Mission and Readiness Assessment for Fusion Nuclear Facilities

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Background and Motivation

- Increased attention to DEMO planning, worldwide.
- Growing understanding of the gaps and R&D needs. U.S. examples:
  - FESAC 2007 ("Greenwald Report")
  - ReNeW 2009
  - Technology Readiness Levels application (Tillack, *et al.*, FS&T 2009)
  - FNS Pathways Assessment (Kessel, *et al.*, 2012)

  ➔ need for intermediate Fusion Nuclear Facility(s) (FNF)
- New design & planning studies for FNFs and DEMOs, e.g.…
  - Europe: e.g., PPCS study, PPST study, early DEMO,…
  - Japan: SlimCS, DEMO-Crest.
  - Japan & Europe: Broader Approach activity,
  - China: Fusion Engineering Test Reactor (CFETR)
  - Korea: K-DEMO
  - U.S.: ARIES; FNF studies by ORNL, GA, PPPL,…

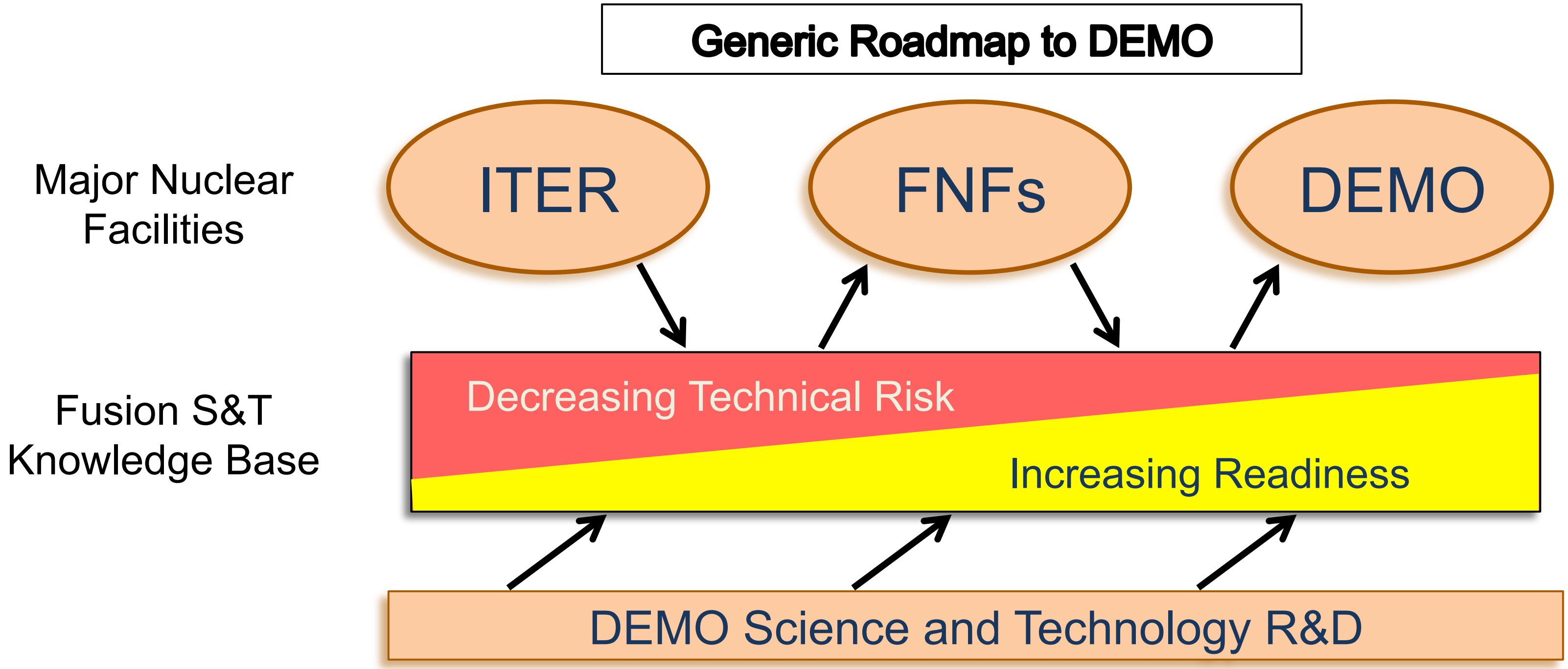
What does a next-step FNF need to accomplish and when could the fusion community be ready to move ahead with one?

Outline

- DEMO and the Roadmap to DEMO
- Two FNF Options
- Mission Assessments
- Readiness Assessments

U.S. studies are used as examples, but the identified needs could be addressed by any party or consortium.

Role of an FNF in the Roadmap to DEMO



- Major facilities (ITER, FNFs) & supporting R&D contribute to knowledge growth and risk reduction.
- There is no absolute standard for FNF or DEMO "readiness" to proceed.
  - Readiness depends on risk: assessment, tolerance, acceptance, management.
- Risk assessment and risk management are central to DEMO planning.
  - Technical and schedule risks must be considered.

DEMO Defined

From Starlite (1997) and FESAC (2007), DEMO must:

- Use the same technologies and plasma scenarios as planned for a commercial power plant.
- Demonstrate reliable steady-state operation as an integrated system under full and partial load conditions.

High-level Goals

1. Net electric output > 75% of commercial
2. Availability >50%; ≤ 1 unscheduled shutdown per year including disruptions. Full remote maintenance of the power core.
3. Closed tritium fuel cycle.
4. High level of public and worker safety, low environmental impact, compatible with day-to-day public activity.
5. Competitive cost of electricity.

As defined, DEMO must be very close to a commercial plant in its design and operation.

FNF Mission Space

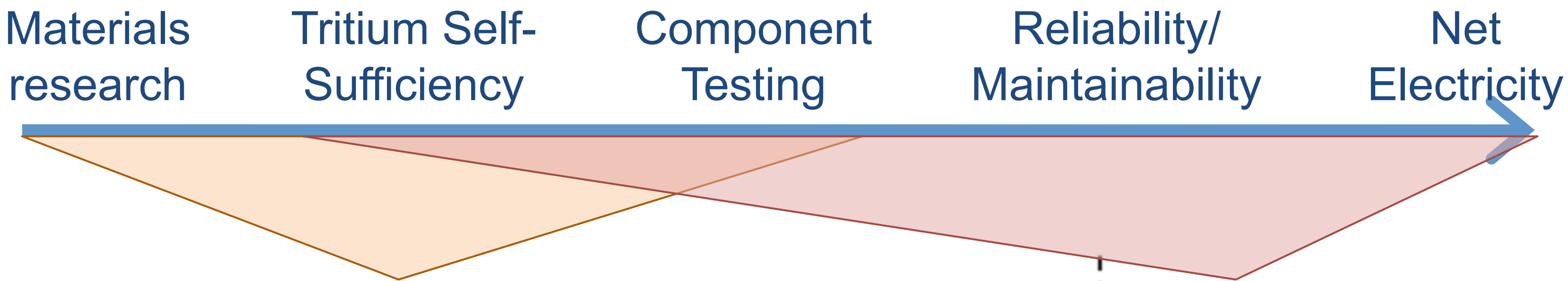
- The FNF mission space is wide:

Materials research
Tritium Self-Sufficiency
Component Testing
Reliability/ Maintainability
Net Electricity

Increasing System Integration

- Basic FNF mission requirements (typ.):
  - Steady-state / high duty-cycle DT plasma.
  - Tritium self-sufficiency.
  - Neutron wall loads (NWL) challenging to internal components: ≤3 MW/m^2.
  - Neutron exposure challenging reliability and lifetime limits: ≥ 2-3 MW-yr./m^2.
  - Accommodation for test blanket modules.
- Optional extras:
  - Prototype reactor design and maintenance.
  - Generate (net) electricity.
  - Achieve high availability.

Two FNF Examples

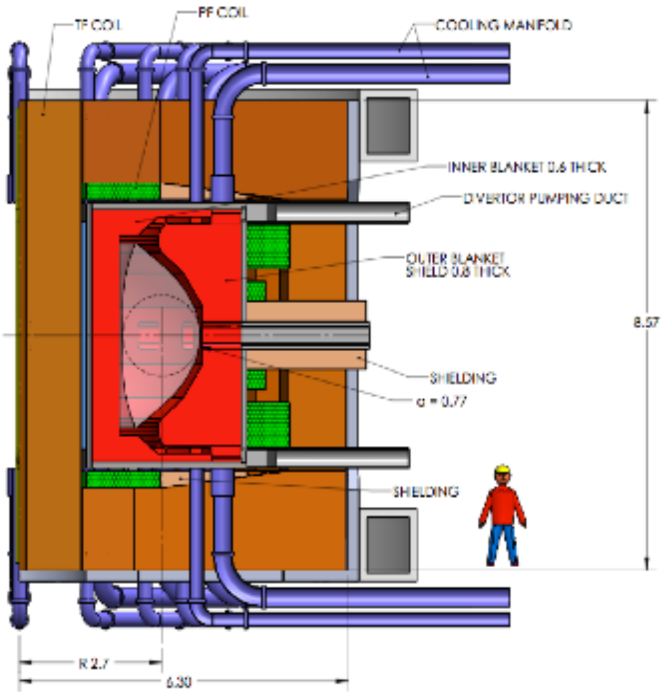

Materials research

Tritium Self-Sufficiency

Component Testing

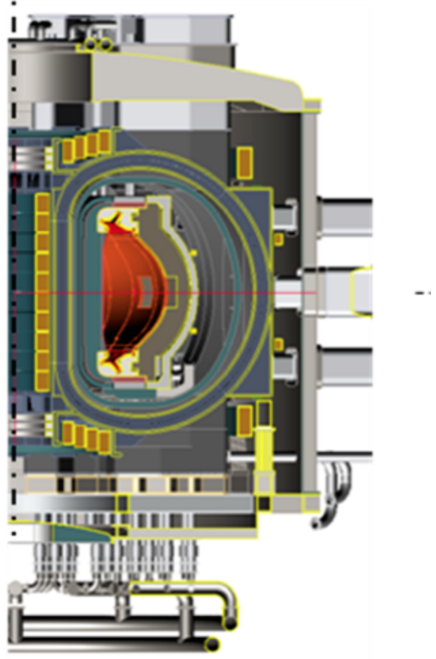
Reliability/ Maintainability

Net Electricity



AT Fusion Nuclear Science Facility (FNSF-AT) – GA

Stambaugh, *et al.*, F.S.&T. **59** (2011)



AT Pilot Plant – PPPL

Menard, *et al.*, NF **51** (2011)

Description of Options

	FNSF-AT	AT Pilot Plant*
Mission	• Steady-state DT plasma • Materials / component testing • Tritium self-sufficiency • Extension of AT physics • Demonstration of process heat and electricity production	• Steady-state DT Plasma • Materials / component testing • Tritium self-sufficiency • Prototyping of a power plant design & maintenance scheme. • Generation of net electricity.
Design	• AT configuration, R/a = 3.5. • R = 2.7 m. • Test blanket modules. • Demountable copper TF coil, extensive machine disassembly for maintenance access. • Internal components removed as full toroidal ring structures.	• AT configuration, R/a = 4. • R = 4 m. • Test blanket modules. • Superconducting magnets • Internal components sub-divided and removed as large segments with magnets at cryogenic temperature.

* Compact stellarator (CS) and ST pilot options also studied.

T. Brown, Session OS9, Wed. a.m.
P. Titus, poster, Tues. p.m.

Performance Parameters Compared

	ITER	FNSF-AT	Pilot Plant	Demo
Plasma duration (s)	500-3000	10^6	10^6-10^7	$3x10^7$
Engineering gain			1 (AT) 2.7 (CS)	4-7
Tritium sustainability (TBR)	none	1.0+	1.0+	1.1
NWL at test modules (MW/m^2)	0.7	2	1.5-3	4.5-6
Blanket fluence ($MW\text{-}y/m^2$)		2	≥ 3	> 10
Life of plant fluence ($MW\text{-}y/m^2$)	0.3	3-6	6-20	120-160
Plasma fusion gain, Q_{DT}	5-10	7	4-7 (AT) 20-40 (CS)	~30
Fusion Power (MW)	500	300	300-600	2,500
$P_{aux+\alpha}/S$ (MW/m^2)	0.2	0.5-1.0	0.5-1.0	0.9
$P_{aux+\alpha}/R$ (MW/m)	25	37	25-30	80

Mission and Readiness Assessment Approach

Assessment Categories

Plasma Configuration & Operation
- Burning Plasma
- Steady-state operation
- Divertor physics performance
- Disruption avoidance

In-Vessel Systems and Tritium
- First wall/ blanket / vacuum vessel
- Tritium processing & self-sufficiency

Plasma Control Technology
- Diagnostics and control systems
- Heating, current drive and fueling
- Superconducting coils

Plant Integration
- High Availability / Remote handling
- Electricity generation
- Power plant licensing

Key Assumptions

- FNFs and other major facilities fully accomplish their missions.
- **A parallel science and technology development program, also aimed at DEMO readiness, accompanies and supports the major facilities.**

Mission Comparison: Plasma Config. / Ops.

Demo readiness gap:

- Needs S&T basis for reliable control of a steady-state $Q_{DT} \approx 30$ ($P_{aux}/P_{\alpha} \approx 1/6$) plasma in a prototypical configuration and operating mode.

FNSF-AT *vs.* AT Pilot Plant Comparison:

- With Q_{DT} limited to <10, both leave a large gap in demonstrated Q_{DT}. Predictive simulation would be crucial to extrapolate from ITER/FNF to DEMO.
- Both substantially narrow the gap in demonstrated pulse length, but with $P_{aux}/P_{\alpha} > 1/2$, both are too reliant on external current drive to prototype an economical DEMO operating scenario.
- Either can incorporate a divertor configuration, divertor operating scenario, and disruption control scheme that could be prototypes for DEMO.

The two tokamak FNF options are comparable. Both significantly narrow DEMO readiness gaps, but leave large gaps in Q_{DT}.

A Stellarator Pilot Plant?

Essentially closes gaps in DEMO Plasma Config. / Ops. Readiness:

- Can demonstrate DEMO Q_{DT} and prototype an economical DEMO operating scenario, because it does not rely on current drive.
- Can prototype a disruption-free configuration design for DEMO

Stellarator Issues are Mostly Generic to Magnetic Fusion

- But stellarator geometry exacerbates technical issues, particularly constructability / maintainability.
  - Concept simplification research is needed.

Stellarators provide solutions that could make it the lowest risk path to DEMO.

Mission Comparison: Plasma Control Technology

Demo readiness gap:

- Needs technology basis for reliable, energy-efficient control of plasma scenarios during all phases of operation.
  - FNF environment and access limitations may limit controllability.

FNSF-AT *vs.* AT Pilot Plant Comparison:

- Either can incorporate and use DEMO-prototypical diagnostics and actuators to demonstrate reliable control.
- A pilot plant, building on ITER superconducting magnet technology, could further reduce risks with performance and reliability data for months-long pulses and high duty factor.

Supporting programs to develop DEMO-compatible diagnostics, heating, fueling, and magnet systems are absolutely critical.

Except for magnets, the two FNF options are comparable.

Mission Comparison: In-Vessel Systems & Tritium

Demo readiness gap:

- Needs technology basis for blankets, first wall, and divertor structures that can successfully operate and survive in the DEMO environment.
- Needs prior demonstration of tritium self-sufficiency.

FNSF-AT *vs.* AT Pilot Plant Comparison:

- Both can demonstrate tritium self-sufficiency and accommodate test modules.
- Pilot plant can provide higher neutron exposures between replacements, and a more prototypical configuration and maintenance scenario.
- FNSF-AT machine disassembly scenario may prolong downtimes, impact productivity.
- Neither is likely to provide much flexibility to change materials or configuration of in-vessel systems.

Supporting programs to develop DEMO-compatible systems for integrated testing in FNF are critical.

Pilot plant goes significantly farther toward DEMO readiness due to greater neutron exposure and more prototypical design.

Mission Comparison: Plant Integration

Demo readiness gap:

- Needs an S&T basis for high availability, lifetime data for all systems, efficient maintenance with remote handling equipment.
- Needs an S&T basis for economical electricity generation.

FNSF-AT *vs.* AT Pilot Plant Comparison:

- A pilot plant could essentially close maintainability / availability readiness gaps to DEMO and demonstrate availability approaching DEMO goals.
- An FNF would contribute but would leave a large gap due to its non-prototypical design and maintenance approach.
- A pilot plant is the more fully integrated system, capable of demonstrating *net* electricity generation from fusion .

Pilot plant, by design, goes significantly farther toward DEMO readiness.

Summary Mission Comparison

3	Nearly closes the gap to DEMO
2	Substantially lowers DEMO risk
1	Lowers DEMO risk
0	Does not affect DEMO risk

	FNSF-AT	PP-AT	PP-CS
Plasma Configuration and Operation			
Burning Plasma	1	1	3
Steady-state operation	2	2	3
Divertor physics performance	3	3	3
Disruption avoidance	3	3	3
Plasma Control Technology			
Diagnostics and control systems	3	3	
Heating, current drive and fueling	3	3	
Superconducting coils	0	3	
In-Vessel Systems and Tritium			
First wall/ blanket / vacuum vessel	1	2	
Tritium processing / self-sufficiency	3	3	
Plant Integration			
High Availability / Remote handling	1	3	
Electricity generation	2	3	
Power plant licensing	1	2	

An AT Pilot Plant takes the larger step toward DEMO, though still leaves a large gap in fusion gain. A stellarator could close that gap.

How do they compare in readiness to move forward?

Readiness Assessment

Given the fusion science and technology advances that could reduce risks and could be achieved world-wide in the next 10 years…

What would be the state of readiness for an FNF to proceed with engineering design 10 years from now?

Readiness Comparison: Plasma Config. / Ops.

In the next 10 years:

- Science basis for high-performance, steady-state plasma control, mostly with H and D plasmas, will advance. ITER will begin to operate.
- Large advances in simulation capabilities for reliable plasma extrapolations could be made.
- Progress in divertor physics beyond ITER needs is likely but, given timescales for testing new solutions, significant risks will remain.
- Disruption risks will remain for tokamaks.

Readiness for a tokamak FNF 10 years from now will be determined by simulation, divertors, disruptions.

Readiness for FNSF-AT and AT Pilot Plant are similar.

Readiness for a Stellarator Pilot Plant?

In the next 10 years:

- Science basis for high-performance, steady-state, diverted plasma operation will advance via LHD and W7-X.
- Physics basis for compact stellarators (CS) based on magnetic quasi-symmetry could be greatly expanded, though limited to short pulses.
- Large advances in simulation capabilities for reliable plasma extrapolations and simpler designs could be made.

Readiness for a stellarator pilot plant based on LHD or W7-X will be determined by progress in those machines

CS basis would be less mature, but its linkages to tokamak physics could mitigate its risks.

Readiness Comparison: Plasma Control Technology

In the next 10 years:

- Significant advances in diagnostic, heating and current drive, fueling, and magnet technologies are likely, but limited to ITER requirements.
- Initiatives to identify and start to develop new solutions for DEMO could further reduce FNF risks.
- Testing in ITER will barely begin.

Readiness for an FNF 10 years from now will depend on investments beyond the needs of ITER.

Readiness for FNSF-AT and Pilot Plant are similar.

Readiness Comparison: In-Vessel Systems & Tritium

In the next 10 years:

- Advances in blankets, PFCs, and tritium technologies are likely, motivated by ITER and some ambitious plans for next-step FNFs.
  - Significant risk reduction in 10 years requires large investments in facilities and programs.
- Irradiation testing results will be limited by the lack of a fusion-spectrum neutron irradiation facility.

Readiness for an FNF 10 years from now will depend on investments in fusion nuclear technology.

Risks for FNF and Pilot Plant will still be high.

Materials-related risks for a Pilot Plant will be higher due to its longer component lifetime requirements.

Readiness Comparison: Plant Integration

In the next 10 years:

- Progress will be determined by the goals set for FNF.

FNSF-AT and Pilot Plant Readiness Comparison

- Either option must ensure maintainability and tritium self-sufficiency.
- A pilot plant requires advances in energy conversion efficiency, wall-plug efficiency of heating and current drive systems, and maintenance technology that go beyond the requirements of an FNSF-AT.

Integration-related risks for a Pilot Plant will be higher due to the broader scope of its mission.

Conclusions - 1

1. Either option could make progress toward closing readiness gaps and reducing risks for DEMO.
   A pilot plant goes substantially farther toward DEMO than an FNSF-AT.
2. The risks can be significantly reduced for both options by considerably increasing the level of DEMO-oriented R&D investment.
   For a given amount of investment, the risks for proceeding with a pilot plant would be higher.
3. The risks could not be reduced to low levels for either option, but **either could proceed 10 years from now with an accompanying strategy for accepting and managing risks.**
4. Quantitative risk analysis must be fully integrated into the planning and management of fusion development programs.

Conclusions - 2

5. Neither tokamak option can prototype a DEMO steady-state plasma control scenario, due to a large gap in Q_{DT}. Extrapolation would rely on simulation.

6. A stellarator path to DEMO would mitigate program risks associated with control of steady-state, high-gain plasmas and avoidance of disruptions, and could be the lowest risk path.

7. Five major R&D initiatives that could make a quantum improvement in readiness:
   - Predictive simulation project
   - Compact stellarator program based on magnetic quasi-symmetry
   - DEMO diagnostics initiative
   - Steady-state, non-nuclear divertor-plasma integration facility.
   - Fusion-neutron materials irradiation facility initiative.