Next Step
Fusion Nuclear Science Facility (FNSF) and Pathway to DEMO

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“The Time to Fusion is always 40 years away” and “expanding”

Recent remarks from key influential people

(Implications and What to Do: Oral Remarks)

Launching an aggressive FNST Program NOW is essential to realizing fusion in the 21^{st} Century

China Can Play a MAJOR Role

Next Step Fusion Nuclear Science Facility (FNSF) and Pathway to DEMO

Outline

1. Introduction

DEMO Definition, Scope of FNST, Need for FNSF

2. Technical Planning and Development Pathways: Prior Studies

What was done, what we learned , and references

3. FNST Development Strategy and Pathway to DEMO

Science Based Framework

Modeling and Experiments in Laboratory facilities

Requirements on fusion nuclear facility (FNSF) to perform FNST experiments

Challenges in Design of FNSF

Technical strategy for experiments in FNSF

Examples of FNSF Designs

3. R&D Needs for FNST **(Blanket, Tritium, PFC, Materials, Safety)**

Modeling and Experiments in Laboratory facilities

4.R&D Needs for Plasma Heating, Current Drive, Fueling, Diagnostics

5. Summary

DEMO

A key goal of fusion plans in the world programs is the construction and operation of a demonstration power plant (Demo), which will enable the commercialization of fusion energy.

It is anticipated that several such fusion demonstration devices will be built around the world.

There are variations in Plans of World Fusion Programs as to:

- WHEN DEMO will be built
- Goals and Requirements for the early phase of DEMO operation

But there is agreement that DEMO must **ultimately** demonstrate the commercial practicality of fusion power.

The US addressed Goals and Requirements for DEMO in a "35-year plan" in 2003

DEMO

(Based on US 35-year Plan, Under section **4.5 Demonstration)**

The fusion demonstration power plant (Demo) is the last step before commercialization of fusion. It must open the way to commercialization of fusion power, if fusion is to have the desired impact on the world energy system.

Demo is built and operated in order to assure the power producers and the general public that fusion is ready to enter the commercial arena. As such, Demo begins the transition from science and technology research facilities to a field-operated commercial system.

Demo must provide energy producers with the confidence to invest in commercial fusion as their next generation power plant, i.e., demonstrate that fusion is affordable, reliable, profitable, and meets public acceptance. Demo must also convince public and government agencies that fusion is secure, safe, has a low environmental impact, and does not deplete limited natural resources.

In sum, Demo must operate reliably and safely on the power grid for a period of years so that industry gains confidence from operational experience and the public is convinced that fusion is a “good neighbor.”

Top-level goals for the fusion Demo (US)

Demonstrate a closed tritium fuel cycle

Safety and environmental impact:

- Not require an evacuation plan.
- Generate only low-level waste.
- Not disturb the public's day-to-day activities.
- Not expose workers to a higher risk than other power plants.

Economics:

- Demonstrate that the cost of electricity from a commercial fusion power plant will be competitive, and that other applications such as hydrogen production are also attractive.

Scalability:

- Use the physics and technology anticipated for the first generation of commercial power plants.
- Be of sufficient size for confident scalability (>50%-75% of commercial).

Reliability:

- Demonstrate remote maintenance of fusion core.
- Demonstrate routine operation with minimum number of unscheduled shutdowns per year.
- Ultimately achieve an availability > 50% and extrapolate to commercially practical levels.

Status of Fusion

And Major Gaps in Readiness for DEMO

ITER will show the Scientific and Engineering Feasibility of:

–**Plasma (**Confinement/Burn, CD/Steady State, Disruption control, edge control)

–**Plasma Support Systems** (Superconducting Magnets, fueling, heating/CD)

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

  (TBM provides very important information, but limited scope)

- **The Fusion Program is yet to embark on a program to show the scientific and engineering feasibility of Fusion Nuclear Science and Technology**

Fusion Nuclear Science and Technology (FNST)

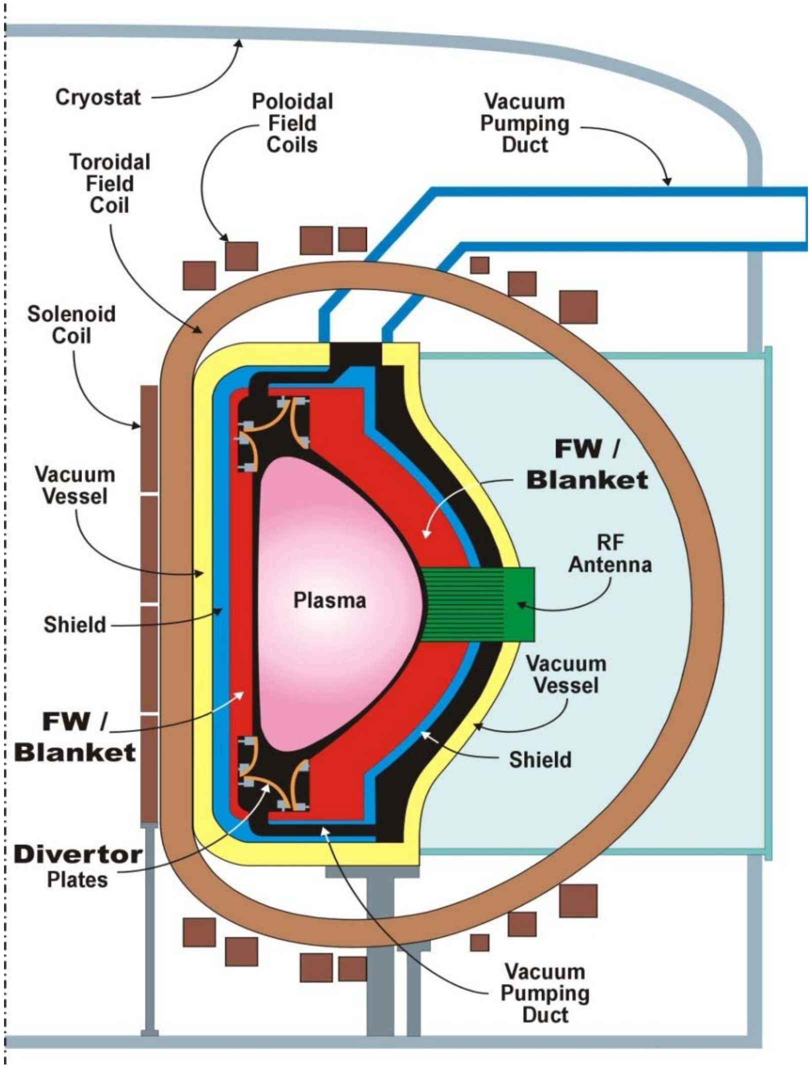
FNST is the **science**, **engineering**, **technology** and **materials**
for the fusion nuclear components that
generate, control and utilize neutrons, energetic particles & tritium.

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**

Other Systems / Components affected by the Nuclear Environment:

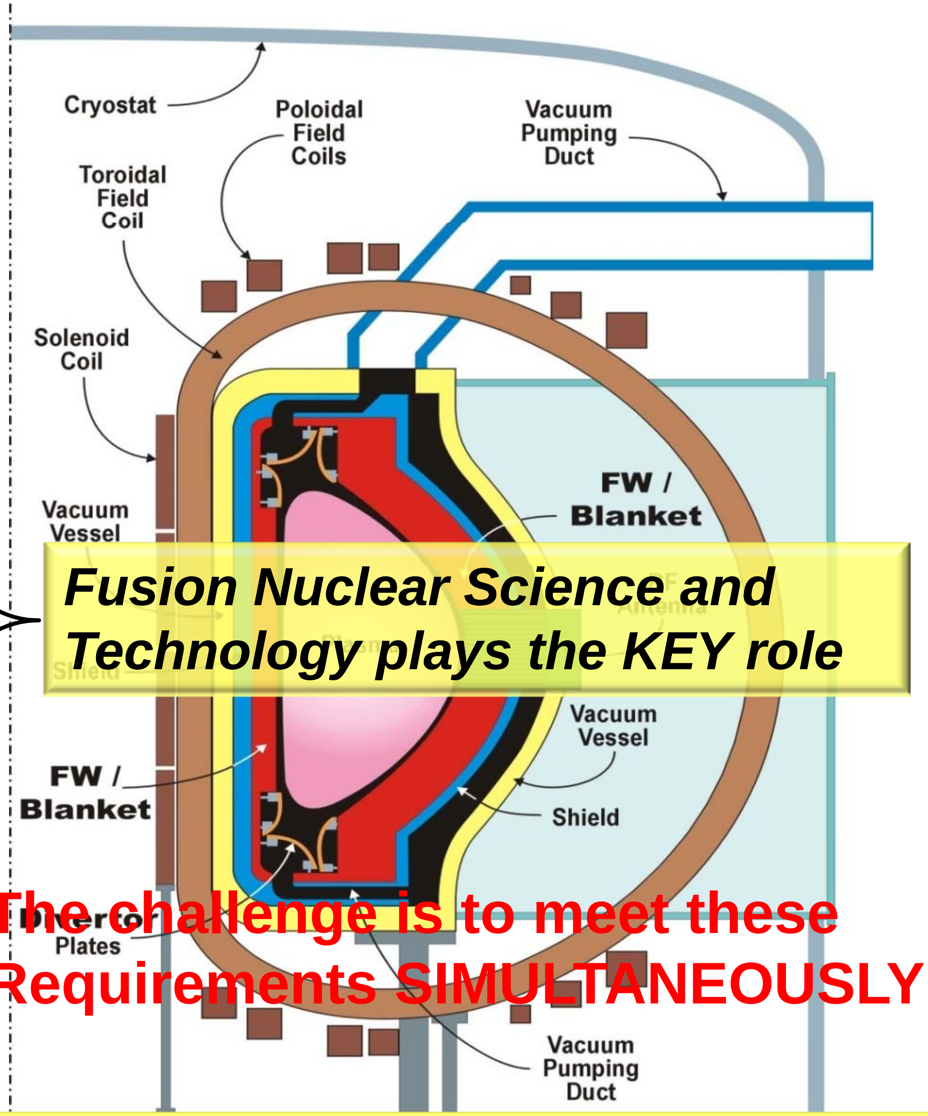
- Tritium Fuel Cycle
- Instrumentation & Control Systems
- Remote Maintenance Components
- Heat Transport & Power Conversion Systems



Fusion Goal: Demonstrate that fusion energy can be produced, extracted, and converted under practical and attractive conditions

<u>**Requirements to realize fusion goal:**</u>

1. **Confined and Controlled Burning Plasma (feasibility)**
2. **Tritium Fuel Self-Sufficiency (feasibility)**
3. **Efficient Heat Extraction and Conversion (feasibility)**
4. **Reliable/Maintainable System (feasibility/attractiveness)**
5. **Safe and Environmentally Advantageous (feasibility/attractiveness)**



Fusion Nuclear Science and Technology plays the KEY role

The challenge is to meet these Requirements SIMULTANEOUSLY

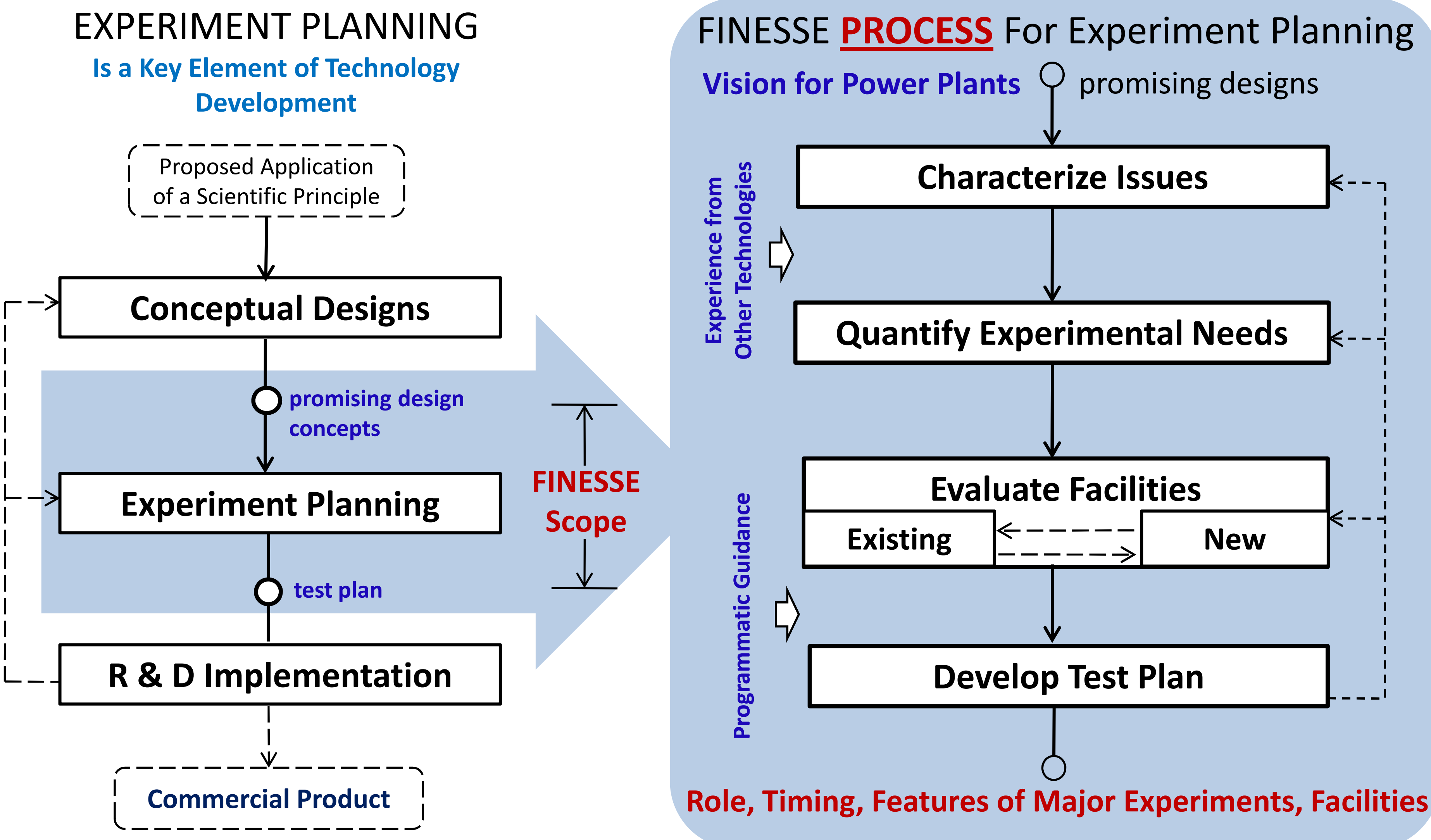
The only way to do experiments that simultaneously test these requirements is in a plasma-based fusion facility- this is what we call FNSF

Extensive FNST Studies (In US) over the past 25 years included Technical Planning and Development Pathway

- **Started** with FINESSE (1983-87), **evolved** in IEA study (1994-96), and **improved** in FNST community efforts the past several years.
- **Involved fusion scientists, engineers (blanket, PFC, PMI, Materials, Tritium, Safety), and plasma physicists .**
- **STRONG participation of experts in Technology development from Aerospace and Fission industries.**
- **Very strong international participation.**
- **Over 200 man-year of efforts domestically and internationally.**
- **Developed processes for "Experiment Planning" based on ROLLBACK Approach and utilized experience from other technologies.**
- **A study (2005-2007) to develop a technical plan and cost estimate for US ITER TBM provided 1-understanding of the detailed R&D requirements (specific tasks, cost, and time) and 2- insights into the practical and complex aspects of preparing to place a test module and conduct experiments in the fusion nuclear environment.**
- **Technical Reports and Journal Publications on website: www.fusion.ucla.edu**

FNST Studies Developed a PROCESS for Technical Planning Using Rollback from Power Plants/DEMO and Analogy to Other Technologies

NUCLEAR FUSION, Vol.27, No.4 (1987)



- **Considered issues before experiments and experiments before facilities**
- **The idea of FNSF emerged from the last step of "Develop Test Plan"**

How To Select "Promising Designs for Technical Planning"?

- **FNST studies utilized vision of reactors for major parameters (wall load, plasma operating mode, etc.) and overall configuration features.**
- **FNST studies concluded it could not just use designs of nuclear components from reactor studies (because point designs make one specific choice to explore it).**
- **FNST studies selected and developed designs best suited for R&D strategy.**
  - **e.g. Blanket comparison and selection study (BCSS) selected two classes of concepts: Liquid Breeders and Solid Breeders as the basis for R&D planning. (Reason: both classes have feasibility issues, can not select before testing in the fusion environment)**
  - **e.g. unrealistic assumption: tritium fractional burnup in the plasma.**

Engineering Scaling for Experiments Must Be Based on Power Plant Parameters (not on DEMO)

- **Engineering scaling is the process to develop meaningful tests at experimental conditions and parameters less than those in a reactor.**
- **DEMO fusion power is smaller than in power plants because of cost considerations. Therefore, wall load in DEMO is lower than in power plant.**
- **e.g. Power Reactors: 3-4 MW/m^2 DEMO: 2-2.3 FNSF: 1-1.5**

Experiments in FNSF must be designed to show nuclear components can extrapolate to power reactor. Hence engineering scaling in FNSF should be based on 3-4 MW/m^2

FNST studies over the past 25 years used **rollback** approach to quantify FNST Needs and Requirements.
It was very useful. It provided foundation for defining a pathway.
For example: 1- it identified specific needs for modeling and experiments in non-fusion facilities, and 2- identified the need for FNSF and quantified its required features and operating parameters.

In the last 3 years, the FNST community started also using a **roll-forward** approach in partnership with the broader community and facility designers to explore FNSF options and the issues associated with the facility itself

We are learning from the roll-forward approach critical information on How to Move Forward:

- The most practical problems we must face today include:
  -- Vacuum Vessel location & design, and failures and maintenance (MTBF/MTTR) of in-vessel components (PFC and Blanket)
  -- Geometry and level of flexibility in FNSF device configuration
- Exact details of the DEMO are much 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.

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**

Example of FNST challenge in the "core"

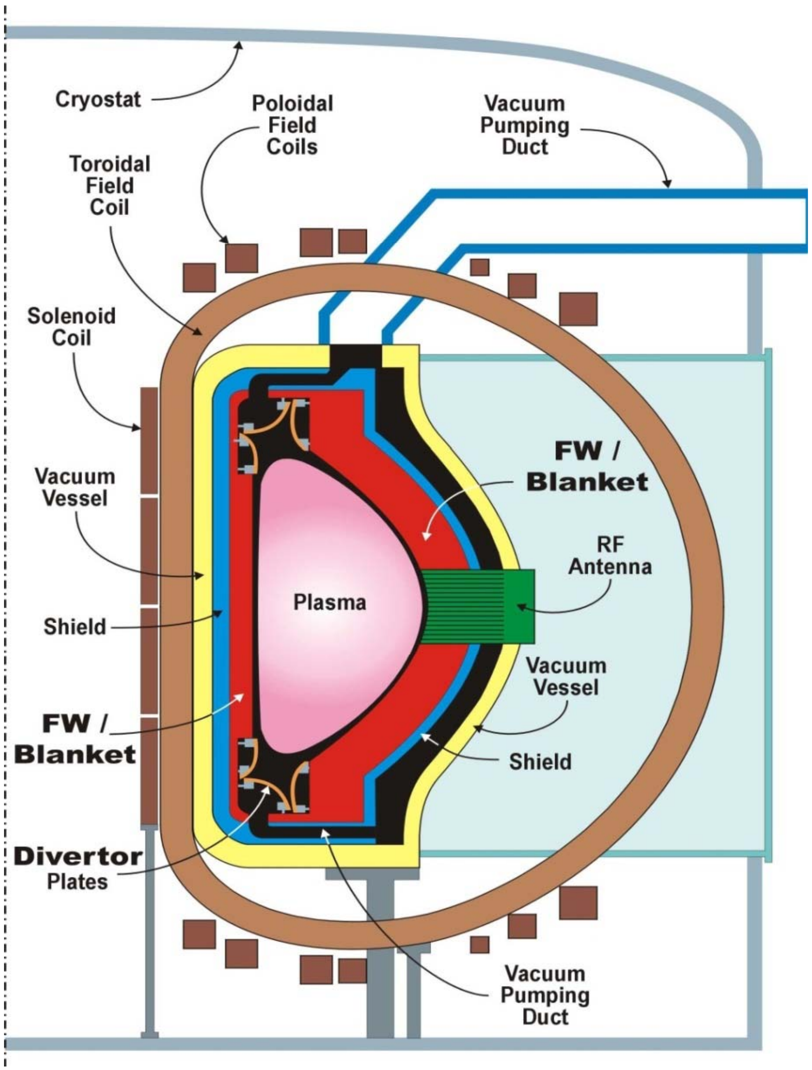
The location of the Blanket / Divertor inside the vacuum vessel is necessary but has major consequences:

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!!



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 simple modeling and experiments
- **Stage I : Scientific Feasibility**
  - 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**
  - 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
- **Stage III: Engineering Development**
  - 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

Where are we today (FNST)?

- **Still in a state of "exploratory R&D" with mostly single-effect and non-prototypic materials and fluids**

When can we demonstrate the scientific feasibility of FNST?

- Only when we perform experiments in the fusion nuclear environment (FNSF will be the earliest facility to provide such environment)

Conclusion established in prior studies:

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

R&D in non-fusion facilities is ESSENTIAL prior to testing in fusion facilities.

Demonstrating the scientific feasibility of tritium self-sufficiency in D-T fusion requires:

- Tritium breeding experiments in "full breeding sector", or full breeding blanket (because uncertainties in extrapolating measurements in the poloidal direction is larger than available margin).
- A large set of other conditions (T fractional burn up in plasma, efficient tritium extraction, fast tritium processing, practical blanket system) must be achieved.

ITER will NOT demonstrate Scientific Feasibility of fusion (only of plasma).

ONLY ITER PLUS FNSF can demonstrate Scientific Feasibility.

Engineering feasibility and engineering development stages will follow the demonstration of scientific feasibility – long way to DEMO.

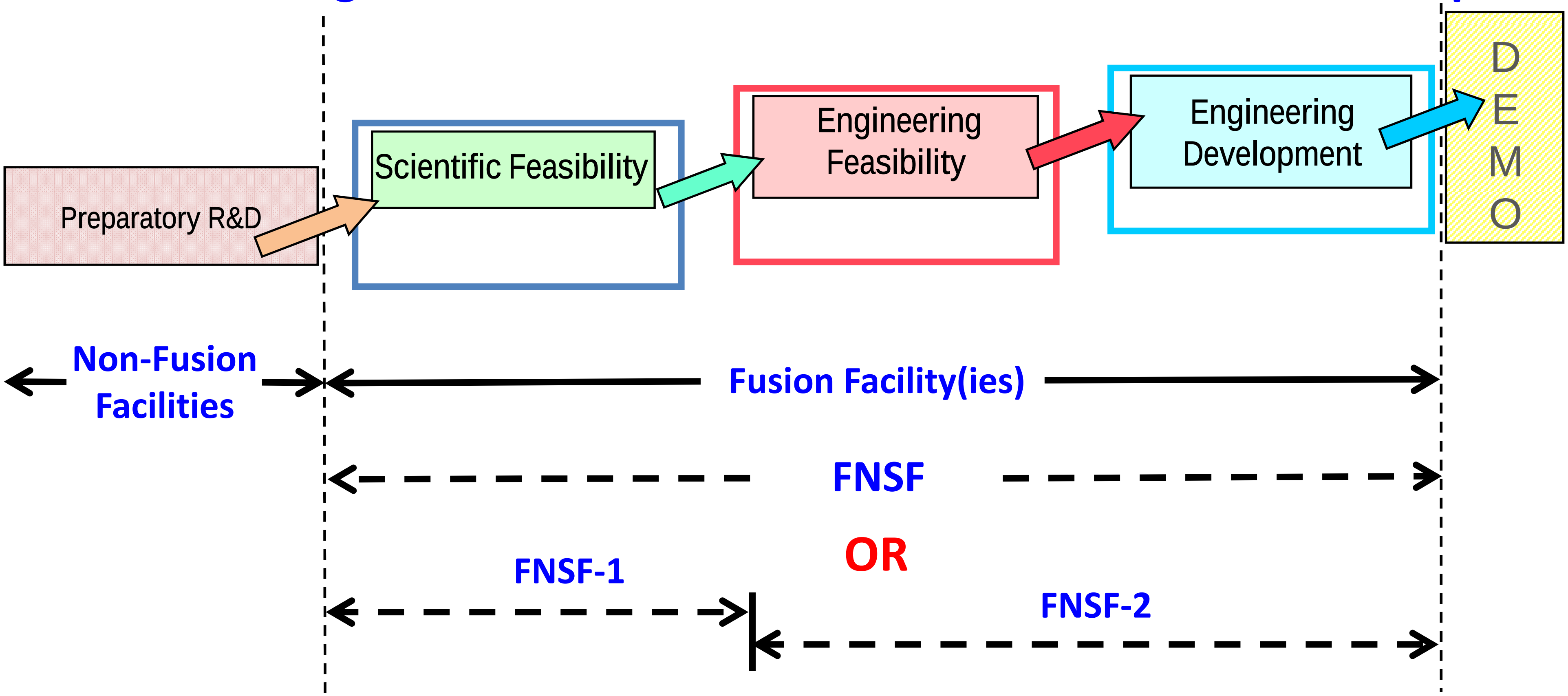
The most important steps we must do now are :

1. Substantially expand exploratory R&D of FNST:

- Enhance modeling activities (fundamental and integrated modeling of important phenomena and multiple/synergetic effects).
- Upgrade existing and build new and substantial laboratory-scale facilities to explore **multiple and synergistic effects using prototypic materials and fluids.**

2. We also must begin exploring design options and engineering challenges for FNSF and develop strategy for FNST experiments on FNSF

Science-Based Pathway to DEMO Must Account for Unexpected FNST Challenges in Current FNST and Plasma Confinement Concepts



- 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)

Fusion Nuclear Environment is complex & unique

Neutrons *(fluence, 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 dependent) –it needs DT fusion facility
The full fusion Nuclear Environment can be simulated only in DT plasma –based facility

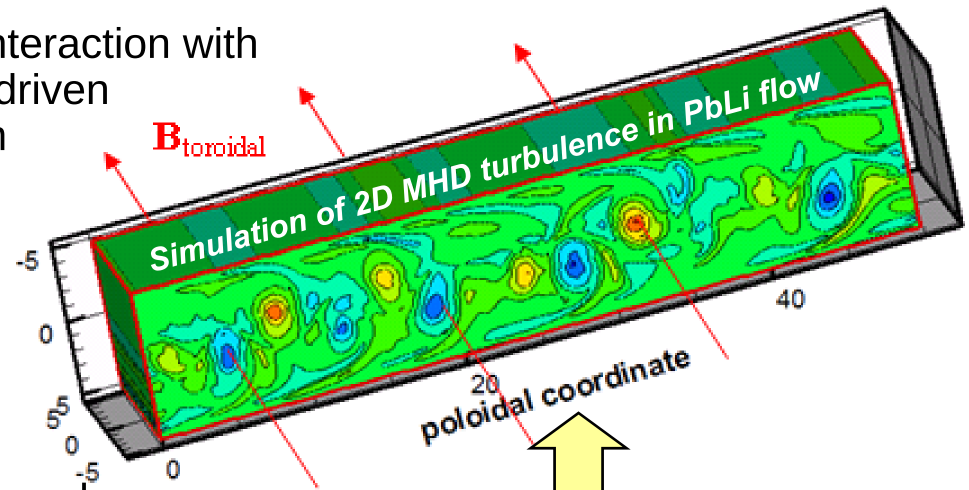
Example: Interaction between MHD flow and FCI behavior are highly coupled and require fusion environment

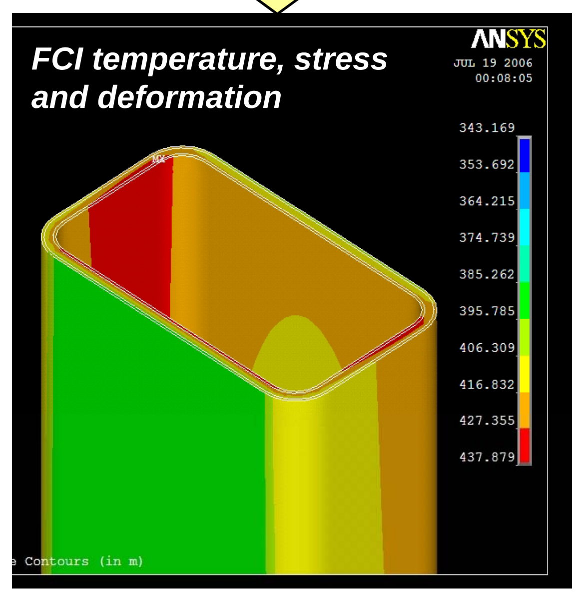
- PbLi flow is strongly influenced by **MHD** interaction with plasma confinement field and **buoyancy**-driven convection driven by spatially non-uniform volumetric **nuclear heating**

- **Temperature** and thermal **stress** of SiC FCI are determined by this MHD flow and convective heat transport processes

- **Deformation** and **cracking** of the FCI depend on FCI temperature and thermal stress coupled with early-life radiation damage effects in ceramics

- Cracking and movement of the FCIs will strongly influence **MHD** flow behavior by opening up new conduction paths that **change** electric **current** profiles





Similarly, coupled phenomena in tritium permeation, corrosion, ceramic breeder thermomechanics, and many other blanket and material behaviors

Lessons learned: The most challenging problems in FNST are at the *INTERFACES*

- Examples:
  - **Corrosion** / Mass Transport
    (liquid/structure interface temperature limit)
  - **Tritium permeation**
  - **MHD insulators**
  - **Thermal insulators**

- **This is where we had disappointments and our progress has been severely limited. The underlying physics is not well understood, hindering further progress towards higher performance blanket.**
- **Our research needs more capable experimental facilities and multi-physics, multi-dimension modelling to address "interfaces" (e.g. liquid-solid) and understand multiple effects.**

Top-Level Technical Issues for FNST (set 1 of 2)

(Details of these issues published in many papers, Last update: December 2009)

Tritium

1. **"Phase Space" of practical plasma, nuclear, material, and technological conditions in which tritium self sufficiency can be achieved**
2. **Tritium extraction, inventory, and control in solid/liquid breeders and blanket, PFC, fuel injection and processing, and heat extraction systems**

Fluid-Material Interactions

3. **MHD Thermofluid phenomena and impact on transport processes in electrically-conducting liquid coolants/breeders**
4. **Interfacial phenomena, chemistry, compatibility, surface erosion and corrosion**

Materials Interactions and Response

5. **Structural materials performance and mechanical integrity under the effect of radiation and thermo-mechanical loadings in blanket/PFC**
6. **Functional materials property changes and performance under irradiation and high temperature and stress gradients** (including HHF armor, ceramic breeders, beryllium multipliers, flow channel inserts, electric and thermal insulators, tritium permeation and corrosion barriers, etc.)
7. **Fabrication and joining of structural and functional materials**

Top-Level Technical Issues for FNST (set 2 of 2)

Plasma-Material Interactions

8. **Plasma-surface interactions, recycling, erosion/redeposition, vacuum pumping**
9. **Bulk interactions between plasma operation and blanket and PFC systems, electromagnetic coupling, and off-normal events**

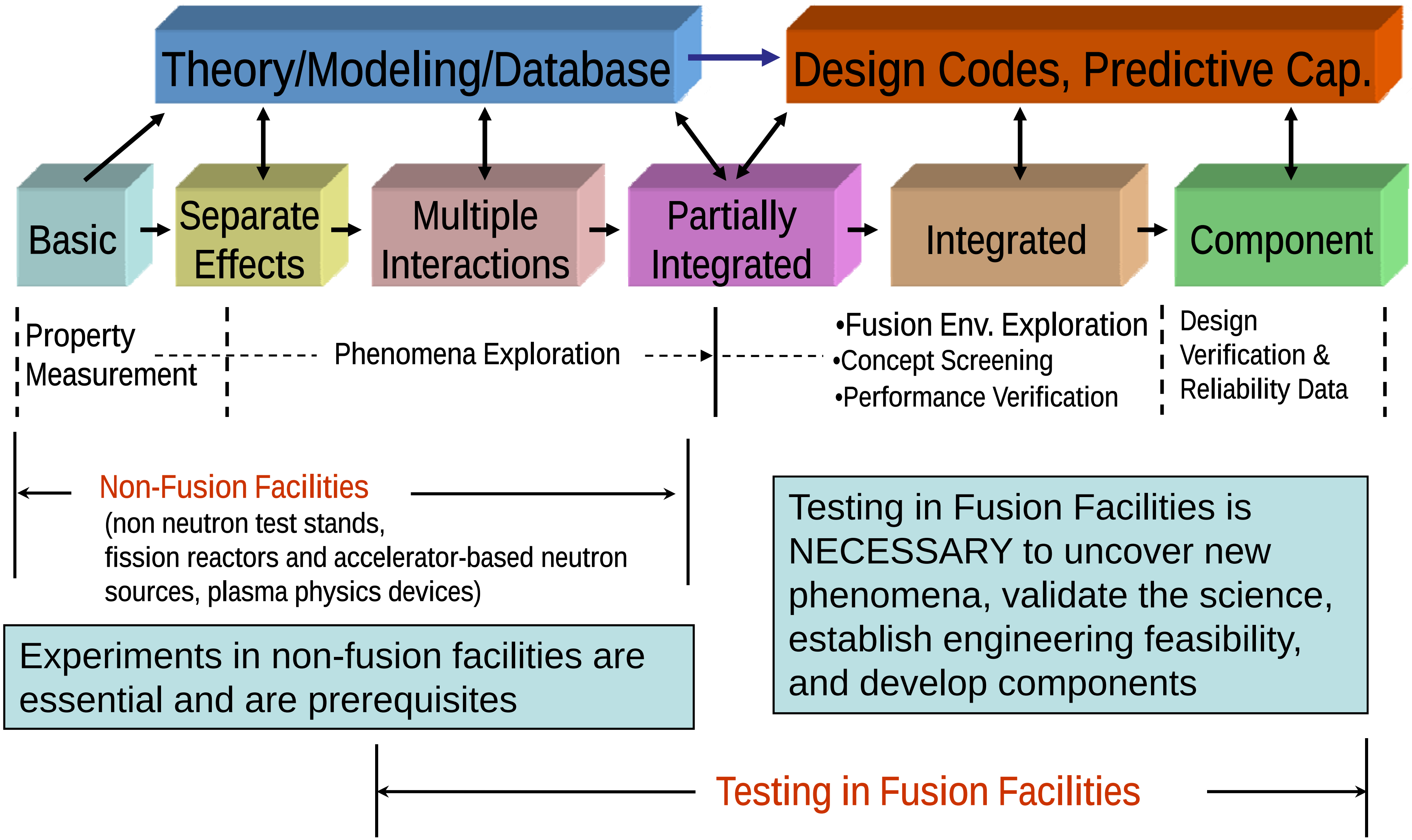
Reliability, Availability, Maintainability (RAMI)

10. **Failure modes, effects, and rates in blankets and PFC's in the integrated fusion environment**
11. **System configuration and remote maintenance with acceptable machine down time**

All issues are strongly interconnected:

- **they span requirements**
- **they span components**
- **they span many technical disciplines of science & engineering**

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



FNST Studies Detailed the Types of Experiments in Non-Fusion Facilities

Example of Figures from NUCLEAR FUSION, Vol.27, No.4 (1987)

Solid Breeders

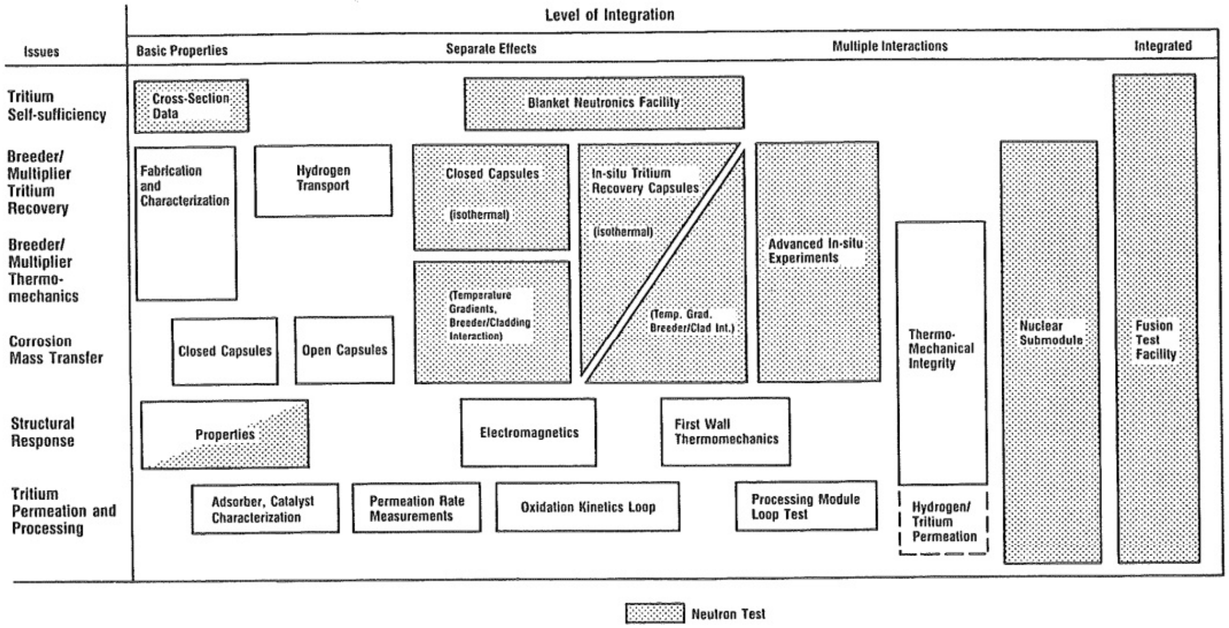


FIG. 5. Types of experiments and facilities for solid breeder blankets (some experiments and/or facilities already exist).

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Liquid Breeders

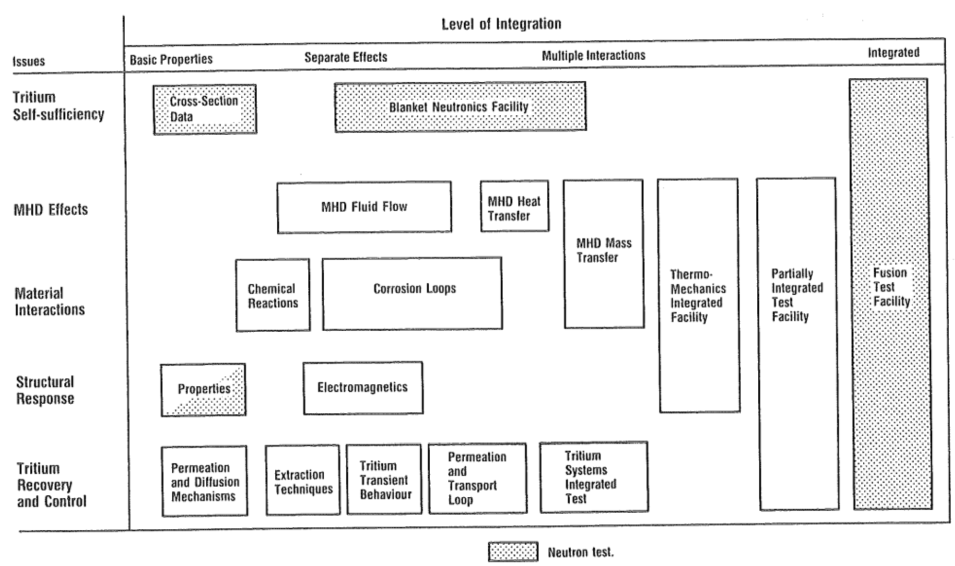


FIG. 8. Types of experiments and facilities for liquid breeder blankets (some experiments and/or facilities already exist).

FNST Studies Defined in Detail
the Types of Experiments in Non-Fusion Facilities (continued)

Example of Figures from NUCLEAR FUSION, Vol.27, No.4 (1987)

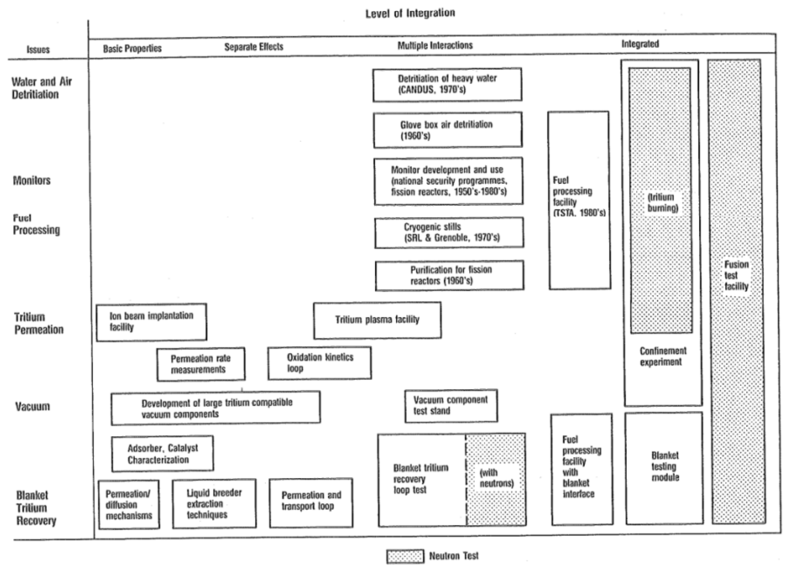


FIG. 15. Types of experiments and facilities for tritium processing and vacuum systems (some experiments and/or facilities already exist).

Tritium Processing

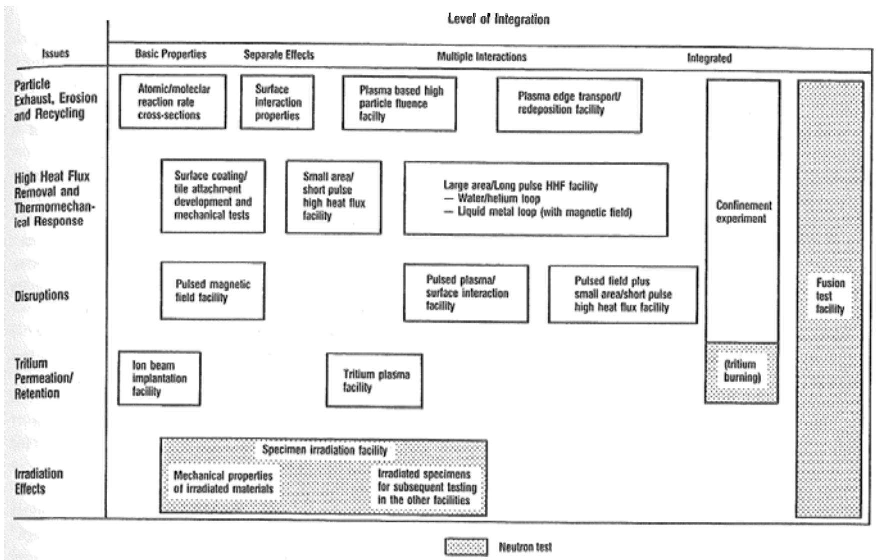


FIG. 16. Types of experiments and facilities for plasma interactive components (some experiments and/or facilities already exist).

PFC

FNST Studies also Defined in Detail the Test Sequence for major R & D Tasks in Non-Fusion Facilities

Example of Figures from NUCLEAR FUSION, Vol.27, No.4 (1987)

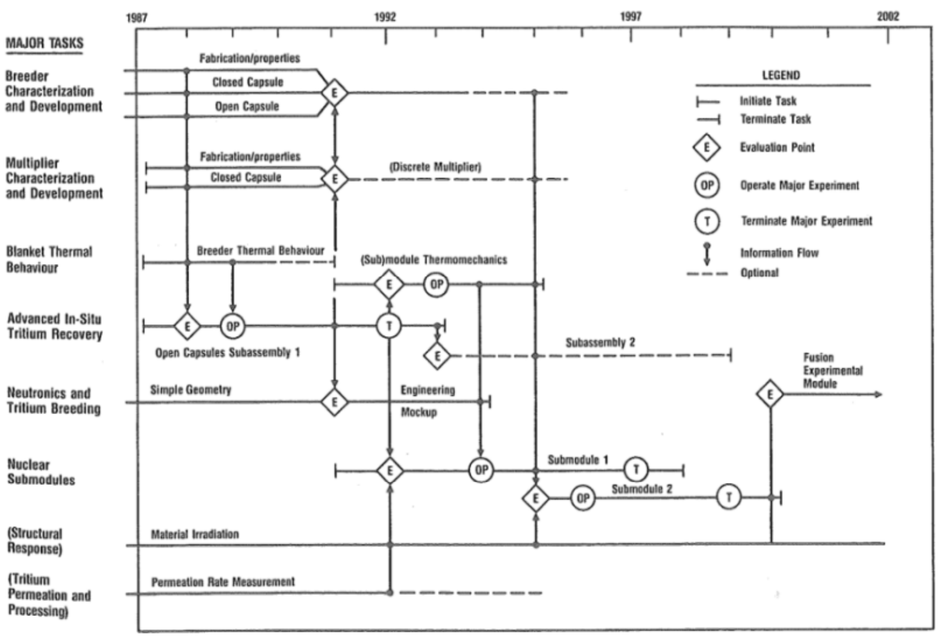


FIG. 7. Test sequence for major solid breeder blanket tasks.

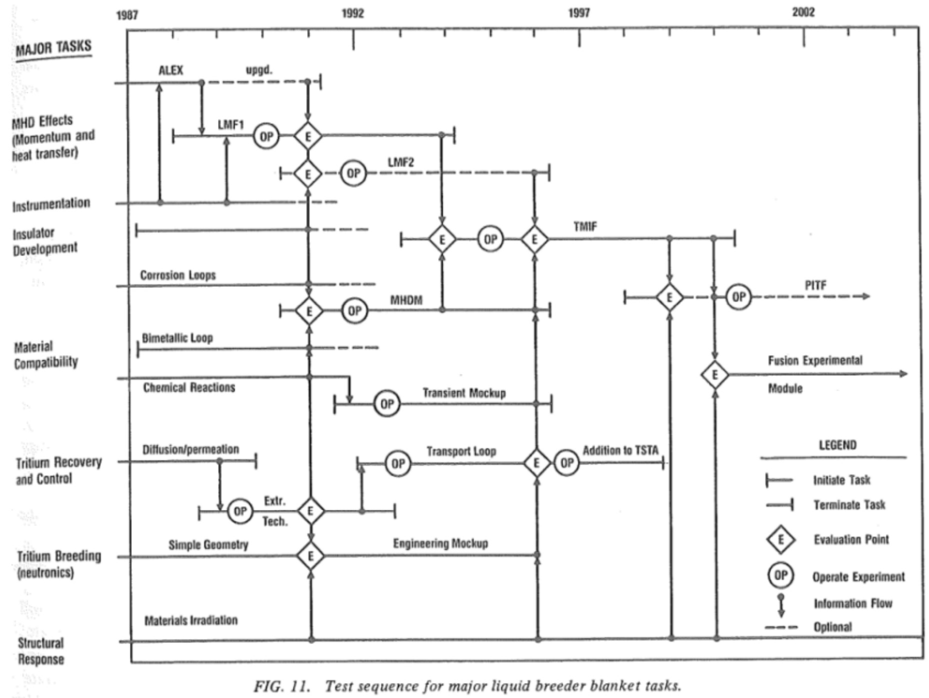


FIG. 11. Test sequence for major liquid breeder blanket tasks.

Solid Breeders

Liquid Breeders

The FNST community updated these plans in 2001.
The changes were modest.
The time line had to be shifted by ~ 20 years.

FNST Studies Science-Based FNST Pathway 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	**0.1 - 0.3 MW-y/m²**	**1 - 3 MW-y/m²**	**> 4 - 6 MW-y/m²**
Wall load / operation	**≥ 0.5 MW/m² 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**
Test articles	Sub-Modules/Modules	Modules (10-20m²)	Modules/Sectors (20-30m²)
Goals	• Establish scientific feasibility of basic functions under prompt responses and under the impact of rapid property changes in early life	• Establish engineering feasibility of blankets/PFC/materials (satisfy basic functions & performance, up to 10 to 20% of MTBF and of lifetime)	• 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

- Details of requirements on wall load, energy fluence, plasma mode, etc. are derived based on engineering scaling and described in several papers
- Other important requirements, e.g. surface heat flux, **B** also defined
- The stages are **consecutive steps** in scientific/technological development, they can be carried out in **one or more facilities**
- Facility operation has to add other considerations, e.g. DD phase, availability

Why FNSF should be Low Fusion Power, Small Size, low Q

- The idea of FNSF emerged in the 1980's from considering the following question:
  - *Should we combine the plasma physics mission with the FNST mission in one facility or two separate facilities?*
- The answer in FINESSE was TWO SEPARATE facilities:

  One for plasma physics (ITER), and Another for FNST (FNSF)

Primary Reason

a. Plasma physics testing requires large fusion power (high Q/ignition) but short operating time.
b. FNST requires small fusion power but long operating time.
   - *Combining a and b results in extremely large tritium consumption (>300 kg) and high-cost , high-risk device.*

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 (including 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).

Challenges of FNST R&D that must also be confronted in FNSF

- **FNSF must breed its own tritium**
  - ITER exhausts world supply of tritium. FNSF needs to breed its own tritium. The FNSF Blanket will have to be constructed of the same material system we are trying to test (typical of the well known quandary of fusion)
- **RAMI is very complex**
  - A key element of FNST development is reliability growth and maintainability, which requires long testing time (many years), and is a key objective of the FNSF mission
  - FNSF as a test bed will be the **first opportunity** to get data and **learn** about MTBF, MTTR, and transition through "infant mortality" in the fusion nuclear environment
  - The availability of the FNSF device is by itself a challenge given that the machine must rely on components it is testing

These challenges must be clearly understood in planning R&D for FNST and for selecting a design and strategy for FNSF. Examples:

- Cost/Risk /Benefit analysis led to important conclusions (e.g.FNSF <150 MW)
- FNSF must be flexibly designed such that **all in-vessel components are considered experimental – Use "bootstrap" approach**

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

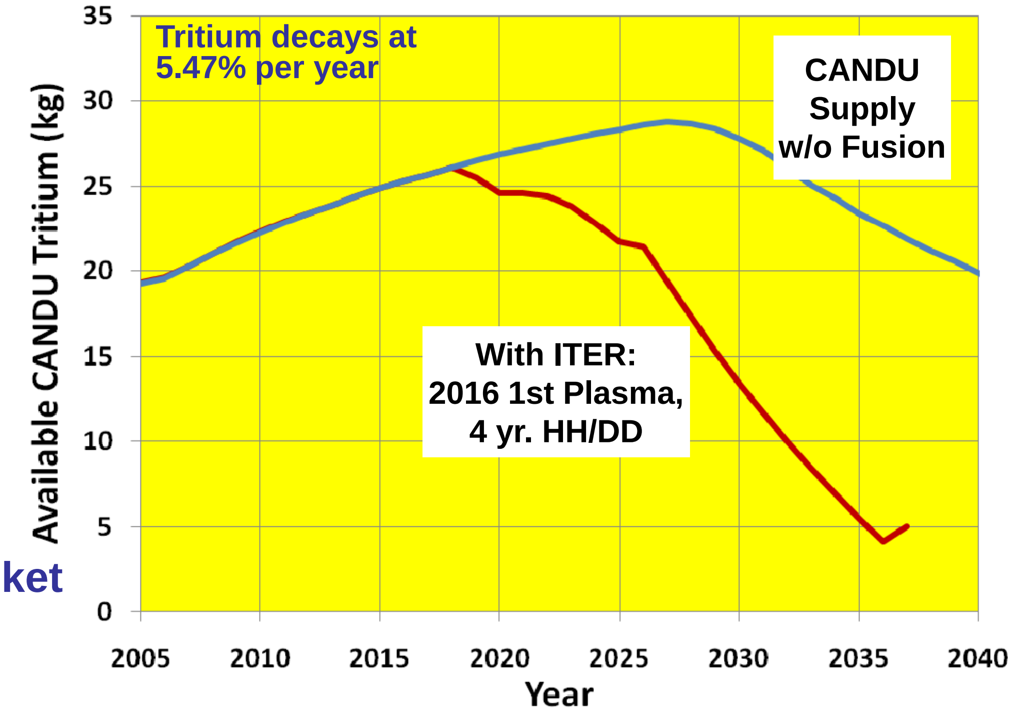
$84M-$130M/kg (per DOE Inspector General*)

*www.ig.energy.gov/documents/CalendarYear2003/ig-0632.pdf

CANDU Reactors: 27 kg from over 40 years, $30M/kg (current)

Tritium Decays at 5.47% per year

- **A Successful ITER will exhaust most of the world supply of tritium. Delays in ITER schedule makes it worse.**
- **No DT fusion devices with fusion power >50 MW, other than ITER, can be operated without a verified breeding blanket technology.**
- **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

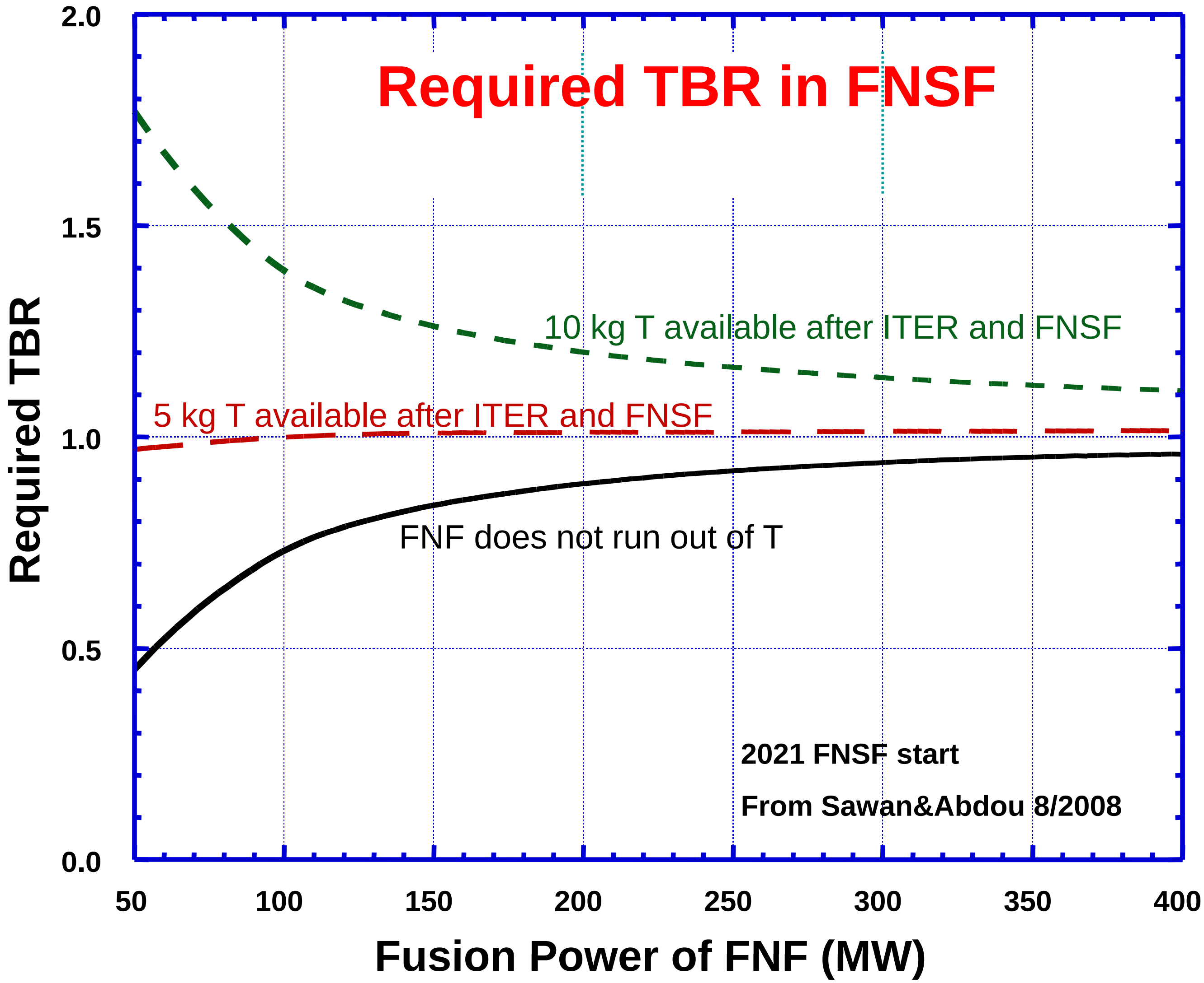
(How many DEMOS will the world build? And where will startup tritium come from?)

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

Base Breeding Blanket and Testing Strategy in FNSF (US Conclusions)

- **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. There is no non-breeding blanket for which there is more confidence than a breeding blanket.
  - Using base breeding blanket will provide the large area essential to "reliability growth". This makes full utilization of the "expensive" neutrons.

- **The two primary concepts for DEMO (DCLL and HCCB in US case) are recommended for both "testing ports" and "Base" Breeding Blanket**

- **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.**

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

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	16	5×10^{-6}	23	10^4	240	0.1	0.098	0.91
C[illegible]								
P[illegible]								
C[illegible]								
Magnet supplies	4	1×10^{-4}	1.14	72	10	0.1	0.007	0.99
Cryogenics	2	2×10^{-4}	0.57	300	24	0.1	0.022	0.978
Blanket	100	1×10^{-5}	**11.4**	800	100	0.05	**0.135**	0.881
Divertor	32	2×10^{-5}	**5.7**	500	200	0.1	**0.147**	0.871
Htg/CD	4	[illegible]						0.884
Fueling	1	[illegible]						0.998
Tritium System	1	[illegible]						0.995
Vacuum	3	[illegible]						0.998
Conventional equipment - [illegible]							[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

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

Structural Material for FNSF

- **Reduced activation Ferritic Steel (FS) is the only structural material option for DEMO. FS should be used in both base and testing breeding blankets on FNSF.**

- **FS irradiation data base from fission reactors extends to ~ 80 dpa, but it lacks He. There is confidence in He data up to 100 appm (~ 10 dpa).**

Structural Material Testing Strategy in FNSF

(from Abdou ,ISFNT-9, September 2009)

- **Strategy for developing structural material data base for design:**
  - Design initial breeding blanket for FNSF with FS for ~ 10 dpa.
  - Obtain real data on FS performance up to ~ 10 dpa in Stage I testing in FNSF.
  - Extrapolate by a factor of 2 (standard in fission and other development) to design next stage blanket in FNSF for 20 dpa.
  - Extrapolate using 20 dpa FNSF data to build Stage III blanket to operate up to 40 dpa.
- **FNSF will provide key information on structural material in 3 ways:**
  - From base breeding blanket – large surface area providing data on property changes, behavior, failure modes, effects and rates in materials, joints, and material interfaces.
  - From “test port-based” modules where the performance is pushed toward higher and lower limits (e.g. temperature) and more complete instrumentation to allow comprehensive data on material behavior and better diagnosis of what happened
  - Thousands of specimens at different operating conditions (e.g., temperatures) in a specifically designed “material test module”.
- **Note results of testing structural materials in FNSF are conclusive.**
  - “Real” fusion environment – no uncertainty of spectrum or other environmental effects.
  - Testing of components with prototypical gradients, materials interactions, joints, and other fusion environmental conditions.

(This is a simplified version of prior slide)

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

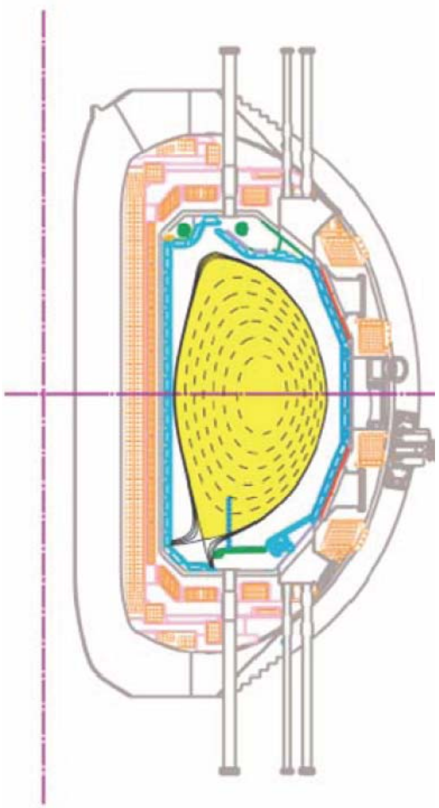
Day 1 Design

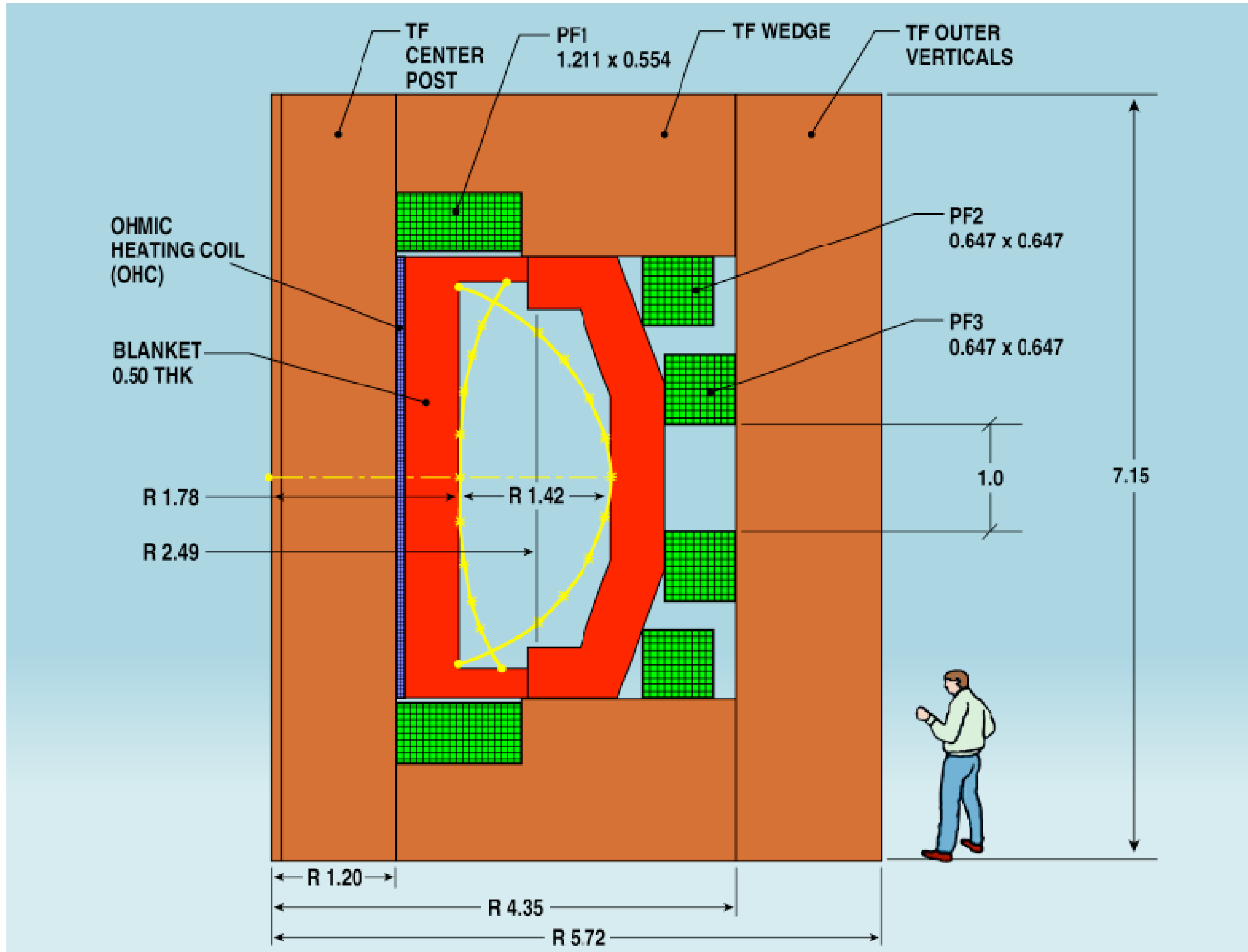
- Vacuum vessel – low dose environment, proven materials and technology
- **Inside the VV** – **all is "experimental."** Understanding failure modes, rates, effects and component maintainability is a crucial FNSF mission.
- Structural material - reduced activation ferritic steel for in-vessel components
- 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, …

Example of Fusion Nuclear Science Facility (FNSF) Design Option: Standard Aspect Ratio (A=3.5) with demountable TF coils (GA design)





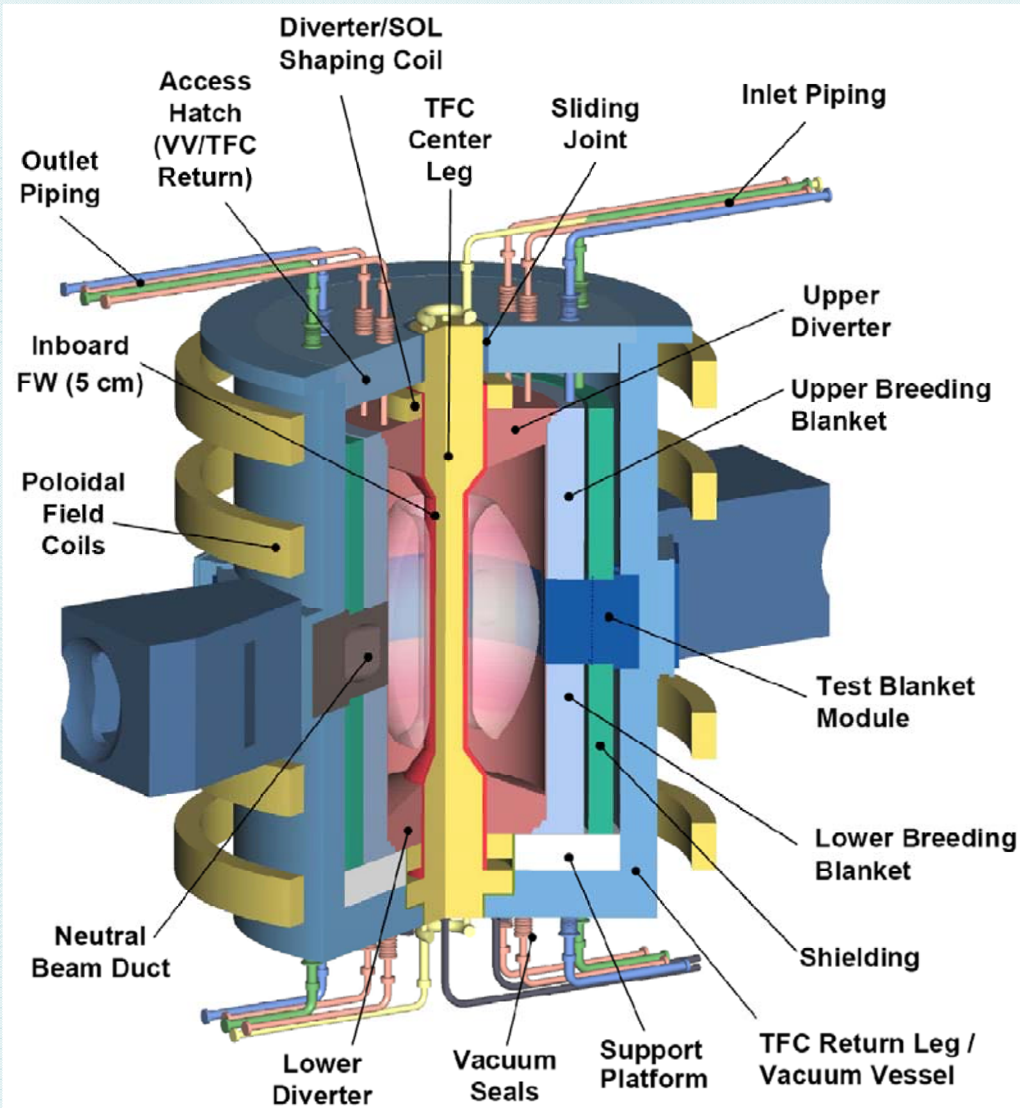
- High elongation, high triangularity double null plasma shape for high gain, steady-state plasma operation

Challenges for Material/Magnet Researchers:

- **Development of practical "demountable" joint in Normal Cu Magnets**
- **Development of inorganic insulators (to reduce inboard shield and size of device)**

Another Option for FNSF Design: Small Aspect Ratio (ST)
Smallest power and size, Cu TF magnet, Center Post

(Example from Peng et al, ORNL) R=1.2m, A=1.5, Kappa=3, Pfusion=75MW



W_L [MW/m^2]	0.1	1.0	2.0
R0 [m]	1.20		
A	1.50		
Kappa	3.07		
Qcyl	**4.6**	3.7	**3.0**
Bt [T]	**1.13**	2.18	
Ip [MA]	**3.4**	8.2	**10.1**
Beta_N	3.8		**5.9**
Beta_T	**0.14**	0.18	**0.28**
n_e [10^{20}/m^3]	**0.43**	1.05	**1.28**
f_{BS}	**0.58**	0.49	**0.50**
T_{avgi} [keV]	**5.4**	10.3	**13.3**
T_{avge} [keV]	**3.1**	6.8	**8.1**
HH98	1.5		
Q	**0.50**	2.5	**3.5**
P_{aux-CD} [MW]	**15**	31	**43**
E_{NB} [keV]	**100**	239	**294**
P_{Fusion} [MW]	**7.5**	75	**150**
T M height [m]	1.64		
T M area [m^2]	14		
Blanket A [m^2]	66		
$F_{n-capture}$	0.76		

Next Step Fusion Nuclear Science Facility (FNSF) and Pathway to DEMO

Outline

1. Introduction

DEMO Definition, Scope of FNST, Need for FNSF

2. Technical Planning and Development Pathways: Prior Studies

What was done, what we learned , and references

3. FNST Development Strategy and Pathway to DEMO

Science Based Framework
Modeling and Experiments in Laboratory facilities
Requirements on fusion nuclear facility (FNSF) to perform FNST experiments
Challenges in Design of FNSF
Technical strategy for experiments in FNSF
Examples of FNSF Designs

3. **R&D Needs for FNST** **(Blanket, Tritium, PFC, Materials, Safety)**

Modeling and Experiments in Laboratory facilities

4. R&D Needs for Plasma Heating, Current Drive, Fueling, Diagnostics

5. Summary

Concluding Remarks (1)

Need to invest in upgrading existing facilities and constructing new substantial non-fusion facilities that are better able to simulate multiple environment / multiple effects of the fusion environment.

- **Thermo-mechanical loads & response** of blanket and PFCs
- **Thermofluid phenomena and Liquid Metal MHD effects**
- **Fluid-Materials interactions / Interfacial Phenomena** e.g., corrosion /mass transport
- Materials Interactions in prototypic unit cells of the blanket (in laboratory & in fission reactors)

Need to Initiate **Theory and "Blanket Simulation" project**
parallel and eventually linked to "plasma simulation" project

Tritium self-sufficiency must be emphasized as top level fusion Goal

- **D-T fuel cycle** in a practical system (very complex topic)
- **Tritium generation, extraction & inventory,** actual operating conditions
- **Tritium implantation, permeation & control** in blanket and PFCs

FNST has many examples of science-based issues as well as engineering challenges

Concluding Remarks (2)

- **Need to start exploring designs, investigating engineering challenges, and planning for early construction of FNSF.**

  Each major world fusion program must build its own FNSF prior to DEMO

-Resources allocated to FNST in the World Programs must be substantially increased soon. In particular, Need Substantial expansion of Blanket Program

Incremental Budget Increase of ~ a factor of 10 for areas related to Blanket R&D (e.g. Thermofluid MHD, Tritium Extraction and Control, Tritium Fuel Cycle Modeling, Thermomechanics, Materials Engineering, Safety). The ramp up should start now and the budget increment should be realized in the next 3 years.