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Charting the Roadmap to Magnetic Fusion Energy*

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Abstract— **With the ITER era now well underway, the fusion community is considering the next major steps in magnetic fusion energy (MFE) development. It follows that there is heightened interest worldwide in understanding the roadmap to commercial MFE. In reality, there is no unique roadmap. An important differentiator among possible pathways is risk, i.e. the risks accepted in going from step to step and how risks are mitigated through R&D programs that accompany and support the progression of major nuclear devices. We consider a rollback approach, starting from a definition of what Demo (a power plant that is the last step before commercialization) must accomplish. We assess, in fusion science and technology terms, the mission and requirements for Demo, its prerequisites, and the requirements for a major nuclear devices and the accompanying programs that could precede Demo in order to satisfy its pre-requisites. One option for a pre-Demo MFE device is a pilot plant, a facility that would develop and test nuclear components surrounding the plasma, prototype maintenance schemes applicable to a power plant, and demonstrate both tritium self-sufficiency and net electricity generation. An initial assessment of the pilot plant, in terms of its potential to satisfy Demo prerequisites and the associated risks, is presented.***

Keywords- fusion energy, Demo, roadmap, risk

I. INTRODUCTION

With the ITER era now well underway, the fusion community is considering the next major steps in magnetic fusion energy (MFE) development. It follows that there is heightened interest worldwide in understanding the roadmap to commercial MFE. In reality, there is no unique roadmap. An important differentiator among possible pathways is risk, i.e. the risks accepted in going from step to step and how risks are mitigated through R&D programs that accompany and support the progression of major nuclear devices.

Here we consider a rollback approach, starting from a definition of Demo, a power plant that would be the last step before commercial deployment, in terms of what it must accomplish. We assess, in fusion science and technology terms, the mission and requirements for Demo, its prerequisites, and the major nuclear devices and accompanying programs that could precede Demo in order to satisfy its prerequisites. We consider a pilot plant as an option for “Demo minus 1” (the device that would immediately precede Demo) that would substantially narrow the gaps to Demo if successful.

II. DEMO GOALS AND PREREQUISITES

A. Demo Socio-Economic Goals

The goals for a fusion Demo has been documented in a U.S. study [1], with input from fusion research institutions as well as representatives of utilities and support industries. An MFE Demo must use the same technologies and plasma operating scenarios as are planned for a commercial power plant. It must demonstrate reliable 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, compatible with day-to-day public activity.
5. Competitive cost of electricity.

These goals are defined so as to make the step from Demo to the first commercial power plant a small one. It is assumed that some of the development will be completed on Demo itself, so that these are accomplishments to be achieved by the end of Demo’s mission, not necessarily at the beginning. The goals are fundamentally socio-economic in nature, in that they do not *a priori* restrict the scientific and technical solutions. There is freedom in the choices among available machine configurations (e.g., between tokamaks and stellarators), plasma scenarios (e.g., between pulsed and steady-state), and technologies (e.g., among the various plasma heating and current drive technologies) to be pursued in addressing Demo goals. A major differentiator of the various options is risk. Solutions which have been successful to date in developing the fusion plasma knowledge base (e.g., pulsed, neutral-beam heated tokamaks, solid plasma-facing materials) may not be compatible with the requirements of a tritium self-sufficient power plant having high availability. They carry risk even though much is known about them. One can mitigate the risks by diversifying the investments and pursuing promising but less well-developed alternatives and developing multiple options in parallel.

Although one might choose to target a less ambitious Demo, we target the goals given here on the assumption Demo that must be very close to a commercial plant in its design and operation and must be steady-state in order to convincingly demonstrates fusion’s readiness for deployment. One could

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chose to lower the goals and leave a larger gap between Demo and a commercial plant, and in so doing accept greater risk that an additional step beyond Demo, and an additional time delay of perhaps several decades, will be needed to develop fusion. Risk management choices such as these are available at every step along the development path. Risk tolerance and the assumptions used to evaluate risks, i.e. the likelihood and consequences of uncertain outcomes, are variables that affect the steps in the development path, and the cost and timeline to fusion energy. Charting the optimum roadmap to fusion energy is a task in which risk management has a central role.

B. *Scientific and Technical*

In order to develop a scientific and technical (S&T) roadmap, the Demo requirements must be re-expressed in terms of magnetic fusion S&T properties and parameters. Following I. Cook, *et al.* [2], we identify 13 S&T categories with which to quantify missions, requirements, and prerequisites for major fusion nuclear facilities.

Plasma Configuration
- Burning Plasma
- Steady-state operation
- Divertor performance
- Disruption avoidance
- Stellarator-specific issues

Control
- Diagnostics and control systems
- Heating, current drive and fueling
- Superconducting magnets

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

Plant Integration
- High Availability and Remote Handling
- Electricity generation
- Power plant licensing

Next we consider the S&T requirements that Demo must satisfy in order to meet its socio-economic objectives, as well as the prerequisites that ideally would establish readiness for such a Demo, in each of these categories.

B.1) PLASMA CONFIGURATION

Burning Plasma: A Demo requires a plasma gain Q (ratio of fusion power to plasma heating power) of ~30 to be economical. As a prerequisite, a preceding device, e.g., Demo minus 1, should demonstrate controlled plasma operation in a steady-state scenario prototypical of that planned for Demo and commercial plants. It follows from this and other prerequisites that the configuration and operating scenario for the first commercial power plant is effectively decided at the Demo minus 1 step. It is planned that ITER will demonstrate operation at $Q = 5$ in a steady-state scenario and will provide relevant data and experience at $Q = 10$, albeit in a pulsed mode. Successful accomplishment of these missions in ITER may be sufficient to satisfy Demo prerequisites in this category if there is by then a physics basis for confident extrapolation to high-gain conditions. The technical risk of such a step must be weighed against the cost and schedule risk of requiring a facility to demonstrate Demo-like gain as a prerequisite for Demo.

Steady-state operation: A Demo must reliably operate in steady state at full and partial power for periods of at least 9-12 months. Demo minus 1 can be a much lower power device but should at least demonstrate reliable steady-state operation at its design parameters for periods of at least 4-6 months, so that the step to Demo is no more than a factor of 2 extrapolation.

Divertor performance: It is expected that the Demo will have steady-state heat losses corresponding to average heat flux through the plasma surface $\langle P/S \rangle$ of about 1 MW/m^2, and will operate with plasma-facing component temperatures of ~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. As a prerequisite for Demo there must certainly be an S&T knowledge base for confident extrapolation to Demo requirements, and it should include demonstrated successful operation at $\langle P/S \rangle \geq 0.5$ MW/m^2 and first wall temperatures of ≥ 400 C.

Disruption avoidance: As defined, a Demo can tolerate at most one scheduled shutdown per year. Certainly this means that there can be no more than one disruption per year that requires an in-vessel inspection for damage afterward, since even the inspection time could unacceptably impact availability. Mitigated disruptions, defined to mean that the facility can return to operation immediately afterward without a time-consuming inspection, may be more tolerable. As a prerequisite, there should be high confidence that Demo can meet this objective, including demonstrated successful operation in Demo minus 1 of continuous operation in for at least 6 months without an event that would cause a vessel intervention in Demo, and demonstrated successful performance of any mitigation schemes planned for Demo.

Stellarator-specific issues: A stellarator configuration could be chosen for Demo as a strategy to reduce the risks associated with steady-state operation and disruptions. If so, the Demo minus 1 facility should be prototypical, so the choice among possible stellarator configurations (i.e., W7-X-like, LHD-like, or quasi-symmetric) would have to be made at the Demo minus 1 stage. At the highest level, most Demo objectives are generic to MFE. The requirements for demonstration and understanding of burning plasmas, steady-state operation, divertor and first wall performance, most technologies, and high availability apply equally to tokamaks and stellarators. By choosing to follow a stellarator instead of a tokamak path to Demo, one could reduce or eliminate risks and R&D costs associated with current sustainment, disruptions, and control; while accepting the risks and mitigation costs associated with a less mature physics basis and more complex magnet and in-vessel component geometries. There are no risk-free paths to a fusion Demo, but one is free to choose paths that encounter certain risks while avoiding others, and to invest in strategies to mitigate the encountered risks.

B.2) CONTROL

Diagnostics and control systems: A Demo must demonstrate precise control of plasma scenarios during routine plasma startup and shutdown; during full- and reduced-power steady-state operation; and during transitions between power levels at prescribed, safe ramp rates. The diagnostic and control systems must be sufficiently reliable that there is only a small (e.g. < 25%) contribution to machine down time due to failures in these systems. Challenges for Demo diagnostics include a harsh operating environment due to radiation, and severe constraints on available space after providing adequate blanket coverage for tritium self-sufficiency. The development path for Demo diagnostics includes demonstration of techniques to make the minimum set of measurements required for reliable, robust control and machine protection, over the life of the facility, for a steady-state Demo plasma scenario. The necessary development requires a broad-based program using a range of plasma facilities and test stands, but a demonstration in Demo minus 1 is needed to satisfy Demo prerequisites.

Heating, current drive and fueling: Four plasma heating and current drive technologies (neutral beam injection, ion cyclotron waves, electron cyclotron resonance heating, and lower hybrid waves) are in use throughout the fusion community, reflecting a risk management strategy of developing multiple options in parallel. Similarly, there are multiple fueling options including pellets, cold gas, and compact toroids. This diversification strategy is wise in light of the risks facing these technologies (especially heating and current drive) in a Demo environment. Neutral beams have been very successful in non-burning plasma experiments but their requirement for large openings in the blanket and shield is a large challenge for a burning plasma device. Nuclear compatibility is an issue for techniques that require wave launchers close to the plasma, for example ion cyclotron, lower hybrid, and some electron heating applications. Reaching efficiencies compatible with net electricity generation is an challenge for all current drive technologies. As with diagnostics, the necessary development can be broadly dispersed but a demonstration of the Demo heating, current drive, and fueling scenario in Demo minus 1 is needed to satisfy Demo prerequisites.

Superconducting magnets: A Demo requires superconducting magnets that must operate reliably for the life of the facility. As a prerequisite, the technology must be established in fusion conditions. Success in ITER with its superconducting magnet system could possibly satisfy Demo prerequisites, provided only modest technology extensions beyond ITER are required for Demo. Some ITER requirements, e.g. compatibility with fast current ramps and a large number of cycles, may be relaxed in the Demo application, and may permit higher magnetic fields and current densities. Such advances would be favorable for reducing machine size. If large advances in performance or reliability were needed, they would be developed in non-fusion facilities. Reliable operation of superconducting magnets in a fusion environment prototypical of Demo would have to be demonstrated in Demo minus 1.

B.3) IN-VESSEL SYSTEMS AND TRITIUM

First wall / blanket / vacuum vessel: The Demo blankets must efficiently convert fusion neutrons into process heat and must provide a tritium breeding ratio (TBR) greater than unity to ensure tritium self-sufficiency of the plant. Operation at a temperature of ~600 C is required for thermal efficiency. The TBR requirement means that coverage of the plasma surface by the blanket must be near-complete and conformal, and that transparency to neutrons of the plasma facing armor must be high. The former restricts available access for heating systems and diagnostics; the latter is potentially incompatible with disruptions. In addition, the plasma-facing armor must withstand the plasma heat and particle loads and maintain required properties for the service life of a blanket module (6 MW-yr./m^2 initially and up to 20 MW-yr./m^2 of integrated average neutron wall load at maturity) Helium-cooled tungsten alloys and liquid metals are candidates for the first wall material. Blanket structural materials must maintain adequate properties under these conditions and must shield the vacuum vessel so that it can maintain adequate structural properties (e.g., fracture toughness, re-weldability) over the life of the facility (>120 MW-yr./m^2 integrated neutron wall load), and the superconducting magnets so they can operate at temperature around 4 K. As a Demo prerequisite, these systems, including any special required materials, must be thoroughly developed, including demonstration in a Demo minus 1 facility of successful operation at $\langle P/S \rangle \geq 0.5$ MW/m^2. first wall temperatures of ≥ 400 C and lifetimes corresponding to an integrated average neutron wall load of 3 MW-yr/m^2.

Tritium processing and self-sufficiency: In order to be tritium self-sufficient, Demo will require a processing system to extract tritium from the breeder material and re-supply the fueling system at a rate sufficient to keep up with daily tritium burn-up (~0.6 kg) while maintaining acceptably low inventories (<6 kg). The necessary extension of the technology beyond ITER can be carried out using dedicated facilities, but ultimately a successful demonstration of tritium self-sufficiency in Demo minus 1 is a prerequisite for Demo.

B.4) PLANT INTEGRATION

High Availability and Remote Handling: Demo is required to demonstrate availability ≥ 50% by the end of its life. To achieve this goal, the facility must be capable of being maintained, including all scheduled and unscheduled maintenance operations, by remote handling equipment. A prerequisite is that facility and all maintainable components must be configured from the outset to be compatible with the design and operational constraints imposed by remote handling. The facility must include systems for transport of components between the power core and hot cells where they can be safely handled and serviced. In addition, validated operational lifetime data are required for all systems. Non-replaceable systems (generally considered to included the vacuum vessel and the magnets) must have lifetimes under operating conditions exceeding that of the plant. Replaceable systems must have lifetimes and replacement times compatible with availability goals. There must be operational experience with validated maintenance equipment and procedures in a relevant environment, demonstrated in a Demo minus 1 facility. The Demo minus 1 should achieve overall availability of 10-30% by the end of its life.

Electricity generation: Demo is required to demonstrate net electricity generation at levels close to that of a commercial power plant, e.g., 750 MWe, as well as being able to operate at reduced power. Electricity generation requires a high level of integrated 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, especially plasma heating and current drive systems, to minimize recirculating power requirements and be compatible with attractive economics. As a prerequisite, there must be an adequate S&T knowledge base to show that Demo can achieve its net-electricity goals, and electricity generation from an integrated magnet fusion system, e.g. Demo minus 1, should be demonstrated.

<u>Power plant licensing</u>: Demo is required to 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 Demo prerequisites, there must be substantial data and experience on safety performance and failures in a relevant fusion nuclear system; ITER will make a large contribution in this area. A regulatory framework needs to be established by the competent authorities, the Nuclear Regulatory Commission in the case of the United States. Facilities leading up to Demo, including Demo minus 1, could be licensed as R&D facilities by, for example, the U.S. Department of Energy, providing valuable data and experience on licensing.

III. Roadmap Elements and Logic

Having established a working set of prerequisites for Demo, we continue the rollback analysis by considering program options for the step that precedes Demo on the roadmap. In terms of program requirements we consider two types: 1) operation of major fusion integration facilities and 2) S&T research and development. Major fusion integration facilities combine the designs, technologies, and operating modes approaching those envisioned for Demo, and test their integrated performance. Examples are ITER, a Demo minus 1 facility that could satisfy the Demo prerequisites described in Section II, and Demo itself. S&T research and development programs are needed to resolve plasma physics issues and develop the technologies to be tested and demonstrated in the integration facilities and Demo. These programs may themselves be large and require costly facilities, e.g., a materials irradiation facility or new plasma research facilities, to develop solutions to be tested or demonstrated in integration facilities. From the discussion in Section II, examples of fusion S&T programs that are to be needed to feed into Demo minus 1 and Demo are:

Plasma Configuration

- Physics of steady-state burning plasmas.
- Plasma heat and particle exhaust solutions compatible with impurity control and good plasma performance.
- Disruption avoidance and mitigation solutions compatible with high availability and tritium breeding.
- Plasma configuration optimization.

Control

- Diagnostics compatible with minimum control requirements, fusion environment, and tritium self-sufficiency.
- Efficient heating, current drive, and fueling systems compatible with minimum control requirements, fusion environment, and tritium self-sufficiency.
- Superconducting magnets compatible with a fusion environment.

In-Vessel Systems and Tritium

- First wall and blanket systems, including materials compatible long-term service in the fusion environment.
- Tritium processing systems

Plant Integration

- Integrated fusion system designs compatible with Demo objectives including net electricity generation maintenance by remote handling, safety, and licensing.
- Remote handling systems.

The roadmap to magnetic fusion is illustrated schematically in Figure III-1 Information from ITER, from a Demo minus 1 facility, and from a broad-based fusion S&T research and development program is combined to address the Demo prerequisites. Of interest here is a plan which develops fusion in a timely manner, with Demo constructed and operating well before 2050. For that reason, we consider a logic in which there is, besides ITER, only one other major fusion integration facility, namely Demo minus 1, before Demo. We assume that construction of Demo minus 1 could proceed in parallel with ITER. If Demo minus 1 must wait for ITER to finish, or if a sequence of two or more major integration facilities is required to satisfy Demo prerequisites, then the schedule for Demo most likely extends to well beyond mid-century. Though not addressed in this paper, another strategy is to proceed directly to Demo as the next step, with no Demo minus 1 step. Such a logic has been analyzed in EU Demo studies. Given the time required to secure approval for and execute a major facility step in fusion (e.g., ITER), moving to Demo as both the last step before commercial a power plant and the next step going forward would be attractive from a schedule perspective.

With a schedule objective included along with Demo's S&T objectives, schedule risk becomes a consideration alongside technical risk at each step along the roadmap. The decision to take each next step entails significant technical risk

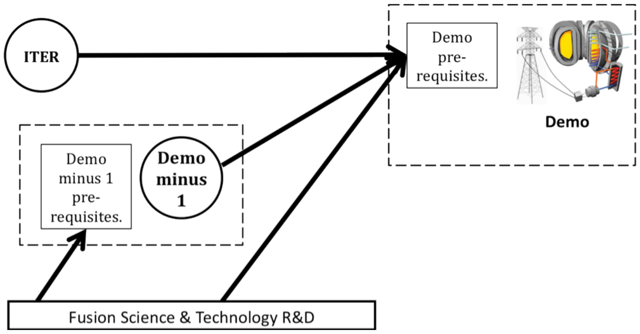

Figure III-1. Schematic Roadmap to an MFE Dem

Table IV-1. Pilot Plant Performance Parameters compared with ITER and Demo.

	ITER	**Pilot Plant**	**Demo**
Plasma duration (s)	500-3000	10^6-10^7	$3x10^7$
Engineering gain		1 - 3	4-6
Tritium sustainability (TBR)	none	1.0+	1.1
Avg. neutron wall load ⟨NWL⟩ (MW/m^2)	0.5	1-2	3-4
NWL at the test modules (MW/m^2)	0.7	1.5-3	4.5-6
Life of plant in years	20	20-30	30-40
Life of plant fluence (MW-y/m^2)	0.3	6-20	120-160
Life of blanket fluence (MW-y/m^2)		≥ 3	6 - 20
Blanket lifetime damage (dpa)		≥ 30	60 - 200
Total availability	2.5-5%	10-30%	50-85%
Plasma fusion gain, Q	5-10	4-7	~30
Fusion Power (MW)	500	300-600	2,500

in any case, due to the extrapolations in performance that are involved. Delays in major integration steps to complete additional R&D can reduce technical risks but increase schedule risks. Making such tradeoffs is a key element the risk management that is required in planning and executing the roadmap.

IV. A PILOT PLANT AS DEMO MINUS 1

A. *Pilot Plant Mission*

A potentially attractive option for Demo minus 1 is that of a pilot plant, a device with 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 first mission is also known as the CTF (for "component test facility") or FNSF (for "fusion nuclear science facility") mission. Interesting studies have been carried out for driven-plasma devices targeting the CTF/FNSF mission. [3, 4] Such devices typically use copper coils, are not intended to be prototypical of a power plant in their design, and consume net electricity. The overall pilot plant goal is to integrate key science and technology capabilities of a fusion power plant in a next-step facility. The motivation for considering such a device is to make as much progress as possible with the next-step facility toward fully satisfying the Demo prerequisites. Too limited a mission raises the risk of needed an additional step in the step in the roadmap. Given the time required to secure approval for and execute a major facility step in fusion (e.g., ITER) an additional step could delay Demo by several decades. The aim of the pilot plant is to minimize the gap between the next step and Demo.

B. *Pilot Plant Design*

The requirements for a pilot plant are compared with those of ITER and Demo in Table IV-1. The Pilot Plant column is based on PPPL studies and the Demo column was compiled based on ARIES power plant studies. Pilot plants are required to have Q_{eng} (ratio of electricity produced to electricity consumed) greater than unity, average neutron wall load (NWL) ≥ 1 MW/m^2 (for blanket testing), and pulse lengths of several months. They must be designed for high availability, with a goal of achieving up to 30% at maturity. The plant would be equipped initially with a reliable "base blanket" capable of providing tritium self-sufficiency from the beginning of its operational lifetime. Access for test blanket modules would be provided to support testing of advanced blankets for later phases of the pilot plant and eventually Demo.

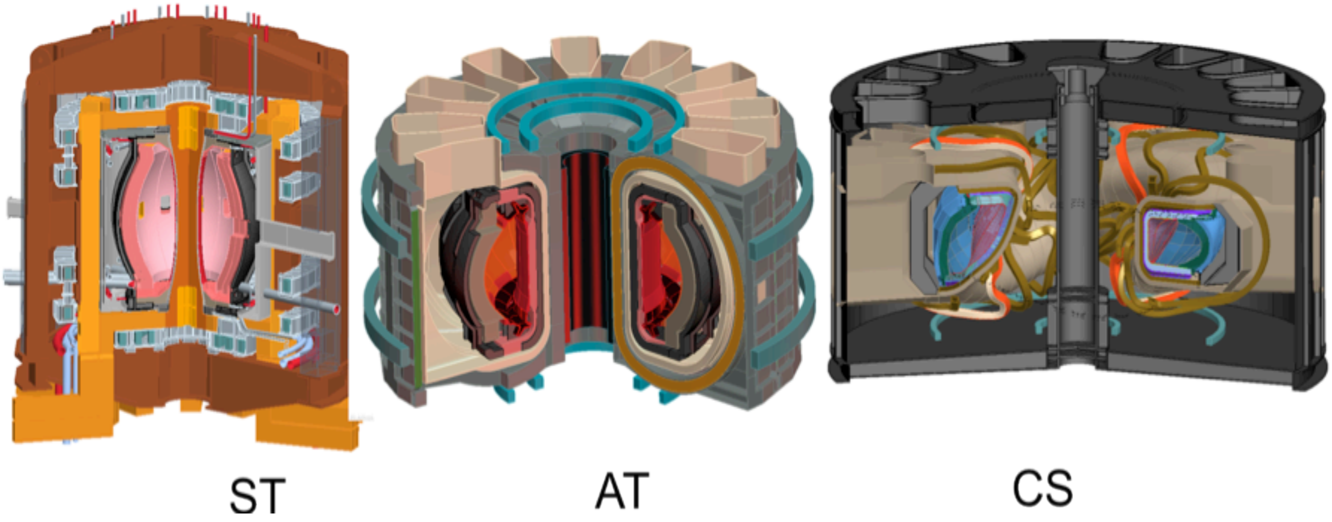

Figure IV-1. Pilot plant configuration designs based on the spherical torus (ST), advanced tokamak (AT), and compact stellarator (CS).

Three steady-state magnetic configurations have been examined for the pilot plant: the advanced tokamak (AT), spherical tokamak (ST), and compact stellarator (CS). [5] These configurations are considered because: the tokamak presently has the most well-developed physics basis, the ST offers the potential for simplified maintenance and high neutron wall load, and the CS offers disruption-free operation with low recirculating power. The three configurations are depicted in Figure IV-1. In all cases, availability is a key driver in the development of the configuration designs. In the AT and CS, the internal components (blanket, shield, support structures, divertor hardware, and plasma-facing armor) are segmented, and the magnet system is designed to provide wide inter-coil spacing, so as to permit sector removal and replacement of the internal components. In the case of the stellarator, it is assumed that the main coils can be made straight and parallel on the outboard side, using local coils or magnetic materials within a sector to help shape the plasma on the outboard side. These and other feasible strategies for designing a maintainable compact stellarator have been identified. [Neilson, IAEA]. The ST uses a jointed copper toroidal field coil and a jointed vacuum vessel can be partially disassembled to allow the central column and the internal components to be removed vertically as large units.

System codes and 1D neutronics calculations are used to size each of the pilot plant designs. The results are summarized in Table IV-2. In linear dimensions they are about two-thirds the size of the corresponding ARIES power plant designs. The ST has the highest neutron wall load but also requires ~50% higher fusion power than the other designs in order to power the toroidal field magnet (the poloidal coils are superconducting). The AT and the CS both use all low-temperature superconducting magnets. It is assumed the average magnet current densities can be about twice that of ITER, based on technology advances and reduced number of cycles and disruptions in a pilot plant compared to ITER. The magnet current density is a key size determinant in the these options. The AT size is driven by engineering gain while the CS size is driven by the neutron wall load requirement because the lack of a need for current drive greatly reduces recirculating power so it easily achieves $Q_{eng} > 1$.

Table IV-2. Pilot plant design parameters for the AT, ST, and CS, for blanket thermal efficiencies η_{th} of 0.3 and 0.45.

	AT		ST		CS	
η_{th}	0.30	0.45	0.30	0.45	0.30	0.45
$A = R_0 / a$	4	4	1.7	1.7	4.5	4.5
R_0 [m]	4	4	2.2	2.2	4.75	4.75
P_{fus} [MW]	553	408	990	630	529	313
P_{aux} [MW]	79	100	50	60	12	18
$\langle W_n \rangle$ [MW/m^2]	1.8	1.3	2.9	1.9	2	1.2
Peak W_n [MW/m^2]	2.6	1.9	4.5	3.0	4.0	2.4
Q_{DT}	7.0	4.1	19	10.5	42	17
Q_{eng}	1	1	1	1	2.7	2.7

C. *Assessment of a Pilot Plant Roadmap against Demo Prerequisites*

In Table IV-1, we summarize the Demo mission and prerequisites in each of the S&T categories introduced in Section II.B. In the last column we assess the potential to satisfy the Demo prerequisites with a roadmap that includes ITER and a pilot plant as precursor major fusion integration facilities and also includes the full set of S&T research and development programs listed in Section III. Such a program could satisfy the prerequisites in most categories.

For a tokamak-based roadmap, the most significant gap is the lack of demonstrated steady-state burning plasma control at Demo-like plasma gain ($Q \approx 30$). The attendant risk is that of Demo being unable to operate with economically low levels of recirculating power. Some mitigation of this risk could be achieved by developing a predictive tokamak simulation capability, validated against ITER burning plasma data, that can project Demo performance. A moderate-pulse-length tokamak experiment focused on high-gain burning plasma control could add valuable data to the validation basis and could further reduce the risk.

A stellarator pilot plant would operate at Demo-like Q values and therefore would fully satisfy Demo prerequisites in the burning-plasma category. For a stellarator-based roadmap, the risk is instead borne at the pilot plant step, since it would proceed on a less mature science and technology data base, in particular lacking a burning-plasma step analogous to ITER. Some mitigation of the risk could be achieved by developing designs with improved engineering characteristics and by accelerating stellarator physics research. A validated predictive stellarator simulation capability would be essential. Research aimed at deepening the understanding of the physics connections between tokamaks and stellarators would support stellarator simulation development by providing a link to the tokamak data base, including ITER, that could further reduce risks.

V. CONCLUSIONS

With the ITER project moving toward full realization, magnetic fusion is firmly on an energy path. The government investments in a reactor-scale integrated fusion nuclear facility indicate a readiness to take major steps toward fusion energy and to accept attendant risks. There is a sufficient understanding of the socio-economic goals for an MFE Demo, a facility intended to demonstrate readiness for commercial deployment, to define its S&T goals and prerequisites. For these reasons it is now both necessary and possible to apply a rollback approach, starting with an understanding of the end product, to the task of laying out a roadmap to Demo.

Under the assumption that there is some time-urgency to develop fusion energy and given the long time required to plan and execute a major fusion integration facility such as ITER, there can be at most only one more major integration facility before Demo. We call such a facility "Demo minus 1" but do not rule out the possibility that multiple such facilities could be build worldwide, provided they are built in parallel with ITER. Moreover, the possibility of omitting the Demo minus 1 step entirely and moving directly to Demo as the next major step may be a way to accelerate fusion development, depending on the risks of such a plan. We will analyze this option in the future.

Risk attends every step in fusion roadmap, so risk management must have a central role in the planning and execution of the fusion development program. Risk considerations are prominent in making R&D investment choices among the available options in, for example, magnetic configurations, plasma operating scenarios, and fusion technologies. Each option has risks and uncertainties in a Demo application that must be weighed against their proven capabilities in conditions far from Demo.

The choice of a mission and design for a Demo minus 1 facility entails risks both in the step from the present knowledge base to Demo minus 1, and in the step from Demo minus 1 to Demo. If too large a step to Demo minus 1 is taken, then it risks failure to satisfy too many of the Demo prerequisites; if too small a step is taken, then there is a risk of leaving too large a gap to Demo afterward to close without an additional, time consuming facility. If fusion development is being held to a milestone schedule, then schedule risks must be considered and weighed against the technical risks at each major decision point.

A pilot plant is being analyzed as an option for the Demo minus 1 step that would integrate key science and technology capabilities of a fusion power plant and, if successful, would substantially narrow the gap to Demo. The pilot plant mission is to: 1) test internal components and tritium breeding, 2) prototype a power plant machine configuration and maintenance scheme, and 3) generate net electricity. Analysis of the risks in taking the step *to* a pilot plant is necessary but has not yet been completed and will be reported in the future. The decision on the configuration and mission of the next major integration step must be informed by a careful analysis and comparison of the "before" and "after" risks of all candidate options. Decisions should be taken in the context of optimizing the roadmap to a magnetic fusion Demo. In addition, there must be a broad-based R&D program to develop the science and technology, using the major facilities such as Demo minus 1 and Demo primarily for testing and demonstration.

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Table IV-1. Summary of Demo goals and prerequisites and assessment of Pilot Plant development path against Demo prerequisites

	Demo Goal	**Demo Prerequisite (Ideal Case)**	**Assessment of Pilot Plant + ITER + Fusion S&T R&D programs *vs* Demo Prerequisite**
Plasma Configuration			
Burning Plasma	$Q \approx 30$	Demonstrated control at $Q >> 10$.	ITER: $Q = 10$ (pulsed), 5 (steady-state) . Pilot plant (steady-state): Q 5-7 (for AT); Q 17-42 (for CS)
Steady-state operation	Continuous operation for 9-12 months	Demonstrated continuous operation for 4-6 months.	Could fully satisfy.
Divertor performance	$\langle P/S \rangle \approx 1$ MW/m^2, $T \geq 600$ C, compatible with low impurity, high-performance plasma.	$\langle P/S \rangle \geq 0.5$ MW/m^2, $T \geq 400$ C, compatible with low impurity, high-performance plasma.	Could fully satisfy.
Disruption avoidance	< 1 unmitigated disruption per year	Demonstration of < 1 unmitigated disruption in 6 months, demonstrated mitigation schemes (if required).	Could fully satisfy
Stellarator-specific issues		Satisfy all Demo prerequisites in a Stellarator Demo minus 1.	Could fully satisfy provided pilot plant is a stellarator.
Control			
Diagnostics and control systems	Effective for all scenarios, reliable, compatible with tritium self-sufficiency	Demonstrated effectiveness, reliability, and TBR > 1 compatibility of an integrated system.	Could satisfy for pilot plant performance and conditions.
Heating, current drive and fueling	Efficient and effective for all scenarios, reliable, compatible with tritium self-sufficiency.	Demonstrated efficiency, effectiveness, reliability, and TBR > 1 compatibility of an integrated system.	Could satisfy for pilot plant performance and conditions.
Superconducting magnets	Effective, reliable for life of facility	Demonstrated success of design and operation under Demo-like conditions.	Could satisfy for pilot plant performance and conditions.
In-Vessel Systems and Tritium			
First wall / blanket / vacuum vessel	$\langle NWL \rangle \approx 1$ MW/m^2, blanket lifetime neutron fluence 20 MW-yr./m^2, $\langle P/S \rangle \approx 1$ MW/m^2, TBR > 1, vessel lifetime neutron fluence ≥ 120 MW-yr./m^2	Demonstrated $\langle NWL \rangle \approx 1$ MW/m^2, blanket lifetime neutron fluence > 3MW-yr./m^2, $\langle P/S \rangle \geq 0.5$ MW/m^2, TBR > 1, vessel lifetime neutron fluence ≥ 20 MW-yr./m^2	Could fully satisfy
Tritium processing and self sufficiency	Tritium self sufficiency, low inventory.	Demonstrated tritium self sufficiency, low inventory.	Could fully satisfy
Plant Integration			
High availability and remote handling	Availability > 50%	Demonstrated availability 10-30%	Could fully satisfy
Electricity generation	~750 MWe net electricity	Demonstrated electricity generation	Could demonstrate *net* electricity generation.
Power plant licensing	Licensable by competent authority for commercial plants.	Demonstrated licensability by appropriate authority, data base for Demo licensing.	Could fully satisfy
Demonstration of power plant technologies and operating scenarios.	Full demonstration	Demonstration of a fully-integrated system	Could fully satisfy

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