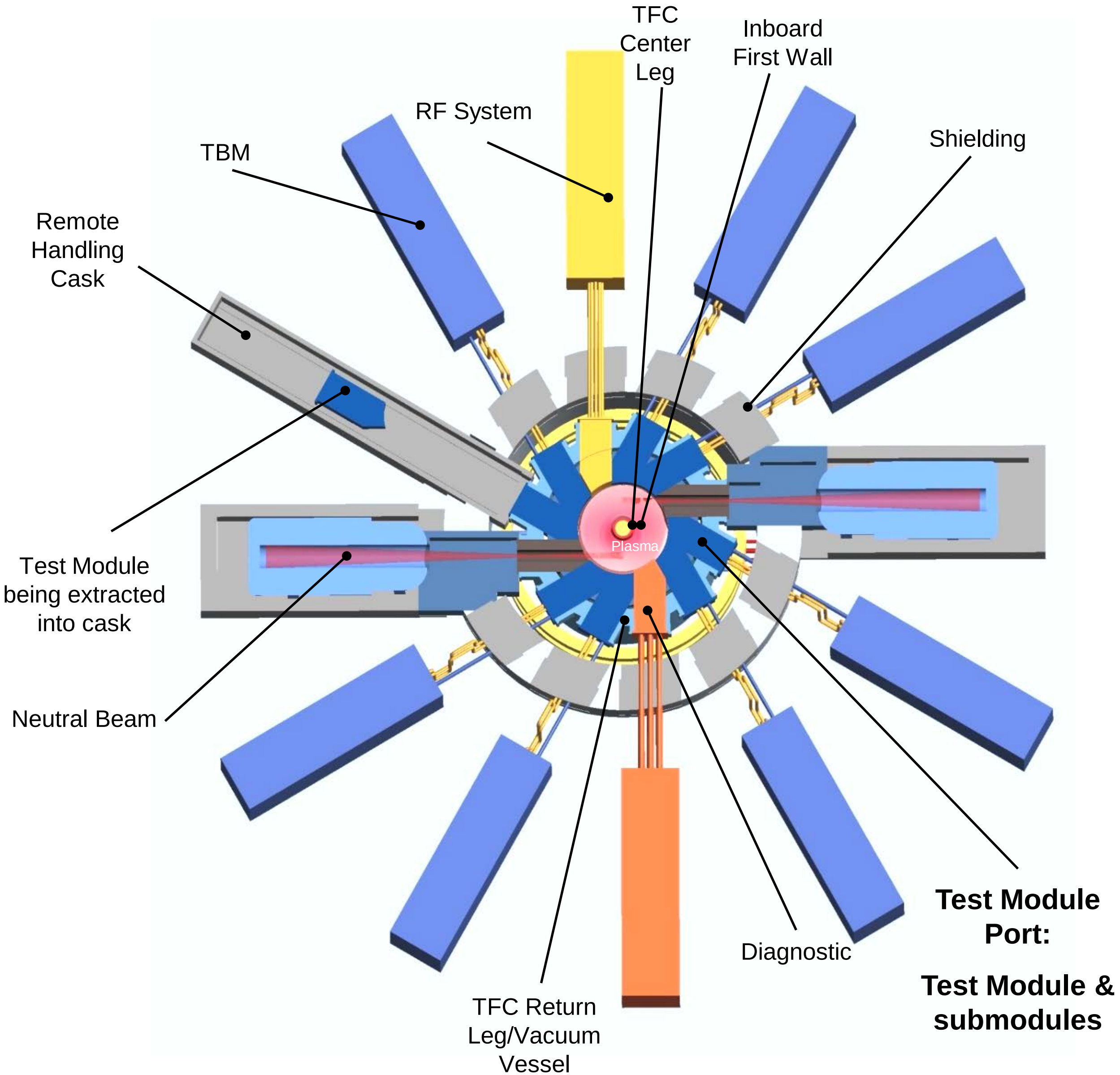
What we want to test (the breeding blanket) is by itself An ENABLING Technology

Recommended Base Breeding Blanket and Testing Strategy in CFETR

- **A Breeding Blanket should be installed as the "Base" Blanket on CFETR from the beginning**
  - Needed to breed tritium. (for internal use in CFETR 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 Base Blanket should be one of the candidates for DEMO
- **Both classes of Blanket Concepts, liquid metal and ceramic breeders, should be tested in especially designed "test ports"**
- **Both "port-based" and "base" blankets should have different operating parameters and "testing missions"**
  - Base blanket operating in a more conservative mode run initially at reduced parameters/performance (will obtain data on module to module interactions, reliability growth from large FW surface area/many modules, etc.)
  - 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 CFETR should be utilized to optimize the plasma and for performance verification of divertor and FW/blanket without neutrons

Illustrative Example of mid-plane Blanket Test Ports allowing faster Replacement and Maintainability of Test Blanket Modules



Reliability/Availability/Maintainability/Inspectability (RAMI)

- RAMI, particularly for nuclear components, is one of the most challenging issues for DEMO and Power Plants.

- A primary goal of fusion facilities prior to DEMO (e.g. CFETR) is to solve the RAMI issue by providing for “reliability growth” testing and maintenance experience

- But achieving a reasonable Availability in CFETR/FNSF device is by itself a challenge

- 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

Reliability / Maintainability / Availability / Inspectability Critical Development Issues

Unavailability = U(total) = U(scheduled) + U(unscheduled)

This you design for

This can kill your DEMO and your future

Scheduled Outage:

- Planned outage (e.g. scheduled maintenance of components, scheduled replacement of components, e.g. first wall at the end of life, etc.).
- This tends to be manageable because you can plan scheduled maintenance / replacement operations to occur simultaneously in the same time period.

Unscheduled Outage: *(This is a very challenging problem)*

- Failures do occur in any engineering system. Since they are random, they tend to have the most serious impact on availability.

This is why "reliability/availability analysis," reliability testing, and "reliability growth" programs are key elements in any engineering development.

Reliability/Availability/Maintainability/Inspectability (RAMI) is a serious challenge that has major impact on priorities and strategy for fusion R&D

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	16	5 x10^{-6}	23	10^4	240	0.1	0.098	0.91
P C								
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 equipment- instrumentation, cooling, turbines, electrical plant								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!!

Fundamental Reasons why we have Serious Problems with short MTBF, long MTTR, and very low expected availability in current fusion “confinement” systems

- Location of Blanket/FW/Divertor **inside*** the **vacuum vessel**:

  → ***low fault tolerance*** → ***short MTBF Because*** many failures (e.g. coolant leak) require immediate shutdown, also no redundancy possible.

  → ***long MTTR Because*** repair & replacement requires breaking “vacuum seal” and many connects / disconnects, and many operations in the limited access space of tokamaks, stellerators, and other “toroidal/closed” configurations ** The decision to put the blanket inside the vacuum vessel is necessary to protect the vacuum vessel, which must be robust and cannot be in high radiation/temperature/stress state facing the plasma.*

- Large surface area of the first wall results in high failure rate for a given unit failure rate per unit length of piping, welds, and joints → ***short MTBF***

Results show: anticipated MTBF is hours/days (required is years), and MTTR is 3-4 months (required is days), and availability is very low < 5%

Contrast this to fission reactors:

- Can continue operation with ~2% of fuel rods with failures (MTBF ~ years)
- An entire fuel bundle can be replaced in ~ 2 days (MTTR ~ 2 days).
- Fission reactors have been able to achieve 90% availability

Observations and Suggestions for improving the situation with RAMI, the *Achilles' Heel is*sue for fusion

- MTBF/MTTR will be the key issue in determining the feasibility of plasma confinement configurations and the feasibility of blanket concepts and material choices (structure, breeder, insulators, T barriers, etc.)
- Performance, Design Margin, Failure Modes/Rates should be the focus of FNST R&D
  Not a long dpa life

1. **Setting goals for MTBF/MTTR is more important NOW than dpa goals for lifetime of materials (RAFS with 10-20 dpa, 100 ppm He is sufficient for now)**
2. R&D should Now focus on:
   - Scientific understanding of multiple effects, performance and failures so that functions, requirements & safety margins can be achieved, and designs simplified and improved
   - Subcomponent tests including non-nuclear tests
   - Understand that Reliability Growth takes very long time, Build FNSF early as "experimental" facility that focuses only on the FNST components inside the vacuum vessel. Realistic understanding of MTBF/MTTR can be obtained in such FNSF
   - Be prepared for surprises and be ready to change pathway.

How Many Modules/Submodules Need to Be Tested For Any Given One Blanket Concept?

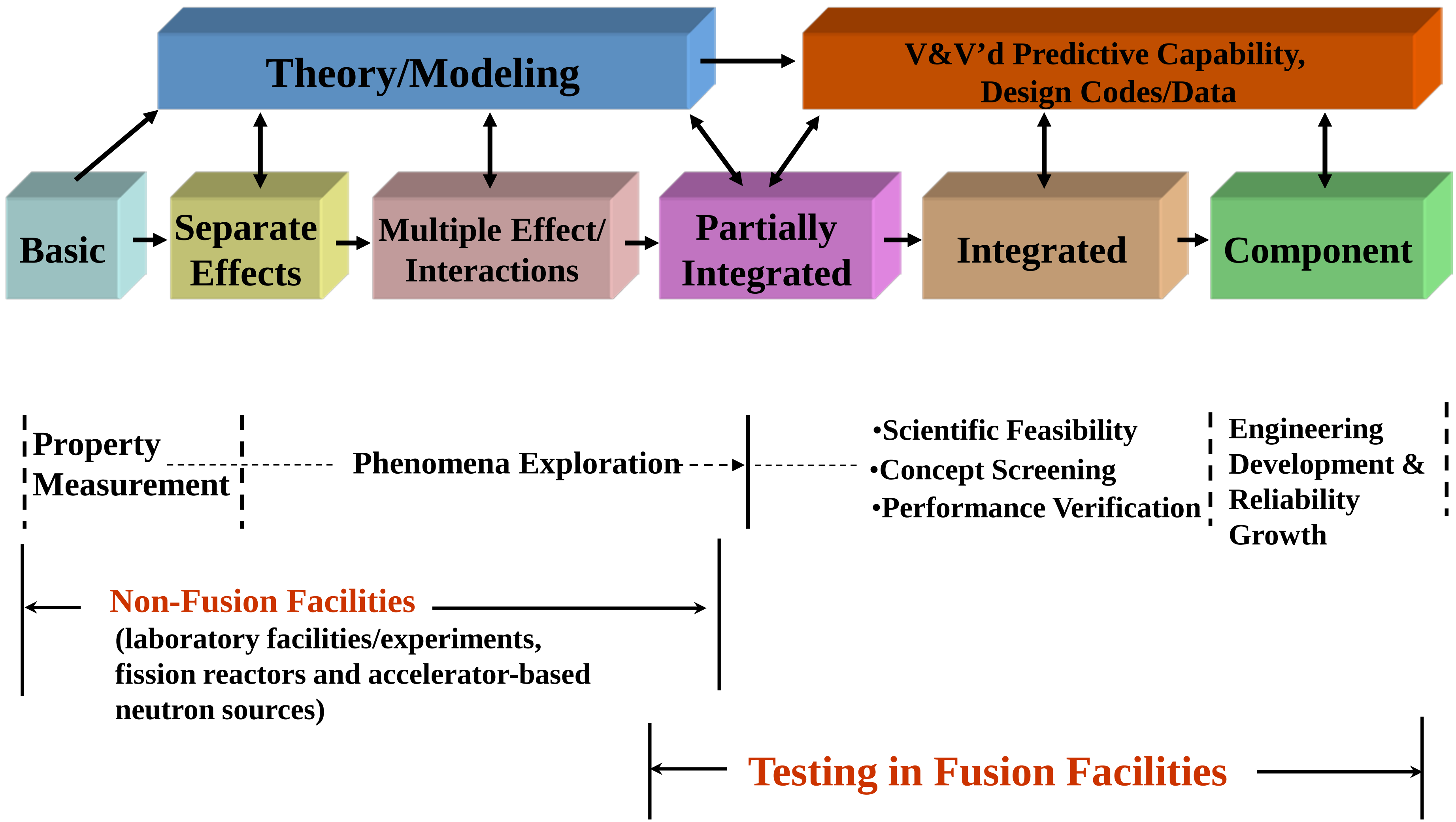
- Never assume one module, because engineering science for testing shows the need to account for:
  1. Engineering Scaling 2. Statistics
  3. Variations required to test operational limits and design/configuration/material options
- Detailed analysis in several studies in the US indicated that a prudent medium risk approach is to test the following test articles for any given One Blanket Concept:
  - One Look-Alike Test Module
  - Two Act-Alike Test Modules
  - (Engineering Scaling laws show that at least two modules are required, with each module simulating a group of phenomena)
  - Four supporting submodules (two supporting submodules for each act-alike module to help understand/analyze test results)
  - Two variation submodules (material/configuration/design variations and operation limits)

These requirements are based on "functional" and engineering scaling requirements. There are other more demanding requirements for "Reliability Growth" *(See separate section on this)*

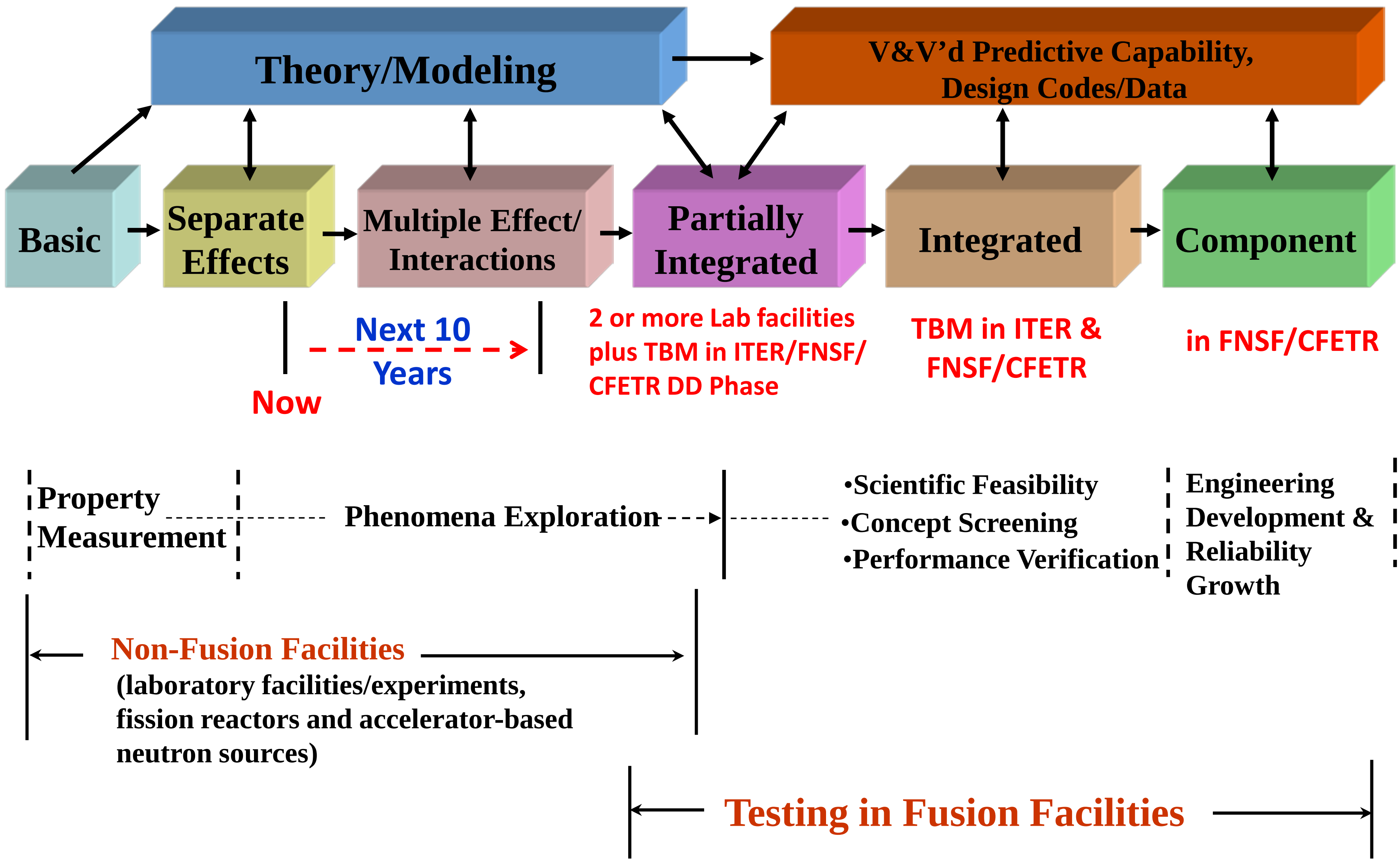
Scientific Framework and Strategy for Fusion Development

1. Role and Features of required non-fusion and fusion facilities
2. FNST Requirements on FNSF/CFETR Parameters and Features
3. Timing and Stages of FNSF(s)/CFETR, How many FNSF(s)/CFETR do we need?
4. Solving the paradox of short MTBF/long MTTR and what to do about dpa

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



We are now in mostly "Separate Effects" stage. We Need to move to "multiple effects/multiple interactions" experiments and modelling



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

Non-fusion facilities

Preparatory R&D

Modeling and experiments in non-fusion facilities

- Basic property measurement
- Understand issues through modeling and single and multiple-effect experiments

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

FNST Testing in Fusion Facilities

Scientific Feasibility	Engineering Feasibility	Engineering Development
Stage I	Stage II	Stage III
Fluence ~0.3 MW-y/m²	**1 - 3 MW-y/m²**	**> 4 - 6 MW-y/m²**
NWL ≥ 0.5 MW/m² **Plasma burn > 200 s**	**1-2 MW/m²** **steady state or long burn** **COT ~ 1-2 weeks**	**1-2 MW/m²** **steady state or long burn** **COT ~ 1-2 weeks**
Sub-Modules/Modules	Modules (10-20m²)	Modules/Sectors (20-30m²)

Scientific Feasibility (Stage I)

- Discover and understand new synergistic phenomena
- Establish scientific feasibility of basic functions under prompt responses and under the impact of rapid property changes in early life

Engineering Feasibility (Stage II)

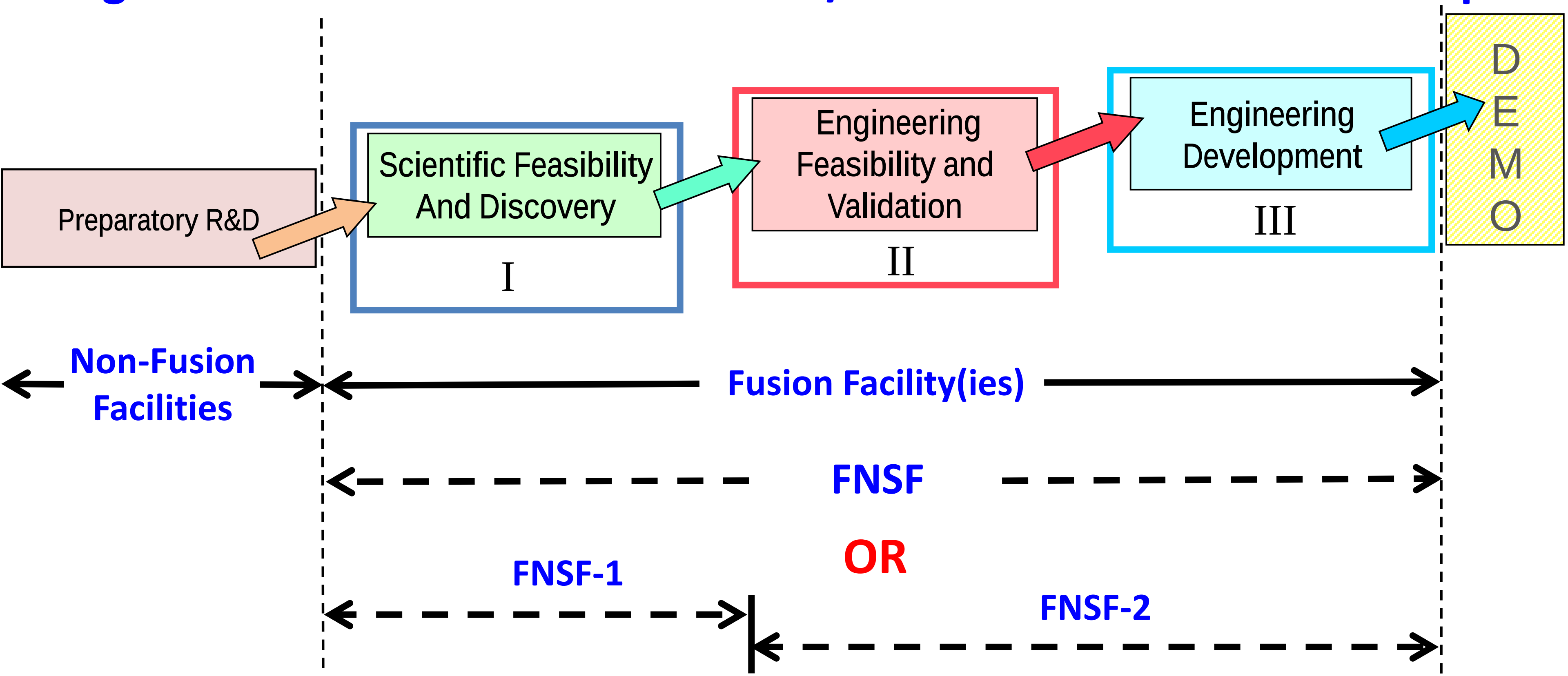
- Establish engineering feasibility of blankets/PFC/materials (satisfy basic functions & performance, up to 10 to 20% of MTBF and of lifetime)
- Show basic RAMI feasibility

Engineering Development (Stage III)

- RAMI: Failure modes, effects, and rates and mean time to replace/fix components and reliability growth
- Verify design and predict availability of FNST components in DEMO

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)

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

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, CFETR, CTF.**
- **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 200 appm He (~20 dpa).**
    - **Note: Many material experts state confidence that FS will work fine up to at least 300 appm He (30 dpa) at irradiation temperature > 350°C.**

Staged Approach Strategy for Breeding Blankets, Structural Materials, PFC & Vacuum Vessel in FNSF/CFETR

- 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/CFETR (real environment) for testing materials:

  - no uncertainty in spectrum or other environmental effects
  - prototypical responses, e.g., gradients, materials interactions, joints, …

Concluding Remarks (1 of 4)

- CFETR is a very important fusion Facility for the World Fusion Program.
- There are Many Blanket Concepts proposed worldwide. We do not have sufficient information to make a reliable judgement whether any concept will work, or which concept is better. We will not know until we test blankets in the Fusion Nuclear environment (FNSF, CFETR, CTF).
- We cannot afford to develop all blanket concepts.
- **CFETR should focus on testing TWO Classes of Concepts:**

  Liquid Metal Blanket Concept
  Ceramic Breeder blanket Concept

  - Both classes have serious feasibility and attractiveness issues that cannot be resolved prior to testing in the fusion nuclear environment. It is prudent to test BOTH classes of concepts (very risky to focus only on one of these two classes).
  - However, the coolant and configuration variations within each class of concepts can be narrowed considerably

Concluding Remarks (2 of 4)

- **External Tritium Supply is very limited and expensive AND achieving tritium self-sufficiency in fusion devices has many uncertainties**
  - **A full Breeding Blanket should be installed as the “Base” Blanket on CFETR from the beginning. Start DT phase with low fusion power. Perform R&D for higher T burn fraction and fueling efficiency**
- **Both liquid metal and ceramic breeder blanket concepts should be tested in especially designed “test ports”**
- **Both “port-based” and “base” blankets should have different operating parameters and “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
- **I fully support the recent EUROfusion DEMO team decision to use DEMO as a Component Test Facility (CTF) for the breeding blanket:**
  - A “driver” blanket with more conservative parameters and technologies
  - test advanced blanket concepts in ports/segments – use of more risky performance parameters and technology choices
  - This is very consistent with the Strategy we developed in the US for FNSF in 2008

Concluding Remarks (3 of 4)

- **Validation of achievable and required TBR, and ultimately T self-sufficiency can be realized only from experiments and operation of DT fusion facility(ies).**
  - There are Large uncertainties in achieving Tritium Self Sufficiency because of low plasma burn fraction and fueling efficiency, in addition to the inability to narrow the current uncertainties in the achievable TBR without testing a full blanket sector in a plasma-based device

- 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: relatively expensive but a small fraction of the cost of tests in DT fusion facilities

- 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**.

  Building 2 or 3 FNSF-type facilities around the world (e.g.. FNSF in the US, CFETR in China, CTF in EU as first stage of EU DEMO) has tremendous benefits and is very strongly recommended

Concluding Remarks (4 of 4)

- **RAMI is the "Achilles heel" for fusion. RAMI will be the key issue in determining the feasibility of plasma confinement configurations and blanket concepts**
  - 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

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

Thank you!

谢谢