Need for

Fusion Nuclear Science and Technology Program

- **Issues and Strategy for Fusion Nuclear Science Facility (FNSF)**
- **Key R&D Areas to begin NOW (modeling and experiments in non-fusion facilities)**

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Fusion Nuclear Science and Technology (FNST)

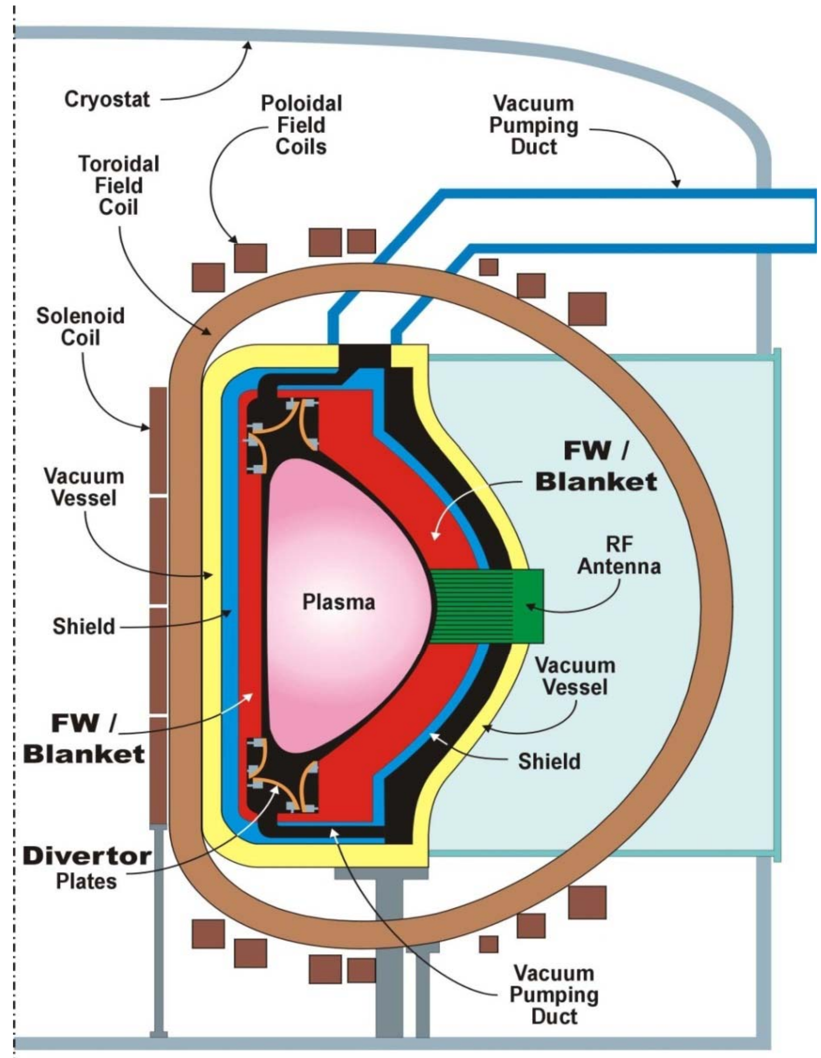
FNST is the **science**, **engineering**, **technology** and **materials**
for the fusion nuclear components that
generate, control and utilize neutrons, energetic particles & tritium.

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:

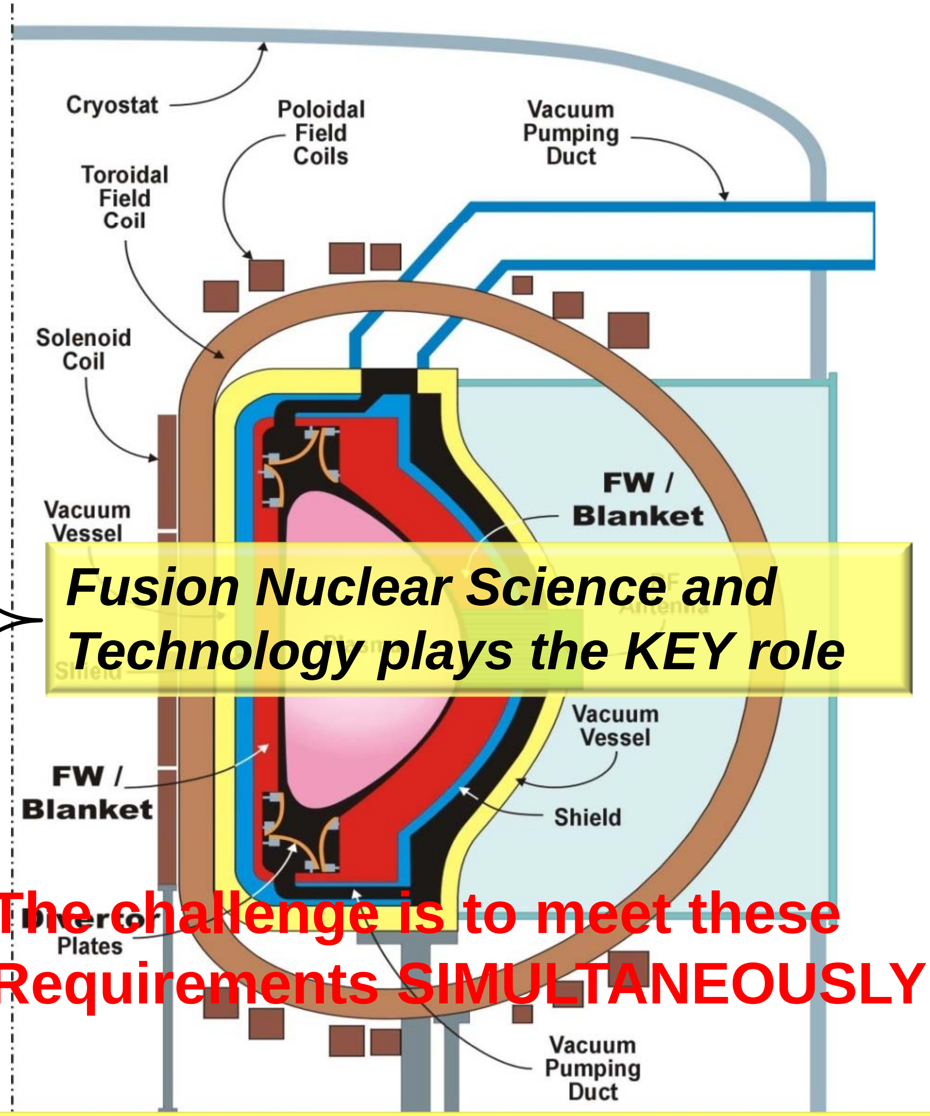
- Tritium Fuel Cycle
- Instrumentation & Control Systems
- Remote Maintenance Components
- Heat Transport & Power Conversion Systems



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

Requirements to realize fusion goal:

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

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.

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Example of FNST challenge in the "core"

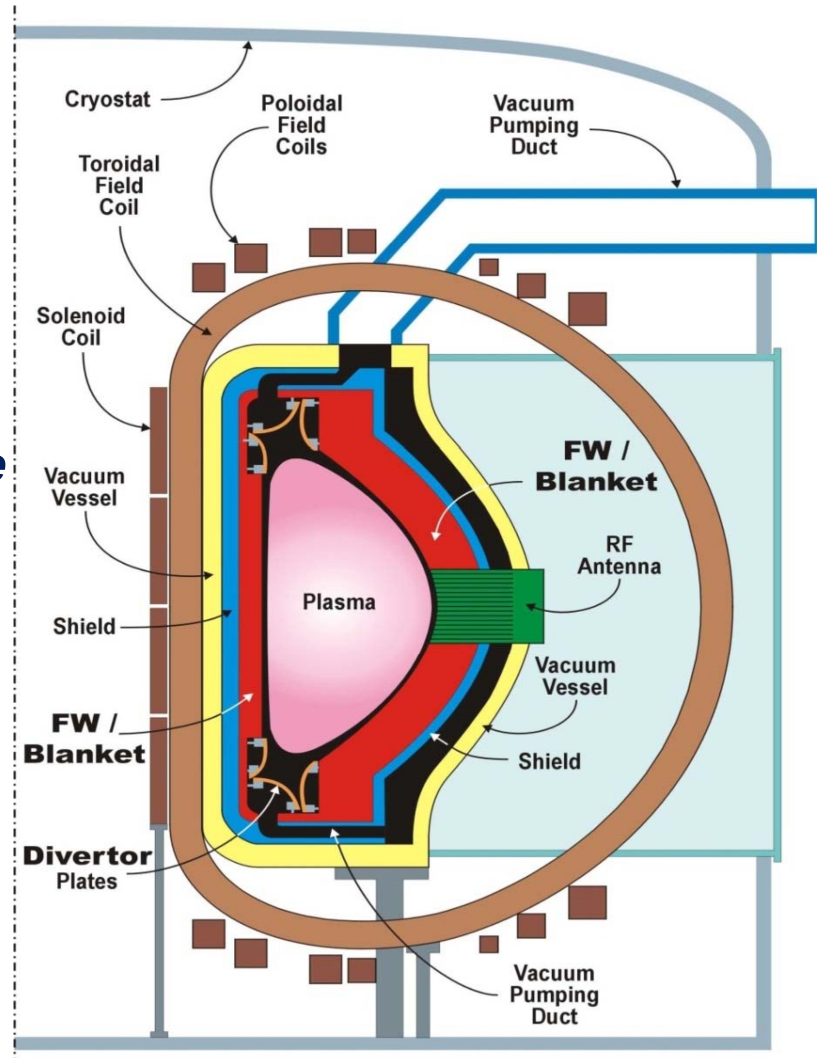
The location of the Blanket / Divertor inside the vacuum vessel is necessary but has major consequences:

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!!



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**

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, …

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 x10^{-6}	23	10^4	240	0.1	0.098	0.91
Magnet supplies	4	1 x10^{-4}	1.14	72	10	0.1	0.007	0.99
Cryogenics	2	2 x10^{-4}	0.57	300	24	0.1	0.022	0.978
Blanket	100	1 x10^{-5}	**11.4**	800	100	0.05	**0.135**	0.881
Divertor	32	2 x10^{-5}	**5.7**	500	200	0.1	**0.147**	0.871
Htg/CD	4							0.884
Fueling	1							0.998
Tritium System	1							0.995
Vacuum	3							0.998
Conventional equi…								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

Stages of Fusion R&D (see Fusion Technology article, Abdou et al)

- **Stage I : Scientific Feasibility**
  - Establish scientific feasibility of basic functions under prompt responses 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

Status of Fusion

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**

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

	Stage I	Stage II	Stage III
	Scientific Feasibility	Engineering Feasibility	Engineering Development
Fluence	**0.1 - 0.3 MW-y/m²**	**1 - 3 MW-y/m²**	**> 4 - 6 MW-y/m²**
Wall load / burn	**≥ 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 article	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**

- 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)

FNST R&D will set the Pace for Fusion Development

Example: Time required to do R&D for Reliability/Availability/Maintainability (RAMI) for FNST is very long – longer than any other research element.

Summary of RAMI issues

- Many major components, each needs high ***AVAILABILITY***
- Blanket/ PFC seem to have **short MTBF** (inside vacuum ,harsh environment) and **long MTTR** (inside the vacuum in complex confinement configuration)
- **Using Standard "Reliability Growth" Methodology, it is predicted that the required cumulative "energy fluence" in the fusion environment (e.g., FNSF) is ~ 6 MW-y/m^2**

Development Phases	Duration	Notes
Testing in non-fusion facilities	~ 10 years	Essential prior to testing in the fusion env.
Design, Construction & H/DD Phase of FNSF	~ 10 years	Can partly overlap with R&D in non-fusion facilities
Testing in DT Phases of FNSF	**15-40 years Uncertain**	Depends on what results we find and on FNSF availability & performance **Determined by Laws of Nature**
Solve problems encountered	??	Major flaws in blankets, PFC, etc.

An aggressive FNST program must start now to improve the time scale outlook for fusion energy development – "towards fusion's credibility".

Concluding Remarks

- **FNSF is a Required and Exciting Step in Fusion Development**
  - (Building FNSF in the US, parallel to ITER, is a most important element in restoring US leadership in the world fusion program.)
- **We have already learned from "roll back" studies over the past 25 years. Now, we need to start "roll forward" process to confront challenges in moving forward with FNST toward improving fusion credibility, and to identify the best option for FNSF**
  - Address practical issues of building FNSF "in-vessel" components of the same materials and technologies that are to be tested.
  - Evaluate issues of facility configuration, maintenance, failure modes and rates, physics readiness (Quasi-steady state? Q ~ 2-3?). These issues are critical - some are generic while others vary with proposed FNSF facility.
- **Must Greatly Enhance Base FNST R&D program NOW**

Details and Priorities of needs are available (will discuss Dec 3rd). Such fundamental R&D does not depend on details of vision for DEMO or pathway. Results from this R&D will help us improve the vision and pathway.

- Fundamental and integrated modeling of important phenomena and multiple synergistic effects.
- Experiments in new and existing non-fusion facilities
- TBM in ITER accompanied by both research and development programs. (FNSF needs the same R&D identified for TBM and much more.)