Next Steps for Realizing Fusion Power and Comparative Analysis of Roadmaps of World Major Fusion Programs

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Related publications can be found at www.fusion.ucla.edu

TOFE 2012
ANS 20th Topical Meeting on the Technology of Fusion Energy
Nashville, TN
29 August 2012

Renewed Interest in "Roadmapping"

- There were many plans for commercialization of fusion power by the major world fusion programs in the 1970's and 1980's. Such planning activities declined in the 1990's and 2000's *(The world was too busy debating scientific and programmatic issues for ITER!!)*.

- With the beginning of the construction of ITER in 2009, there has been renewed strong interest worldwide in defining in detail the "roadmap" to realizing fusion power. Examples:
  - Series of studies in the US to define pathway to DEMO
  - EFDA in EU has developed a draft plan on missions to DEMO
  - China developed an ambitious plan requested by government
  - IAEA initiated a new series of "DEMO Programme" workshops (the first will be held at UCLA October 15-18, 2012)

- **This presentation will discuss the major technical elements in the roadmap to realizing fusion power and compare the key features in USA, EU, and China roadmaps.**

Outline

1. Recent Interest in Roadmapping

2. Commercialization and DEMO
   - What is DEMO
   - Major Systems of Power Plant
   - GAPS

3. Summary of FNST Major Issues and Facilities

4. Options for FNSF
   - Standard A, ST
   - Normal Cu vs. Superconducting TFC

5. Summary of Roadmaps: US, China, EU

6. Evaluation of Roadmaps
   - Comparison and Main Differences
   - Role and Why FNSF
   - Does IFMIF have a role?

7. What is Most Important to do NOW

Commercialization and DEMO

- Fusion programs have defined the successful construction and operation of a Fusion Demonstration Power Plant (DEMO) as the last step before commercialization of fusion.

  i.e. DEMO must provide energy producers with the confidence to invest in commercial fusion.

  * DEMO must satisfy all functions (tritium self sufficiency, power extraction, etc.) with reasonably high performance & high availability.

  * <u>DEMO also must be</u>:
    - Reliable
    - Safe and meets public acceptance
    - Affordable AND extrapolate to competitive cost of energy

"DEMO must operate reliably and safely on the power grid for a period of years so that Government, Industry, and the Public gain enough confidence to open the way to commercialization of fusion power."

R&D Tasks to be Accomplished Prior to Demo

1) Plasma

- Confinement/Burn
- Disruption Control
- Current Drive/Steady State
- Edge Control

2) Plasma Support Systems

- Superconducting Magnets
- Fueling
- Heating
- Diagnostics

3) Fusion Nuclear Science and Technology (FNST)

"In-vessel" Components

- **Divertor and nuclear aspects of heating/CD**
- **Blanket** and **Integral First Wall**
- **Vacuum Vessel** and **Shield**

The nuclear environment also:

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

4) Systems Integration

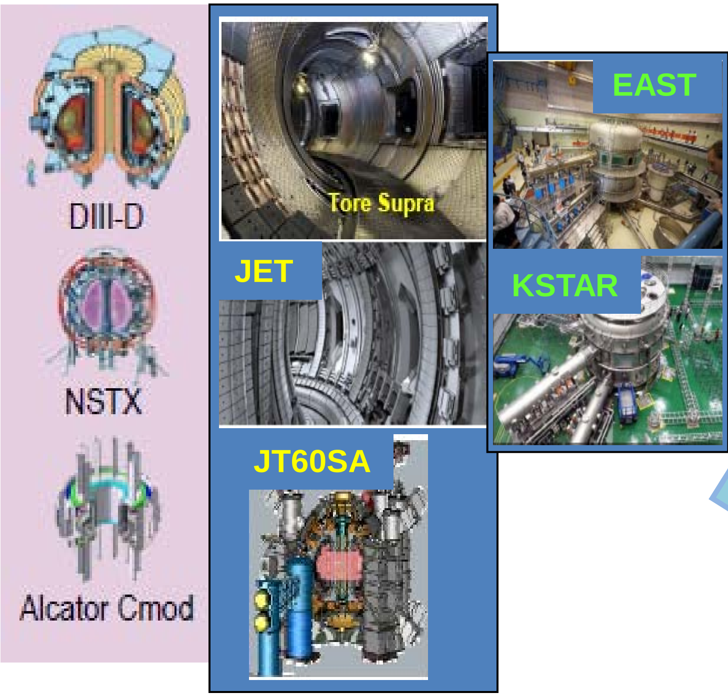
Where Will These Tasks be Done?!

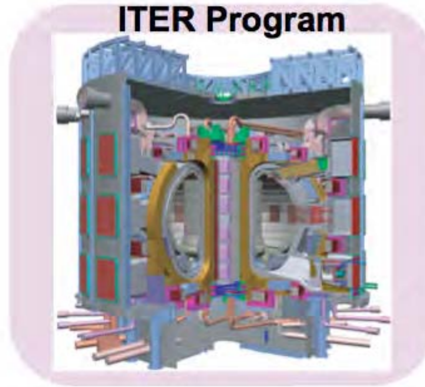
World programs agree:

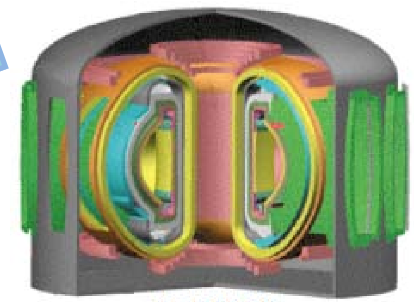
- Burning Plasma Facility (ITER) and other plasma devices will address 1, 2, & much of 4
- FNST is the major element missing
- How and Where will Fusion Nuclear Science and Technology (FNST) be developed?
  - Central question for roadmapping
  - Some key differences among world programs strategies

Old Roadmap: ITER is the Only Step to DEMO (Proved to be Not Credible)

Plasma Confinement Devices



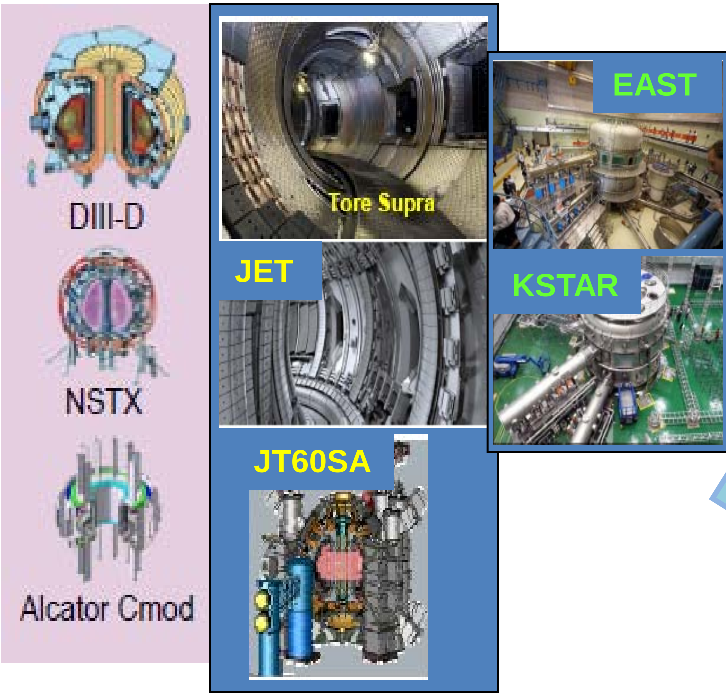




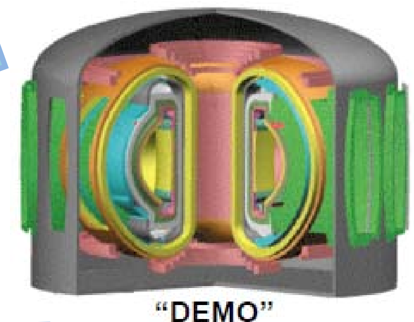
Present → **ITER timeframe 2020 - 2035** → **Construct Decision 2030-2035**

New More Credible Fusion Roadmap Includes Fusion Nuclear Science and Technology R&D with FNSF Parallel to ITER

Plasma Confinement Devices



FNST Fusion Facility
?



FNST R&D in Non-fusion Facilities

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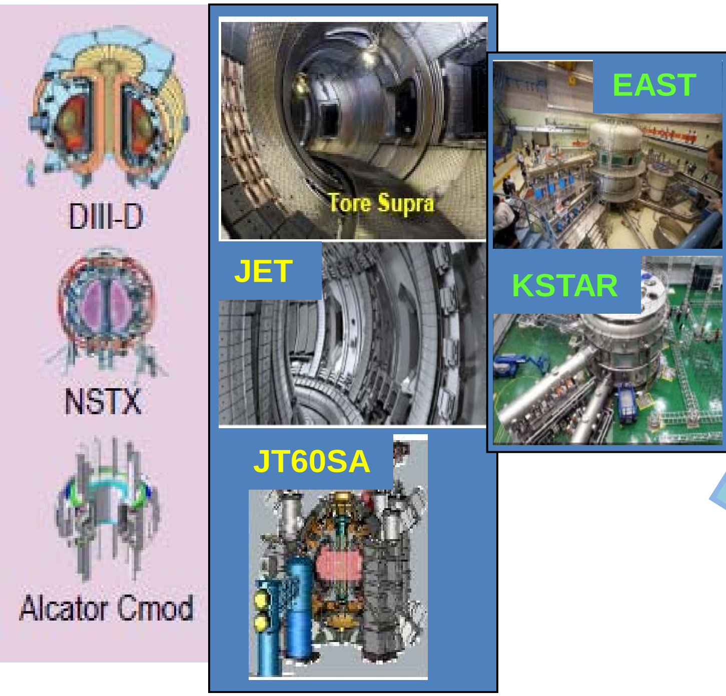
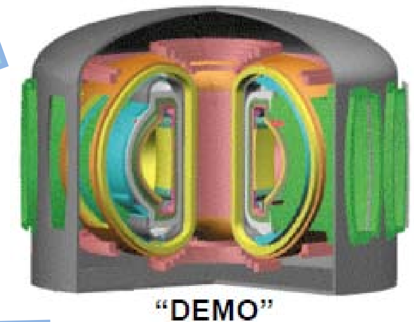
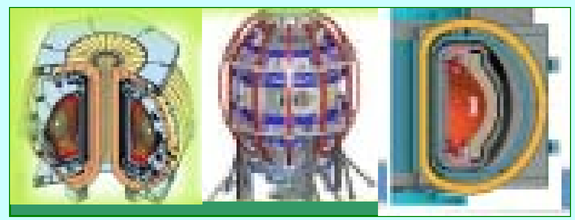




US: FNSF



AT ST Pilot

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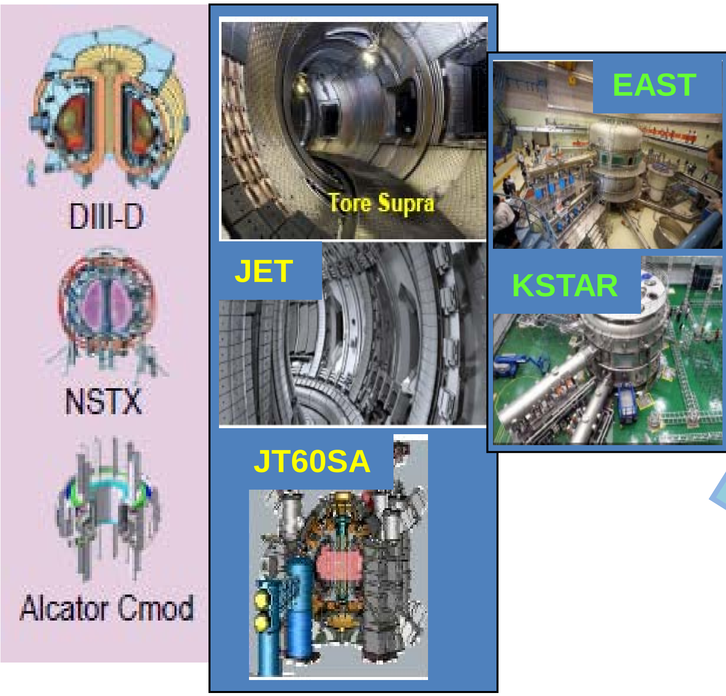
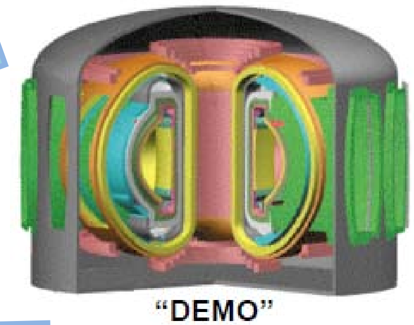


China: CFETR

(FNSF)

Device being defined



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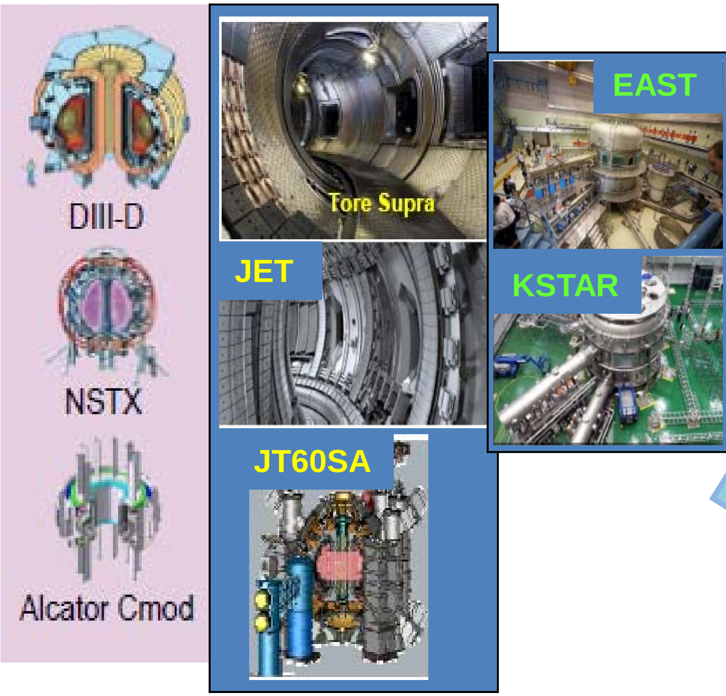

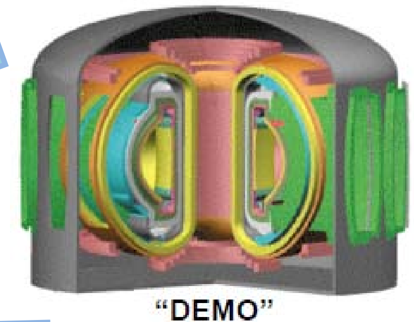

EU: No FNSF
Only Accelerator-Based Point Neutron Source, IFMIF

FNST R&D in Non-fusion Facilities

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Summary Comparison of US, China, EU Roadmaps for Fusion Nuclear Development

- US
  - Plan for Fusion Nuclear Science Facility (FNSF) to test and develop FNST
  - Three versions for design of FNSF
    - **Standard A (~3.5)**
      Fusion Power < 200 MW, R ~ 2.5 m, P_{nw} ~ 1-2 MW/m^2
      Normal conducting magnet
    - **Small Aspect Ratio (ST)**
      Fusion Power ~100 MW, R ~ 1.2 m, P_{nw} ~ 1-2 MW/m^2
      Normal conducting magnet
    - **Pilot Plant**
      FNSF mission, but with much more aggressive goals of plant life and emphasis on net electricity production, option for superconducting magnets
- China
  - Plan for FNSF type facility called CFETR
  - Different design options being considered
    - Fusion power ~ 50-200 MW, TBR > 1.2
    - Duty cycle (availability factor) ~ 0.3-0.5
- EU
  - No FNSF, relies only on ITER TBM for fusion nuclear component testing and development
  - Only an accelerator-based neutron source, IFMIF, with focus on testing thousands of mm-scale specimens to high dose, dpa

Key Questions Currently Being Discussed

1) What should be the major parameters and key design features of FNSF?

2) What are the key problems to be expected in construction and operation of FNSF?

3) How ambitious should we plan the mission of FNSF?
   Is *one* FNSF enough?

4) Is it credible to have "Material" development strategy separate from fusion nuclear component development? Can IFMIF replace FNSF?

- The answer to these questions were investigated in two comprehensive technical studies:
  - FINESSE in the 1980's (US-led study with international participation)
  - IEA HVPNS study in the 1990's (international study)

- They were further illuminated in US community FNST workshops in 2007-2009 and FNS study in 2010-2011.

What are the principal challenges in simulating the fusion nuclear environment?

- The Fusion Nuclear Environment: Multiple field environment (neutrons, heat/particle fluxes, B, etc.) with high magnitude and complex gradients.
- Nuclear heating in a large volume with complex gradients
  - *essential to simulate temperature and temperature gradients*
  - *drives most FNST phenomena*
  - *but simulation of this nuclear heating can be done only in DT-plasma based facility.*
- Complex configuration with FW/Blanket/Divertor inside the vacuum vessel. RAMI is a major driver for simulation, development, and roadmap.

The fusion nuclear environment can be meaningfully simulated only in a DT plasma-based device.

- It cannot be simulated in non-fusion facilities.
- It cannot be simulated in accelerator-based neutron source like IFMIF (wrong spectrum, wrong “gradients”, wrong “anisotropy”, volume too small to simulate subcomponents, etc.).

Fusion Nuclear Science Facility (FNSF) is required prior to DEMO – to “enable” FNST experiments and obtain fundamental data on fusion nuclear components

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 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!!

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Conventional equipment- instrumentation, cooling, turbines, electrical plant							0.05 [uncertain]	0.952
TOTAL SYSTEM	(Due to unscheduled maintenances)						0.624	0.615

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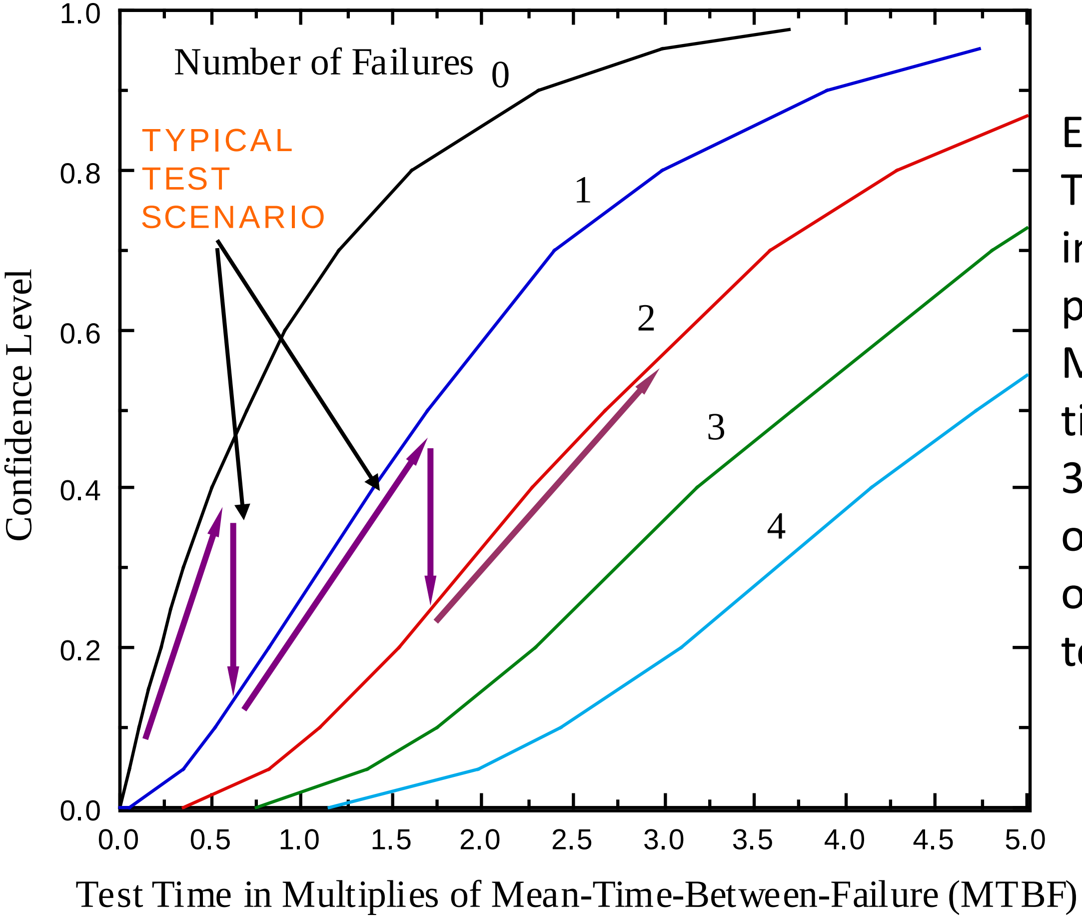
FNSF is required to 1) obtain data on failure modes, MTBF/MTTR, and 2) "reliability growth" testing

Quantify "Confidence" or "Risk" Level

In fusion development, we must start to quantitatively evaluate "confidence level" (or "risk level") for various options as part of planning.

Example: "Reliability Growth":

There are well established statistical methods to determine confidence level as function of test time (n x MTBF) and test results (e.g. number of failures).



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

Applying this methodology using 80% confidence level shows that blanket tests in ITER alone cannot demonstrate a blanket system availability in DEMO higher than 4%.

M. Abdou et. al., Fusion Technology, vol. 29 (January 1996)

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

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

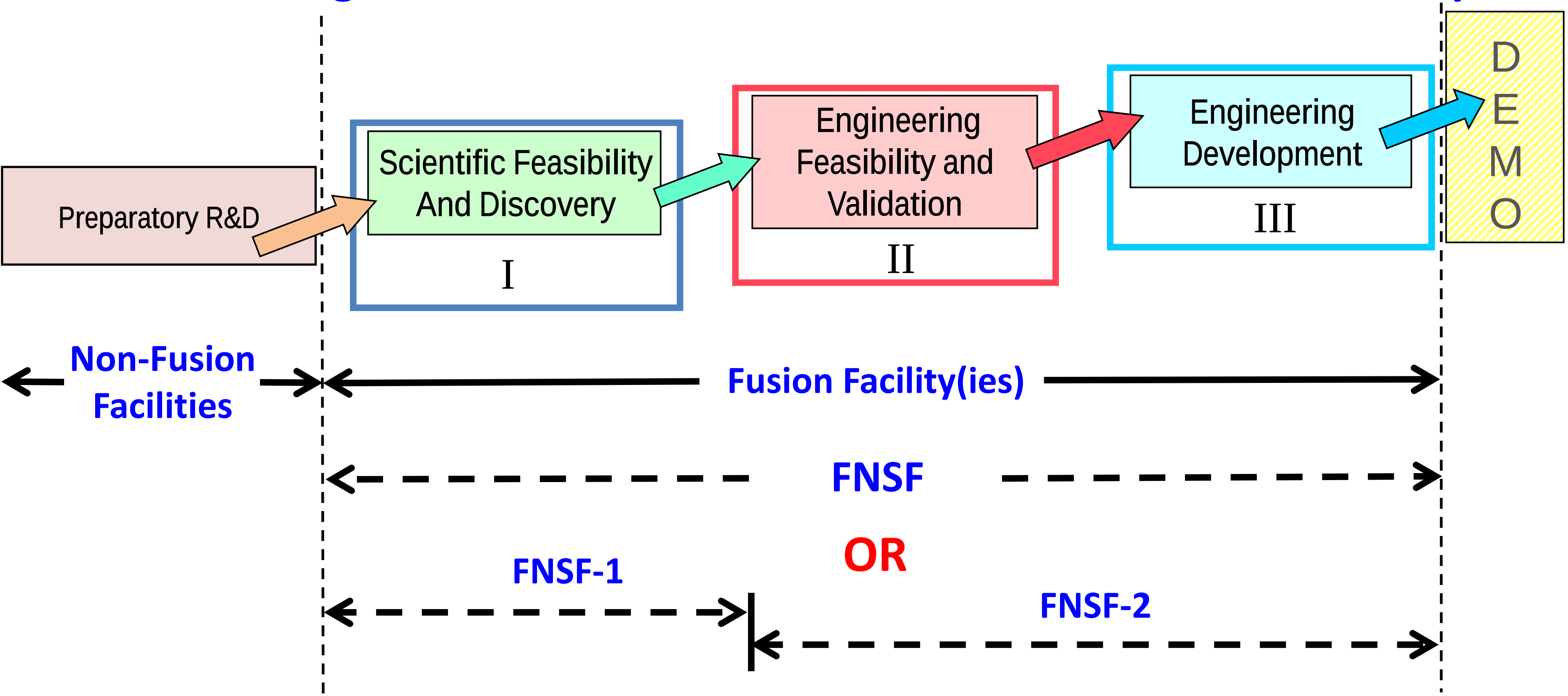
Parameter	Value
Neutron wall load[a] (MW/m^2)	**1 to 2**
Plasma mode of operation	**Steady State[b]**
Minimum COT (periods with 100% availability) (weeks)	**1 to 2**
Neutron fluence at test module (MW·y/m^2)	
Stage I[C]: scientific feasibility (less demanding requirements than II & III)	**~0.1- 0.3**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

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

Why FNSF should be low fusion power, small size

- To reduce risks associated with external T supply and internal breeding shortfall
- To reduce initial and operating costs (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 for tokamaks leads to the conclusion that FNSF fusion power <150 MW
- For tokamak (standard A & ST) this leads 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)
  - The DD Phase of FNSF also has a key role in providing integrated testing without neutrons prior to the DT Phase.

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



- Today, we do not know whether **one** facility will be sufficient to show scientific feasibility, engineering feasibility, and carry out engineering development

  OR if we will need **two or more** consecutive facilities.

  May be multiple FNSF in parallel?!

We will not know until we build one!!

- Only Laws of nature will tell us regardless of how creative we are. We may even find we must change "direction" (e.g. New Confinement Scheme)

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

- **FS is used for TBMs in ITER and for mockup tests prior to ITER.**
- **FS should be the structural materials for both base and testing breeding blankets on FNSF.**
- **FS irradiation data base from fission reactors extends to ~80 dpa, but it generally lacks He (only limited simulation of He in some experiments).**
  - ✓ **There is confidence in He data in fusion typical neutron energy spectrum up to at least 100 appm He (~10 dpa).**
    - – **Note: Many material experts state confidence that FS will work fine up to at least 300 appm He (30 dpa) at irradiation temperature > 350°C.**

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

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

"first Stage" 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, …

IFMIF

- IFMIF is an accelerator-based "point" neutron source to irradiate thousands of "miniaturized specimens, mm-scale" in a very small volume (0.5 litre at flux ~2MW/m^2)

- The reason IFMIF was conceived back in the 70's was the **mistaken belief then that**:
  - **Fusion Development would be very fast: DEMO by 1980-90**
  - **The only challenge was attaining long life, 200dpa in structural materials**

- **BUT "Today", we understand :**
  - **Experiments on FNST (blankets/divertors) require a plasma-based DT fusion facility to simulate complex fusion nuclear environment** (particularly nuclear bulk heating in large volume, surface heat flux, plasma transients, etc) and neutron reactions and materials interactions.
  - **We do not know the failure modes, and there is no data on MTBF but is likely to be short minutes/hours** on our current never built, untested, in-vessel components. So "reliability growth" is needed in imperfect non-nuclear testing facilities and then in fusion nuclear facilities. **It may take 10-20 years of fusion nuclear testing to get to 10-20 dpa.**

Role of IFMIF?

*** Can we skip FNSF, use IFMIF and ITER TBM and go directly to DEMO (like in the old world-strategy or current EU Strategy)?**

No, this is not credible

It would violate the results of extensive scientific and engineering FNST studies of the past 25 years.

"blanket tests in ITER alone can not demonstrate a blanket system availability in DEMO higher than 4%....... The presence of IFMIF does not significantly change this conclusion." *

*** Does FNSF need IFMIF?**

Absolutely Not!!

– FNSF will do the first experiments on the nuclear components. RAMI issues, testing and reliability growth will be dominant (most likely it will take > 10 years to get 10 dpa). There is enough data from fission and other sources to design for this first stage.
– Once we pass the first stage of 10 dpa in FNSF, we can extrapolate by a factor of 2 from "real results" as we outlined earlier.

* *M. Abdou et. al., Fusion Technology, vol. 29 (January 1996)*

We must start now climbing the "FNST Pyramid"

We need substantial NEW laboratory-scale facilities NOW while we plan for building FNSF

FNST Pyramid

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

Functional tests: ITER TBM Experiments and PIE

Engineering Feasibility Testing in a Fusion Nuclear Science Facility

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

Blanket Mockup Thermomechanical/ Thermofluid Testing Facility

Tritium Fuel Cycle Development Facility

Bred Tritium Extraction Testing Facility

Fission Irradiation Effects Testing on Blanket Mockups and Unit Cells

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

PbLi Based Blanket Flow, Heat Transfer, and Transport Processes

Plasma Exhaust and Blanket Effluent Tritium Processing

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

Ceramic Breeder Thermomechanics and Tritium Release

Structural and Functional Materials Fabrication

Thank You!

Other Issues yet to be resolved for IFMIF

- IFMIF is not needed before FNSF. Whether IFMIF can play a role "in the long term" requires assessment of the following issues:

  1 - Some Issues Related to Accelerator

  2 - Neutron Spectrum Issues

  - The neutron spectrum from the D-Li IFMIF source extends to 50 MeV (not a D-T fusion spectrum).

    - About 70% to 80% of the helium and hydrogen production rates come from neutrons above 15 MeV.
    - About 30% to 40% of dpa comes from neutrons above 15 MeV. (note dpa is a "calculated" not measured response. It is highly dependent on secondary neutron energy and angular distributions which have high uncertainty at IFMIF high neutron energy.)
    - It is argued that the He/dpa ratio is close enough.
    - However, the key problem is that nuclear data above 15 MeV is highly uncertain. There are no good measurements of cross sections and secondary particle spectra and no adequate neutron sources to do such measurements. Data generated by "nuclear models" are being used in IFMIF predictions. However, it is known that these models fail for "weak reaction channels" such as (n,alpha).
    - These and other issues related to neutron spectrum in IFMIF need to be assessed in more detail by nuclear data and neutronics experts.

Other issues yet to be resolved for IFMIF (cont'd)

3 - Evaluation of Transmutations and their Effects

4 - Effect of the Steep Flux Gradients in IFMIF test cell

5 - Ability to determine (or measure) the radiation damage indicators (flux, He production rate, dpa, etc.) in the specific specimen (to correlate observed effects with irradiation conditions) in IFMIF test cell.

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

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

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

  2- acquiring maintenance experience and data to Quantify MTTR

  3- providing for "reliability growth" testing

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

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

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

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

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

Key Summary Points (1 of 3)

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

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

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

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

Key Summary Points (2 of 3)

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

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

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

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

Key Summary Points (3 of 3)

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

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

  Both have "testing missions".

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

Concluding Remarks

- **Launching an aggressive FNST R&D program now is essential to defining "informed" vision and "credible" pathway to fusion energy.**

Most Important Steps To Do Now

1. **Substantially expand exploratory R&D**
   - Experiments and modeling that begin to use real materials, fluids, and explore multiple effects and synergistic phenomena
     - Major upgrade and new substantial laboratory-scale facilities
     - Theory and "FNST Simulation" project (parallel and eventually linked to "plasma simulation" project).

   ➢ This is essential prior to any "integrated" tests (TBM, FNSF, etc.)

2. **Move as fast as possible to "integrated tests" of fusion nuclear components – these can be performed only in DT plasma-based facility.**

   a) TBM in ITER

   b) FNSF: Initiate studies to confront challenges with FNSF (think of "0+1" not "DEMO-1").

   – Address practical issues of building FNSF "in-vessel" components of the same materials and technologies that are to be tested.

   ➢ Evaluate issues of facility configuration, maintenance, failure modes and rates, physics readiness (Quasi-steady state? Q ~ 2-3?). These issues are critical - some are generic while others vary with proposed FNSF facility.

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