A Pilot Plant as the Next Step toward an MFE Demo*,†)

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An assessment of Demo goals and of prerequisites for Demo readiness motivate an examination of a pilot plant: an intermediate facility designed to substantially narrow the technical gap to Demo in a next step. A pilot plant would: 1) test internal components and tritium breeding in a steady-state fusion environment, 2) prototype a maintainable design and maintenance scheme for a power plant, and 3) generate net electricity. Preconceptual designs based on the advanced tokamak (AT), spherical tokamak (ST), and compact stellarator (CS) have been developed in order to compare their relative merits as fusion systems. Any of them would take a large step toward Demo in key performance metrics, e.g. engineering gain Q_{ENG} (≥1), neutron wall load (> 1 MW/m^2), tritium breeding ratio (> 1), pulse length (10^6–10^7 s), blanket lifetime fluence (≥ 3 MW-yr/m^2), plant lifetime (6-20 MW-yr/m^2), and availability (10-30%), but they differ in their associated risks.

Keywords: pilot plant, Demo, technology, roadmap, tokamak, spherical tokamak, stellarator

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1. Introduction

With the ITER project now launched on its mission to answer outstanding questions regarding the control of a burning plasma, the next steps toward commercial magnetic fusion energy (MFE) are under consideration with renewed intensity worldwide. Substantial science and technology development is required beyond ITER, for example in energy and tritium extraction, rapid replacement of internal components, plasma exhaust handling, and steady-state plasma control with minimal recirculating power. An intermediate integration device between ITER and a demonstration power plant (Demo) may be required to reduce the risks in developing a reliable fusion system with increased availability.

We consider Demo to be a power plant that would be the last step before commercial deployment, and assess its scientific and technical (S&T) requirements and prerequisites. We consider a pilot plant as an option for a "Demo minus 1" device that would immediately precede Demo and would substantially narrow the gaps to Demo if successful.

2. Demo Requirements and Prerequisites

The goals for a fusion Demo have been documented in a U.S. study [1]. 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.

Demo 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. The technical risks must be largely eliminated in the steps preceding Demo by demonstrating the key technologies in an integrated system at performance levels approaching Demo, such that large extrapolations are not required.

In order to assess Demo prerequisites, we consider S&T categories, following Ref. [2], in four groups: Plasma Configuration, Control Technology, In-Vessel Systems and Tritium, and Plant Integration. Next we consider the S&T requirements that Demo must satisfy in order to meet its objectives, as well as the prerequisites that ideally would establish readiness for such a Demo, in each of these categories. These characteristics are generally based on U.S. power plant design studies. [3, 4]

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2.1 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 is planned that ITER will demonstrate operation at $Q = 5$ in a steady-state scenario and will provide relevant data and experience at $Q = 10$ in a pulsed mode. Accomplishment of these aims in ITER may suffice for Demo if there is a physics basis for confident extrapolation to high-gain.

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 P/S of about 1 MW/m^2, and will operate with 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. As a prerequisite for Demo, successful operation at P/S ≥ 0.5 MW/m^2 and first wall temperatures ≥ 400 C should be demonstrated.

Disruption avoidance: Since a Demo can tolerate at most one scheduled shutdown per year, there can be no more than one disruption per year that requires an extended shutdown, although mitigated disruptions may be more tolerable. As a prerequisite, successful operation in Demo minus 1 of continuous operation for at least 6 months should be demonstrated.

Stellarator-specific prerequisites: A stellarator configuration could be chosen for Demo as a strategy to reduce the risks associated with steady-state operation and disruptions. Prerequisites for burning plasmas, steady-state operation, divertor and first wall performance, most technologies, and high availability are about the same for stellarators as for tokamaks. By choosing to follow a stellarator path, one could reduce or eliminate risks and R&D costs associated with current sustainment, disruptions, and control; while accepting risks associated with a less mature physics basis and more complex magnet and in-vessel component geometries.

2.2 Control technology

Diagnostics, heating, current drive, fueling, and control systems: A Demo must demonstrate precise, reliable, and energy-efficient control of plasma scenarios during all phases of operation. 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. Heating and current drive challenges are efficiency (wall-plug to plasma) of current drive, compatibility with the nuclear environment, and impact on tritium breeding if large openings are required. As a prerequisite, successful plasma control, integrating the diagnostics, heating and current drive, and fueling systems planned for Demo, should be demonstrated in Demo minus 1.

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 suffice as a prerequisite if only modest technology extensions beyond ITER are required for Demo. Preferably, reliable operation of superconducting magnets should be demonstrated in Demo minus 1.

2.3 In-vessel systems and tritium

The Demo blankets must efficiently convert fusion neutrons into process heat and, together with the tritium system, must ensure tritium self-sufficiency of the plant. Operation at high temperature is required for thermal efficiency. 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). The tritium processing system must extract tritium from the breeder material and re-supply the fueling system at a rate sufficient to keep up with daily tritium burn-up while maintaining acceptably low inventories. As a prerequisite, successful heat extraction and tritium self-sufficiency, integrating the first wall, blanket, and tritium processing technologies planned for Demo, must be demonstrated in Demo minus 1 at performance levels and lifetime exposures that leave a manageable gap, e.g. no more than a factor of ~2, to the Demo step.

2.4 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 prerequisite, efficient maintenance operations must be demonstrated in a prototypical Demo minus 1, ideally achieving availability of at least 30%.

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.

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 Demo prerequisites, there must be substantial data and experience on safety performance prototypical fusion nuclear system.

3. A Pilot Plant As Demo Minus 1

3.1 Pilot plant mission

A potentially attractive option for Demo minus 1 is 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. Interesting studies have been carried out for driven-plasma devices targeting fusion nuclear science and component testing [5, 6]. Such devices typically use copper coils, consume net electricity, are not intended to be prototypical of a power plant in their design or maintenance. 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 go as far as possible toward fully satisfying the Demo prerequisites.

3.2 Pilot plant design

The requirements for a pilot plant are compared with those of ITER and Demo in Table 1. The Pilot Plant column is based on PPPL studies [7] 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.

The scale of the power handling challenge is represented in Table 1 by the global metrics $P_{\text{aux}+\alpha}/S$ and $P_{\text{aux}+\alpha}/R$ where $P_{\text{aux}+\alpha}$ is the auxiliary + alpha heating power, S is the plasma surface area, and R is the major radius. Large advances beyond ITER in the physics and technology of power handling will be required for a pilot plant, clearly a major R&D issue associated with high NWL requirements. Solutions compatible with practical peak flux limits (e.g., ≤ 10 MW/m^2) require improved understanding of the power scrape-off width, enhanced radiation from the edge or divertor regions to improve heat flux uniformity, and development of enhanced flux-expansion of divertor configurations. [7].

Three steady-state magnetic configurations have been examined for the pilot plant: the advanced tokamak (AT), spherical tokamak (ST), and compact stellarator (CS). 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 NWL for blanket testing, and the CS offers disruption-free operation with low recirculating power. The three configurations are depicted in Fig. 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,

Table 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. NWL ⟨NWL⟩ (MW/m^2)	0.5	1-2	3-4
NWL at 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
$P_{\text{aux}+\alpha}/S$ (MW/m^2)	0.2	0.5-1.0	0.9
$P_{\text{aux}+\alpha}/R$ (MW/m)	25	25-115	80

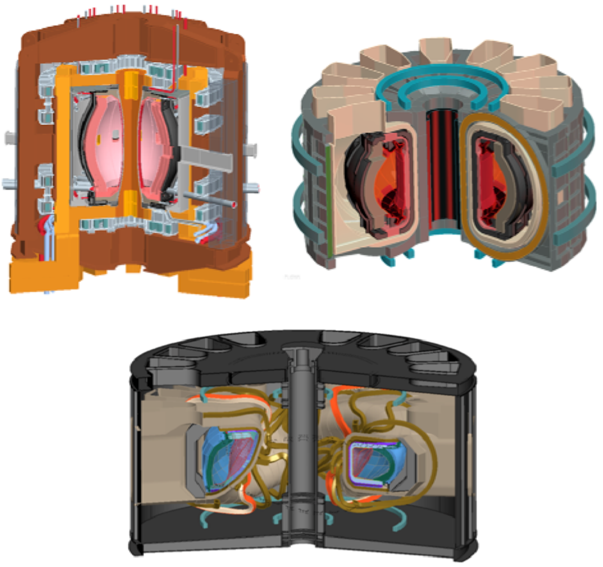

Fig. 1 Pilot plant configuration designs based on (clock-wise from top left) spherical torus (ST), advanced toka-mak (AT), and compact stellarator (CS). Not to scale.

Table 2 Pilot plant design parameters for AT, ST, and CS, and blanket thermal efficiencies η th 0.3 and 0.45.

	AT		**ST**		**CS**	
η_{th}	0.30	0.45	0.30	0.45	0.30	0.45
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
⟨NWL⟩ (MW/m^2)	1.8	1.3	2.9	1.9	2	1.2
Pk. NWL (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
P/S (MW/m^2)	0.87	0.82	0.98	0.73	0.52	0.35
P/R (MW/m)	53	50	115	86	25	17

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 [8]. The ST uses a jointed copper toroidal field coil and a jointed vacuum vessel that 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 2. In linear dimensions they are about two-thirds the size of the corresponding ARIES power plant designs. The ST has the highest NWL 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 these options. The AT size is driven by engineering gain while the CS size is driven by the NWL requirement because the lack of a need for current drive greatly reduces recirculating power so it easily achieves $Q_{eng} > 1$.

4. Assessment of a Pilot Plant Roadmap against Demo Prerequisites

A roadmap that includes a pilot plant as an intermediate fusion integration facility between ITER and Demo could satisfy the proposed Demo 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. 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 than exists for tokamaks and STs. Some mitigation of the risk could be achieved by developing designs with improved engineering characteristics and by accelerating stellarator physics research using existing and new facilities. 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.

In either case a pilot plant would integrate key science and technology capabilities of a fusion power plant and would, if successful, substantially narrow the gap to Demo. Analysis of the risks in taking the step to a pilot plant is necessary but has not been completed and will be reported in the future.

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