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Mission and Readiness Assessment for Fusion Nuclear Facilities

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MISSION AND READINESS ASSESSMENT FOR FUSION NUCLEAR FACILITIES

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Magnetic fusion development toward DEMO will most likely require a number of fusion nuclear facilities (FNF), intermediate between ITER and DEMO, to test and validate plasma and nuclear technologies and to advance the level of system integration. The FNF mission space is wide, ranging from basic materials research to net electricity demonstration, so there is correspondingly a choice among machine options, scope, and risk in planning such a step. Readiness requirements to proceed with a DEMO are examined, and two FNF options are assessed in terms of the contributions they would make to closing DEMO readiness gaps, and their readiness to themselves proceed with engineering design about ten years from now. An advanced tokamak (AT) pilot plant with superconducting coils and a mission to demonstrate net electricity generation would go a long way toward DEMO. As a next step, however, a pilot plant would entail greater risk than a copper-coil FNSF-AT with its more focussed mission and technology requirements. The stellarator path to DEMO is briefly discussed. Regardless of the choice of FNF option, an accompanying science and technology development program, also aimed at DEMO readiness, is absolutely essential.

I. INTRODUCTION

With ITER construction now under way, the nations engaged in magnetic fusion energy (MFE) research and development are examining the programs needed to move toward a demonstration of electricity generation from fusion, or DEMO. The requirements include fusion nuclear facilities (FNF) that will take fusion beyond ITER by not only producing a steady-state DT plasma, but also using it to generate high neutron fluxes ($\leq$3 MW/m^2) and fluences (>3 MW-yr/m^2) to stress the in-vessel components, test their response to prolonged exposure to intense neutron irradiation, and generate tritium fuel.[1] The span of FNF missions being considered ranges from basic material science and component testing in a fusion nuclear environment, to reactor design / maintenance prototyping, to generation of net electricity and high-temperature heat (Fig. 1.).

The justification for any FNF requires both an assessment of its mission, in terms of how far it would go in closing the gap to DEMO, as well as an assessment of its state of readiness, in terms of the existing gaps in knowledge and technology readiness, the programs needed to narrow those gaps, and the attendant risks. For example, a pilot plant capable of net electricity generation would prototype important aspects of a power plant design and maintenance scheme and would demonstrate overall system efficiency, and thus would go a long way toward demonstration of fusion's potential as an energy source. A driven system with resistive magnets and a narrower mission focused on materials and component testing in a fusion nuclear environment would likely leave a larger gap and the risk of a longer development timeline to DEMO. To complete the comparison requires a comparison of the states of readiness of these two FNF options.

Recently there has been increased attention to gaps and readiness issues for MFE. In the U.S., in particular, the "Greenwald Panel" of the Fusion Energy Sciences Advisory Committee identified gaps in the scientific and technological knowledge base for DEMO under three broad categories: creating predictable high-performance steady-state plasmas, taming the plasma material interface, and harnessing fusion power.[2] That report, followed by reports of the ReNeW[3] and Fusion Nuclear Science Pathways[4] studies described R&D programs designed to narrow or close the identified gaps. Taking a more product-oriented approach, the ARIES team applied the "Technology Readiness Levels" methodology to assess the readiness and current state of knowledge for a reference fusion power plant under the categories of power management, plasma power distribution, and safety and environmental attractiveness.[5]

Both science-oriented and product-oriented analyses come to the conclusion that additional major facilities

Fig. 1. Fusion Nuclear Facility (FNF) Mission Space

intermediate between ITER and DEMO, specifically one or more FNFs, are needed to test and validate plasma and nuclear technologies and to advance the level of system integration. This has motivated studies of machines spanning the FNF mission space; in the U.S. they include the Fusion Development Facility (FDF),[6,7] the Spherical Tokamak–Component Test Facility (ST-CTF)[8,7], and the pilot plant[9] to bridge the gap between ITER and DEMO. In this paper we compare machines near the two ends of the FNF mission space depicted in Fig. 1., assessing their mission and state of readiness as possible next-step facilities. We rely primarily on U.S. studies for this analysis, but the identified needs apply to fusion development generally and could be addressed by any party or consortium of parties.

II. FNF ASSESSMENT METHODOLOGY

Based on the STARLITE definition,[10] an MFE DEMO must use the same technologies and plasma operating scenarios as are planned for a commercial power plant. It must demonstrate reliable steady-state operation as an integrated system under full and partial load conditions. High-level DEMO goals include:

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, compatibility with day-to-day public activity.
5. Competitive cost of electricity.

By this definition, DEMO must be very close to a commercial plant in its design and operation. It needs to largely eliminate the technical risks in the step to a commercial power plant by demonstrating the key technologies in an integrated system at near-commercial performance levels, such that large extrapolations are not required. Although this particular definition of DEMO is not universally adopted, by any name it represents a stage that fusion development must pass through on the path to commercialization.

For this assessment we consider a generic roadmap to

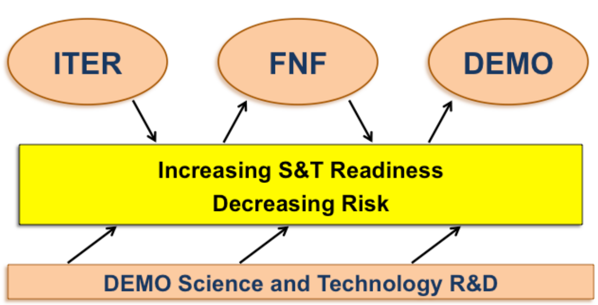

Fig. 2. Generic roadmap for this assessment.

TABLE I. Science and Technology Assessment Categories

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

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

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

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

DEMO as depicted in Fig. 2. We consider "readiness," whether applied to DEMO or an FNF, not as an absolute standard but, rather, as a determinant of technical risk. The stronger the technical basis, the more advanced the state of readiness and lower the risk. The threshold for risk acceptance is a variable that depends partly on political and socio-economic factors such as the degree of urgency for fusion development, and partly on the ability to manage and mitigate risks. While the former may be outside the control of the fusion community, the latter is certainly in scope. Here we assess readiness and risk semi-subjectively, but as fusion moves forward a more quantitative assessment of technical readiness and its relationship to risk will be needed.

We assess requirements and readiness criteria in twelve science and technology (S&T) categories under four headings (TABLE I). The FNF mission assessment follows a roll-back from DEMO approach. The high-level DEMO goals imply certain technical requirements in each of the assessment categories, from which we derive DEMO readiness criteria. The assumed DEMO characteristics are generally based on U.S. power plant design studies.[11,12] Where readiness requires a demonstration of performance or conditions, generally that demonstration must be accomplished in an FNF that precedes DEMO. Where readiness requires an S&T basis for extrapolation, that will be provided by a combination of FNFs and accompanying R&D programs. The readiness assessment for a given FNF option considers the R&D programs needed in each category to address readiness criteria to move forward with engineering design for that option.

TABLE II. Pilot Plant Performance Parameters compared with ITER and Demo.

	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

III. FNF OPTIONS FOR COMPARISON

Here we consider two FNF mission options, an advanced tokamak fusion nuclear science facility (FNSF-AT) similar in design and scope to the FDF[7] proposed by General Atomics and collaborators, and a pilot plant[9,13] based on studies by PPPL and collaborators. Mission parameters for these two options are tabulated along with those for ITER and DEMO in TABLE II. We assume that either option fully succeeds in accomplishing its mission. We are primarily concerned with the value and readiness for particular missions, not in critiquing the very preliminary facility designs that have been described to support those missions. Here we briefly highlight the key characteristics of those designs.

The FNSF-AT offers a tokamak-based facility in which to demonstrate steady state advanced physics operation with burn, develop blankets, close the fuel cycle, and generate electricity. The machine design philosophy features a jointed copper TF coil and vertical removal of the blanket / shield / first wall and divertor structures as complete toroidal ring assemblies. This strategy is adopted with the aim of providing the flexibility to re-configure the in-vessel systems so that the facility can be used for research and development of those systems. The copper OH solenoid is assumed to be replaced whenever the inboard blanket / shield assembly are replace, while the TF coil is designed to last the life of the machine. The size (R = 2.7 m) of its standard aspect-ratio (3.5) tokamak core is intended to minimize tritium requirements and limit the size of the removable toroidal ring structures, while providing sufficient performance for blanket testing based on AT physics rules.

The pilot plant offers three main missions: 1) testing of internal components and tritium breeding in a steady-state fusion environment, 2) prototyping a maintainable configuration and maintenance scheme for a power plant, and 3) generating *net* electricity. The motivation for considering this more ambitious mission is to go as far as possible toward fully satisfying DEMO readiness criteria. Advanced tokamak (AT), spherical tokamak (ST), and compact stellarator (CS) embodiments have been examined, but here we limit consideration to the AT to facilitate comparison with the FNSF-AT and, to a lesser extent, the CS to highlight important differences. The pilot plant machine designs and maintenance scenarios are intended to be prototypical of power plants based on these two concepts. The maintenance strategy features removal / replacement of in-vessel equipment in large sectors with the coils at cryogenic temperatures and with aim of minimizing downtime, a necessity for high availability. All coils are superconducting, a necessity for overall energy breakeven (Q_{eng} ≥ 1). The magnet current density is a key size determinant in these options. It is assumed the average magnet current densities can be about twice that of ITER, based on technology advances and the reduced number of cycles and disruptions in a pilot plant compared to ITER. The AT size (R = 4 m) is driven by engineering gain while the CS size (R = 4.75 m) is driven by the neutron wall loading requirement rather than gain due to the stellarator's low recirculating power.

IV. ASSESSMENT OF FNF OPTIONS

IV.A Plasma Configuration and Operation

Burning Plasma: A DEMO requires a plasma gain Q_{DT} (ratio of fusion power to plasma heating power) of a few 10s (e.g. ~30, or $P_{aux} = P_\alpha/6$ for a steady-state tokamak) in order to be economical. DEMO readiness requires a reliable basis for confidence that such a strongly alpha-dominated plasma can be controlled. It is expected that ITER will provide data in standard pulsed tokamak operation at $Q \approx 10$ ($P_{aux} = P_\alpha/2$) for long-pulses and will demonstrate operation with 100% non-inductively driven current at $Q \approx 5$ ($P_{aux} = P_\alpha$) for 3,000 s. These outcomes may provide a physics basis for confident extrapolation in gain, but the extrapolation to DEMO would be large. The risk for DEMO would be significantly reduced by a demonstration in an FNF of $Q > 10$ in a steady-state operating scenario prototypical of that planned for DEMO, accompanied by a predictive capability for burning plasma physics extrapolation.

FNF mission assessment: Both an FNSF-AT and a tokamak pilot plant would significantly extend advanced operation in terms of pulse length and normalized beta, but only modestly in Q. Neither of these would significantly narrow the gap in Q_{DT} to DEMO, however a stellarator pilot plant could fully close that gap.

FNF readiness assessment: Tokamak and stellarator research over the next decade will continue to advance the physics understanding of plasma operating regimes for DEMO, but mostly in H or D plasmas. The exception is JET, which will expand the data base for pulsed DT operation at $Q \leq 1$. A more focused and intensified plasma simulation effort could provide an improved extrapolation capability, to the significant benefit of FNF readiness ten years from now. Either FNF could proceed then with some risk, or could wait an additional 5-10 years for an experimental demonstration of $Q \gg 1$ in ITER. The wait would lower technical risk at the expense of delay in moving forward with an FNF and possibly a delay in DEMO.

Steady-state operation: A DEMO as defined in Ref. 10 must reliably operate in steady state at full power (~750 MWe) and partial power for periods of at least 9-12 months. Tests of partially and (possibly) full non-inductive plasma operation for ~1,000 s or more at $Q \approx 5$ in ITER will greatly expand the required knowledge base for a tokamak DEMO, though such experience is likely almost 20 years away. Without a prior demonstration of reliable and efficient steady-state operation of an FNF, operating in a DEMO-prototypical plasma scenario at its own design parameters for long periods, DEMO would proceed at very high risk, since steady-state scenarios are highly plasma-configuration specific. To the extent that external current drive is required for sustainment, fundamental limits on current drive efficiency can impact the overall economic attractiveness, so it is desirable develop scenarios that minimize or eliminate current drive. Ideally, a prior FNF will be built and operated continuously for up to 1.5×10^{7} s (i.e., 4-6 months, so the extrapolation to DEMO is no more than a factor of two) in a plasma configuration and operating scenario prototypical of that planned for DEMO.

FNF mission assessment: Both an FNSF-AT and a tokamak pilot plant would substantially narrow the readiness gap in steady-state tokamak operation. With their low Q_{DT} values, both are more reliant on external current drive than DEMO economics could tolerate and their fusion power output is less than DEMO's by factors of at least 4. A DEMO based on either of these would have to rely on predictive plasma simulations to close these readiness gaps. The most significant difference is in pulse length- the FNSF-AT is limited to two weeks while a pilot plant could operate for four months or more, providing a more convincing demonstration of plasma reliability over long periods of time.

Stellarators are advantageous for steady-state operation, since sustainment of the magnetic configuration is independent of plasma parameters and does not require current drive. Control challenges (discussed in Section IV.B) are considerably reduced compared to advanced tokamaks. A stellarator pilot plant could readily prototype steady-state operation for a stellarator DEMO.

FNF readiness assessment: Tokamak and stellarator research over the next decade will continue to advance the physics understanding of steady-state-relevant plasma operation. New superconducting tokamaks are expected to extend scenarios that are now being developed in shorter-pulse facilities to pulse lengths of up to 1,000 s. Success in these programs would significantly improve the scientific basis for steady-state operation of a tokamak FNF, either FNSF-AT or a pilot plant, going forward in about a decade.

The superconducting LHD and W7-X stellarators will continue to advance the performance and understanding of half-hour to hour-long stellarator plasmas, and would significantly improve the scientific basis for steady-state plasma operation for proceeding with a stellarator pilot plant based on those specific designs in about a decade. An additional program would be needed to also develop a physics basis for compact stellarators (CS) based on magnetic quasi-symmetry, though in the next decade progress would be limited to pulse lengths of a few seconds at most. A CS pilot plant could proceed on that basis and the attendant risk would depend on the degree to which it could take advantage of tokamak understanding. The risk for a CS could be further reduced with an investment in a facility and accompanying program comparable to LHD or W7-X that could begin to operate in about a decade. Stellarators have many issues in common with tokamaks, but their geometry exacerbates those issues, particularly those related to construction and maintenance. A stellarator theory and design program aimed at concept simplification, accompanying experimental research, is necessary to narrow FNF and DEMO readiness gaps.

Divertor physics performance: It is expected that the DEMO will operate with steady-state heat losses corresponding to average heat flux through the plasma surface (P/S) of about 1 MW/m^2, and plasma-facing component temperatures of 400-600 C. In this environment the divertor must exhaust the heat and particle losses, must control impurities, and must be compatible with good plasma performance and component lifetimes of 2-3 full-power years. Since ITER will not approach these conditions, DEMO readiness requires a prior demonstration of continuous operations of an FNF with a prototypical plasma and divertor configuration, materials, and operating scenario at $P/S \geq 0.5$ MW/m^2 and first wall temperatures ≥ 400 C. In addition, reliable predictive models would be needed to make the extrapolations needed to close the remaining gap.

FNF mission assessment: Either an FNSF-AT or a pilot plant, in combination with credible predictive simulations, could substantially narrow the gap between ITER and DEMO in demonstrated divertor physics performance, assuming prototypical configurations and materials. While the extrapolation to DEMO in pulse length would be greater for an FNSF-AT, its two-week pulses and 30% duty factor in a year would likely provide a basis for extrapolation in divertor physics performance comparable to that of a pilot plant.

FNF readiness assessment: Currently there are large gaps in divertor performance metrics, i.e., in power density, operating temperature, and pulse length, between ITER and an FNF. It is likely that the development toward an FNF will require discontinuities in either configuration (e.g., to a Super-X or snowflake), operating scenarios (e.g., higher radiated power fraction), or materials (e.g., to liquid metals). A very substantial increase in power exhaust R&D aimed at narrowing the gap from ITER to FNF / DEMO is needed both for tokamaks and stellarators. An FNF proceeding a decade from now without a prior integrated demonstration of a prototypical power exhaust solution in a steady-state non-nuclear development facility would do so with considerable risk. The risk could be reduced substantially with such a facility, but at the expense of a larger investment in power exhaust R&D and a few years' delay. The tradeoff needs to be evaluated.

Disruption avoidance: The sudden release of energy from disruptions poses a large risk of machine damage in a fusion device. The potential for damage if one occurred would precipitate a prolonged shutdown for inspection and possible repair. Since a DEMO can tolerate at most one unscheduled shutdown per year, disruptions must be essentially eliminated. As a readiness criterion, successful operation in an FNF of continuous operation for at least 6 months should be demonstrated.

FNF mission assessment: Either an FNSF-AT or a pilot plant could establish DEMO readiness in this category if it were able to demonstrate a reliable solution for disruption avoidance.

FNF readiness assessment: Disruption avoidance is a serious issue for tokamaks, one that has eluded resolution to date. Ongoing R&D will continue to make at least incremental progress in understanding and avoiding conditions that lead to disruptions and in control strategies that rely on rapid response to precursors where possible. Stellarators use 3D magnetic fields to reduce or completely eliminate the plasma current that is the main source of free energy for disruption-induced damage. The quasi-axisymmetric CS combines 3D magnetic fields with tokamak-like magnetic symmetry that can be viewed as a modification of the tokamak to eliminate all but self-driven currents. An axisymmetric tokamak FNF, whether an FNSF-AT or a pilot plant, proceeding a decade from now will benefit from ongoing R&D for ITER, but will likely still have high risk of frequent disruptions. A stellarator pilot plant based on either the LHD or W7-X designs could go forward with low disruptions risk. An investment in CS research over the next decade would develop a basis for a reliable disruption solution that could substantially reduce the risk for a CS or modified-tokamak FNF.

IV.B Plasma Control Technology

Diagnostics and plasma control systems: A DEMO must demonstrate precise, reliable, and energy-efficient control of plasma scenarios during all phases of operation. The contribution to machine down time due to failures in the diagnostic and control system must be very small. Challenges for DEMO diagnostics include a harsh operating environment due to radiation and constraints on available space while providing adequate blanket coverage for tritium self-sufficiency. Challenges for machine controllability include the limits on the completeness and accuracy of information from diagnostics and the limited external influence available if the plasma is dominated by self-heating and self-driven currents.

Key diagnostic readiness criteria include: 1) specification of the minimum set of diagnostic measurements that are required to sense and control the DEMO plasma in its intended operational regimes; 2) prior demonstration in an FNF of diagnostic techniques to make these measurements at the required accuracy and resolution; 3) an established S&T basis for designing all DEMO diagnostics to satisfy their reliability and their lifetime requirements. Key control system readiness criteria include: 1) prior demonstration of reliable shape control in an FNF with DEMO-prototypical plasma configuration, control coils, and diagnostics; 2) prior demonstration of reliable burn control with DEMO-prototypical Q_{DT}; 3) an S&T basis for assurance that the frequency of unmitigated disruptions can be kept within DEMO requirements, and that potentially dangerous instabilities such as neoclassical tearing modes (NTM), resistive wall modes (RWM), and edge localized modes (ELM) will be absent, tolerable, or actively controlled.

FNF mission assessment: Either FNSF-AT or a pilot plant could substantially narrow DEMO readiness gaps provided they were sufficiently prototypical of DEMO in terms of diagnostic and actuator choices. The primary shortfall is in demonstrating control at DEMO-prototypical Q_{DT}, but ITER results and $Q = 5$-10, accompanied by credible predictive simulations could substantially mitigate the associated risk.

FNF readiness assessment: Readiness for an FNF or DEMO requires that new diagnostic techniques suitable for the DEMO environment will need to be developed.[14] The program must include testing and qualification on ITER in full-power DT operation, and the use of plasma and irradiation facilities to develop the technology. A study by Costley[15] of diagnostic issues for a pilot plant concluded that diagnostic R&D far beyond that needed for ITER will be required, citing measurements of plasma shape and position, radiated power, and divertor conditions as examples of challenges needing new solutions. A substantial increase in R&D investment would accelerate progress and may make it possible establish readiness for either FNF option a decade from now.

Plasma heating, current drive, and fueling: Heating, current drive, and fueling systems are critical plasma control actuators. These systems face challenges in common with diagnostics: a harsh operating environment due to radiation, and constraints on available space. In addition, the candidate heating and current-drive technologies (NBI, ECH, ICRF, LH) face specific challenges associated with current drive efficiency, wall-plug efficiency, steady-state performance, and reliability. Fueling technologies (pellets, compact toroids) face challenges to achieve DEMO flow-rate and penetration requirements.

FNF mission assessment: Either FNSF-AT or a pilot plant could substantially narrow DEMO readiness gaps provided they were sufficiently prototypical of DEMO in terms of technology choices for heating, current drive, and fueling.

FNF readiness assessment: The candidate heating, current drive, and fueling technologies are known, but readiness for an FNF or DEMO requires continued development of those with the potential to meet DEMO requirements. The program includes the demonstration of these technologies on ITER, as well as accompanying programs with dedicated test stands. With a sufficient R&D investment, enough progress could be made to establish readiness for either FNF option a decade from now.

Superconducting magnets: A DEMO requires superconducting magnets that operate reliably for the life of the facility. Success in ITER with its superconducting magnet system could minimally satisfy DEMO readiness criteria if only modest technology extensions beyond ITER are required. Demonstration in a superconducting FNF of reliable magnet system operation for pulse lengths of weeks to months would substantially lower the risk for DEMO.

FNF mission and readiness assessment: It is expected that ITER will provide substantial DEMO-relevant data and experience on superconducting magnet operation for fusion systems. A pilot plant could readily proceed within a decade based on ITER magnet technology, and could further reduce the risks for DEMO by providing performance and reliability data for months-long pulses and high duty factors. Naturally, a copper-coil FNF such as FNSF-AT makes no contribution in this category.

IV.C In-Vessel Systems and Tritium

Clearly DEMO's in-vessel and tritium processing systems are critical to its primary function to efficiently use the energetic neutrons from a burning plasma to produce electricity and tritium. The plasma-facing components must withstand the impact of plasma heat and particle losses and be compatible with the divertor performance requirements discussed in Section IV.A. Systems must maintain minimally required properties for the service life of a blanket module, ≥ 6 MW-yr./m^2 of integrated average neutron wall load, they must shield the magnets from excessive heat loads, and they must be maintainable with minimum down time. The readiness assessment by Tillack[5] concluded that these power core and plant systems will need to undergo major advances in technology and integration, requiring additional major facilities, in bridging the gap from ITER to a DEMO.

FNF mission assessment: Component development and materials testing in a prototypical fusion environment are core missions for all FNF options, including FNSF-AT and pilot plants. Both offer a suitable environment for this mission, including steady-state operation, higher power densities than in present devices or ITER, and prototypical neutron wall loading. Both provide robust breeding blanket and tritium processing systems intended to achieve tritium self-sufficiency with an acceptably small site inventory, which is both a necessity and a mission element for these facilities. A crucial question for this mission is how much reconfiguration flexibility is required for an FNF to be able to test different materials and designs, and whether one option has advantages over the other in this regard. It is likely that either could provide port access for test blanket modules, providing the capability to test a progression of advanced designs. Both must, and do, provide a means, using remote maintenance tooling, of maintaining the in-vessel components, but offer different strategies.

The FNSF-AT strategy is based on a disassembly of a demountable TF coil and replacement of in-vessel systems as complete toroidal ring structures. This approach is potentially advantageous for achieving good alignment of components such as the divertor targets, since the assembly into ring structures is performed *ex situ*, and may simplify the support structure design. However as pointed out by Brown,[13] the jointed TF design may be less reliable in steady-state operation and the disassembly of major subsystems to gain access can add risk in damaging the disassembled components. The complexity and long maintenance turn-around times of today's much simpler machines, such as NSTX and JET, suggests that costs and risks of extensive disassembly of a steady-state nuclear machine like FNSF-AT to gain access may impact its productivity and negate any capabilities it might offer in terms of re-configurability.

The pilot plant strategy is based on in-vessel component systems that are sub-divided into segments which are removed / replaced through ports. The TF coils and vacuum vessel are expanded radially outward to provide large openings for segment transfer in order to minimize the required number of segments. This approach leaves in place most systems, including semi-permanent in-vessel structures, that do not need periodic maintenance. It is intended to prototype a power plant maintenance scenario compatible with high availability, in which internal components are rapidly removed and replaced with components of essentially identical design and interfaces.

The potential to significantly re-configure the in-vessel components with this approach is probably very limited.

In present and past tokamak and stellarator experiments, the internal components are typically re-configured frequently as a way to test new features or expand the operating space. It does not appear practical to offer a comparable degree of flexibility in either FNF design, desirable though it may be, and it would be risky to depend on it. Development of blankets and plasma-facing components for DEMO must rely to the maximum extent possible on supporting programs using facilities that are as accessible and flexible as possible, and using the FNF only to perform component tests in port-mounted modules, and to complete the required integrated fusion-environment testing and demonstration of solutions already well-developed on other facilities.

FNF readiness assessment: Readiness for an FNF requires development of designs and materials for the in-vessel components. It requires further development of tritium processing technology beyond ITER to meet the duty cycle requirements of an FNF. A substantial increase in fusion nuclear science and technology R&D is required. A critical strategic question is whether the timeline for FNF readiness would be set by the time required for materials irradiation testing. A consensus of participants at an international workshop on fusion roadmapping[16] was that limiting the end-of-life irradiation requirements for the first set of core components in a reduced-scope DEMO (or equivalently, FNF) to a damage level of ~50 dpa would relax some of its irradiation prerequisites. Proceeding with such a facility without results from a materials irradiation facility that could test or simulate exposure to DT fusion neutrons would entail a level of risk that may be acceptable. Nonetheless, a true fusion materials irradiation facility is considered a necessity for developing materials for DEMO and for advanced blankets that would be tested in FNF's test blanket modules.

IV.D Plant Integration

High Availability and Remote Handling: In order to demonstrate availability ≥ 50%, DEMO must be capable of being maintained, including all scheduled and unscheduled maintenance operations, by remote handling equipment. In addition, validated operational lifetime data are required for all systems. Non-replaceable systems must have lifetimes under operating conditions exceeding that of the plant, while replaceable systems must have lifetimes and replacement times compatible with availability goals. As a readiness condition, efficient maintenance operations must be demonstrated in a prototypical FNF, ideally achieving ultimate availability of at least 30%.

FNF mission assessment: A pilot plant is intended to prototype a power-plant design and maintenance scenario. Over its lifetime it would enable the accumulation of a wealth of data on component failure rates and lifetimes, as well as relevant experience in remote maintenance operations. In principle it could eventually demonstrate a level of availability sufficient to proceed with confidence to a high-availability DEMO. An FNSF-AT could contribute to narrowing the DEMO readiness gap in this category. It could produce failure rate and lifetime data for some in-vessel components, and develop experience with remote maintenance and hot cell operations. It could in principle demonstrate high availability for itself but because of its non-prototypical design and limited scope, its relevance to DEMO is only partial and it would not provide a basis for proceeding to a high availability DEMO with confidence.

FNF readiness assessment: The current state of readiness for an FNF that is sufficiently maintainable and reliable to carry out its mission is very low. Tillack's[5] technology readiness assessment found maintenance to be the least advanced of all the issue categories considered, even though JET has accumulated extensive data and experience on in-vessel remote maintenance over three decades. ITER will extend the knowledge and experience base but it will not prototype a maintenance approach that can extrapolate to high availability and many of its internal components are not reactor prototypical. Closing the readiness gap for an FNF will require designing the machine for ease of maintenance, developing reliable components, incorporating them in the FNF design with generous safety margins, and developing capable remote handling and maintenance systems.

Electricity generation: DEMO must demonstrate net electricity generation at levels close to that of a commercial power plant, e.g., 750 MWe. Electricity generation requires complete integration of plant operation including the power core equipment, the main heat transfer and transport equipment, and turbine- generating equipment. *Net* electricity generation requires, further, efficient conversion of neutron energy to electricity and efficient plant systems to minimize recirculating power requirements and be compatible with attractive economics.

FNF mission assessment: A pilot plant is intended to achieve a level of plant integration, including both power core and plant systems, needed to produce net electricity, i.e. $Q_{eng} \geq 1$, where Q_{eng} is the ratio of electrical output power to recirculating power. Successful accomplishment of this mission would substantially narrow the readiness gap to DEMO, although DEMO would have to demonstrate a Q_{eng} of 4-7 for acceptable economics. An FNSF-AT could be designed to demonstrate electricity generation, but it would be a net electricity user due to its copper magnets.

Power plant licensing and safety: DEMO must demonstrate a high level of public and worker safety, low environmental impact, and compatibility with day-to-day public activity. Site evacuation should not be required, even for the worst credible accident scenario. As a DEMO

TABLE III. Summary Comparison of FNSF-AT and Pilot Plant Missions

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	2	2	2
Disruption avoidance	3	3	3
Plasma Control Technology			
Diagnostics and control systems	3	3	**Not assessed**
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	

readiness criterion, there must be substantial data and experience on safety performance of prototypical fusion nuclear system.

FNF mission assessment: In the U.S., it is expected that either FNF option could be constructed and operated within the Department of Energy (DOE) regulatory framework based on an updated DOE standard. Experience with DOE licensing of either FNF will be useful, but it is not expected to be a DEMO prerequisite.

V. SUMMARY COMPARISON OF FNF OPTIONS

V.A Mission Comparison

We summarize our assessment of the FNSF-AT and Pilot Plant missions by comparing the degree to which they would reduce the risks for DEMO, using a 0 to 3 scale and corresponding colors, similar to Greenwald[2]. It is assumed that either FNF option fully succeeds in accomplishing its mission, and that either is accompanied by a parallel science and technology development program also aimed at DEMO readiness. The summary mission comparison is presented in TABLE III. Naturally, a pilot plant with its higher neutron fluence, and broader mission goes farther toward DEMO readiness than an FNSF-AT. However, neither tokamak option narrows the large gap in fusion gain Q_{DT} between ITER and DEMO, since neither could prototype a DEMO steady-state plasma control scenario, in which the plasma is dominated by self-heating and self-driven currents, with little external control possible. A well-validated predictive simulation capability would be essential to reduce the risk left by this large gap. A stellarator pilot plant, on the other hand, leaves no such gap because it operates at DEMO-like Q_{DT} values so its steady-state control scenarios can be prototypical of a stellarator DEMO.

V.B Readiness Comparison

We compare the state of readiness for an FNSF-AT and a pilot plant by summarizing the science and technology advances that could be achieved by the world fusion community in the next ~10 years to reduce the risks in proceeding with an FNF 10 years from now.

V.B.1 Plasma configuration and operation

Over the next decade, the world's tokamaks and stellarators will continue to advance the science basis for high-performance, steady-state plasma control, including new DT plasma results at $Q \leq 1$, though mostly with H and D plasmas. ITER will only begin to operate. Investments in simulation capabilities for making reliable extrapolations from current experiments and ITER to FNF and DEMO must be made. An expected increase in emphasis on divertor physics performance issues, motivated by DEMO needs, is likely to narrow the large gap in that area. However, the characteristic timescale for testing new divertor configurations such as a super-X or snowflake, or for assessing new material solutions such as liquid metals, is of order ten years, meaning that an FNF proceeding ten years from now will enjoy some risk reduction but will still have to accept and manage large risks. Similarly, it is likely that an FNF will still face significant risks associated with disruptions at that time unless it is decided to follow a pathway through a stellarator pilot plant and DEMO. In the plasma configuration and operation category, the state of readiness for an FNF ten years from now will depend mainly on progress in resolving divertor and disruption issues in the interim, and will be about the same for both FNSF-AT and pilot plant options.

V.B.2 Plasma control technology

Advances in diagnostics, heating and current drive, fueling, and superconducting magnet technology can be expected over the next decade, driven by the needs of ITER. These will benefit FNF readiness, but larger investments will be needed to prepare control technologies compatible with the harsher FNF environment and more restricted access. Much progress could be made, and the state of readiness for either FNF option ten years from now will be about equal, depending on the amount of R&D investment in the interim.

V.B.3 In-Vessel Systems and Tritium

The growing interest worldwide in planning for a next-step FNF is likely to accelerate the pace of development of blankets, plasma-facing components, and tritium processing systems that go beyond ITER requirements. At this time there are large readiness gaps in this area; for example, the necessary programs and support facilities for development and integration of breeding blankets and tritium processing systems at the component and subsystem levels are not yet in place. Irradiation testing results over the next decade will be limited by the lack of a suitable fusion-spectrum neutron irradiation facility. Improving the state of readiness of in-vessel and tritium systems for an FNF in ten years will thus require a large increase in the level of R&D investment in these technologies and will depend on the required design lifetime for the core components. It is likely that significant risks would exist for either an FNF or a pilot plant to proceed at that time, but the materials-related risks for a pilot plant could be higher because of its longer component lifetime requirements.

V.B.4 Plant Integration

The scope of progress in plant integration over the next ten years will be determined by the goals of the envisioned FNF, which will largely drive the advances in this areas. Either FNF option considered in this paper must achieve a level of integration sufficient to ensure maintainability and tritium self-sufficiency. A pilot plant, with its aim to demonstrate net electricity generation, DEMO-relevant design and maintenance, and high availability, 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.

VI. CONCLUSIONS

From this assessment and comparison of an FNSF-AT and a pilot plant as FNF mission options, we come to the following conclusions.

1. Either option, assuming it accomplishes its mission and is accompanied by a parallel science and technology development program also aimed at DEMO readiness, would make significant progress toward closing readiness gaps and reducing risks for DEMO. However, a pilot plant goes substantially farther than an FNSF-AT.
2. The state of readiness to proceed ten years from now can be significantly improved for both options by considerably increasing the level of R&D investment in critical plasma operation issues, particularly power exhaust and disruptions, and in all critical technologies. A pilot plant, with its broader mission and more advanced level of plant integration, requires a broader R&D program and correspondingly higher levels of investment in the next ten years. The risks could not be reduced to low levels for either option, but either could proceed with an accompanying strategy for accepting and managing the attendant risks.
3. Neither tokamak option narrows the large gap in fusion gain Q_{DT} between ITER and DEMO. A consequence is that neither can prototype a DEMO steady-state plasma control scenario, in which the plasma is dominated by self-heating and self-driven currents, with little external control possible. A well-validated predictive simulation capability is essential to reduce the risk left by this large gap.
4. A stellarator development path through a pilot plant would mitigate program risks associated with control of steady-state, high-gain plasmas and avoidance of disruptions.
5. Five new major R&D initiatives that could make a quantum improvement in FNF readiness and DEMO planning ten years from now are: 1) a predictive simulation project, 2) a compact stellarator program based on magnetic quasi-symmetry, 3) a DEMO diagnostics initiative, 4) a steady-state, non-nuclear divertor-plasma integration facility, and 5) a fusion-neutron materials irradiation facility.
6. Quantitative risk analysis must be fully integrated into the planning and management of fusion development programs, since it is likely that future fusion development steps can only proceed with significant risk.

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