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A Pilot Plant: The Fastest Path to Commercial Fusion Energy

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Introduction

Considerable effort has been dedicated to determining the possible properties of a magnetic-confinement fusion power plant, particularly in the U.S.[1], Europe[2] and Japan[3]. There has also been some effort to detail the development path to fusion energy, particularly in the U.S.[4] Only limited attention has been given, in Japan[5] and in China[6], to the options for a specific device to form the bridge from the International Thermonuclear Experimental Reactor, ITER, to commercial fusion energy. Nor has much attention been paid, since 2003, to the synergies between magnetic and inertial fusion energy development. Here we consider, at a very high level, the possibility of a $Q_{eng} \geq 1$ Pilot Plant, with linear dimensions ~ 2/3 the linear dimensions of a commercial fusion power plant, as the needed bridge. As we examine the R&D needs for such a system we find significant synergies between the needs for the development of magnetic and inertial fusion energy.

Context

Fusion is an attractive low-carbon energy source. There is adequate deuterium and lithium fuel easily available to produce thousands of GW of electricity for thousands of years. A fusion power plant stores so little nuclear energy that it is not capable of runaway reaction or meltdown. Waste from fusion should not require geological storage. Proliferation risks from fusion are significantly lower than from fission. Future energy need projections are such that it would be highly desirable for fusion to become commercially available starting in the middle of the 21st century; however the means to accomplish the transition from government-sponsored experimentation to commercial application are not yet fully defined.

The decision has been taken to construct the International Thermonuclear Experimental Reactor, ITER, at Cadarache, France. This decision was based on results from magnetic-confinement experiments worldwide, in which up to 20 MJ(th) of fusion energy were produced. ITER is planned to produce about 500 MW(th) of fusion power in 300 - 500 second pulses, constituting about 200 GJ(th), with a goal of extending the pulse length to ~ 1 hour. The overall facility is designed to provide 25% duty factor operation at 500 MW(th), producing 10^7 MJ(th) per day. ITER will extend the current scientific understanding of magnetically confined plasmas to fusion reactor scale, and will test many of the technologies relevant to practical fusion power production.

Success on ITER should lead to the next step in the development of magnetic-confinement fusion power – preferably the final step to commercial deployment.

Construction has been completed on the National Ignition Facility, NIF, at Livermore, CA, U.S., and experiments will begin soon with the goal to produce at least 2 MJ(th) of fusion energy and the expectation that 10x higher energy output will be achieved, The pulse repetition rate at high fusion yield is in the range of one per day. While NIF is funded for military purposes, it is planned to demonstrate ignition of the core of a small highly-compressed sphere of fusion fuel and show propagating burn, critical issues for the science of inertial-confinement fusion.

Positive results from NIF should motivate the development of the technologies needed for inertial fusion. Success in the development of these technologies should lead, as with magnetic-confinement fusion, to the final step to commercial deployment.

Needed Science and Technology

Magnetic and inertial fusion have science and technology needs beyond those that will be addressed in ITER and NIF. A recent FESAC study[7] identified three key areas of required further development for magnetic fusion energy:

- Creating Predictable High-Performance Steady-State Plasmas
- Taming the Plasma-Material Interface
- Harnessing Fusion Power

Such an agreed listing is not available for inertial fusion energy, but key issues certainly include:

- Optimizing Ignition Physics: Direct *vs.* Indirect Drive, Hot-Spot *vs.* Fast Ignition
- Driver Development: Lasers (solid-state *vs.* gas), Ion Beams, Pulsed Power
- Cost-Effective Target Manufacture, Accurate Target Injection and Tracking
- Taming the Plasma-Material Interface
- Harnessing Fusion Power

While there are differences between the science and technology needs of magnetic and inertial confinement fusion, there are significant overlaps and synergies, particularly in the areas of plasma-material interaction and harnessing the energy from fusion neutrons.

The plasma performance issues first in the two lists above should be largely addressed on ITER and NIF, supported by smaller research facilities in the U.S. and abroad. Technology test stands will be required to help develop solutions for some of the other issues in both magnetic and inertial fusion. For magnetic confinement fusion, study of the plasma-material interface and its interaction with an optimized core plasma will require an integrated toroidal confinement facility with long-pulse, high power-density operation. Similarly it will likely be necessary to use a realistic plasma environment to develop the plasma-material interface and related technologies (*e.g.*, chamber clearing) for inertial confinement fusion. There are opportunities for synergy between the plasma-materials interaction science and materials technology in magnetic and inertial fusion.

Magnetic and inertial fusion should be able to share a facility for testing materials under intense 14 MeV neutron bombardment, with capabilities such as proposed for the International Fusion Materials Irradiation Facility. These tests will provide the scientific basis to design tritium-breeding blanket modules for a Pilot Plant and commercial fusion application.

The Next Major Step – A Pilot Plant

It would be highly desirable for the next major DT step in either magnetic or inertial confinement fusion, since it will be quite expensive, to provide the needed information for the transition from fully government-sponsored research to commercial fusion energy.[8] To provide adequate confidence for this transition, such a system must test all of the science and technology developed in the programs described above in a realistic fusion power plant environment. It is not necessary, however, that these tests be undertaken at the full size scale of a fusion power plant. Indeed a smaller and therefore less expensive, more timely and more nimble Pilot Plant would be highly preferable. Here we examine, at a very high level, the option of a tokamak fusion Pilot Plant with ~ 2/3 the linear dimensions of a commercial fusion system.

Such a Pilot Plant, if it had the same magnetic field strength as the subsequent commercial system, and the same β, could produce $(2/3)^3$ = 30% of the fusion power. A tokamak operated at the same density and temperature would require 2/3 of the current drive power, while one operated at the same fraction of the Greenwald density limit would require somewhat more current drive power than the commercial system, due to the lower temperature. It would also produce somewhat more than 30% of the power, since the Greenwald limit is constraining at large R. Thus Q_p of the Pilot Plant might be ~3x lower than that of a commercial system, for example 10 *vs.* 30. Q_{eng} might be similarly reduced. But even if the total recirculating power were the same in the Pilot Plant as in the commercial system, if the commercial system had Q_{eng} > 3.3 the Pilot Plant, with 30% of the fusion power, would have $Q_{eng} > 1$, and could provide net electricity – an exciting prospect. This would help drive the development of the high efficiency blankets and balance-of-plant needed for commercial fusion.

Even though the plasma-facing surface area of this Pilot Plant will be 4/9 that of the commercial system, it may have ~1.5x lower neutron wall loading. The plasma-material interface may also be somewhat less challenged than in the commercial system, even taking into consideration the higher ratio of current-drive power to alpha heating. However the values achieved in this system should provide the scientific and engineering data on Taming the Plasma-Material Interface and Harnessing Fusion Power needed to support the moderate extrapolation to a commercial system. It is interesting to note that the 60 MWe Shippingport fission reactor, commissioned in 1957, provided adequate confidence for the 620 MWe commercial fission reactor at Oyster Creek, NJ, commissioned in 1969.

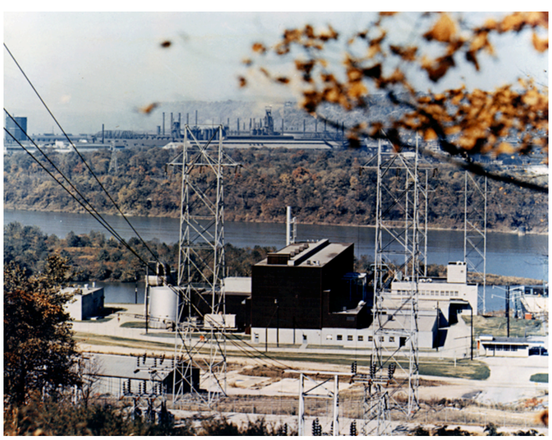

Figure 1. Shippingport reactor, 60 MWe, commissioned in 1957 and Oyster Creek Reactor, 620 MWe, commissioned in 1969.

A central issue for the commercial practicality of fusion will be its achievable capacity factor. Thus the Pilot Plant should be equipped with the same remote maintenance scheme and use the same maintenance technologies as anticipated for commercial systems, and it must ultimately demonstrate the practicality of the techniques needed for high capacity factor operation.

Required Pilot Plant Studies

Until more of the needed science and technology are in hand for magnetic and inertial fusion, it is premature to begin the design of Pilot Plants. However scoping studies to determine the key issues that should be addressed in advance of a Pilot Plant *vs.* those that should be addressed within the program of the Pilot Plant itself are appropriate at this time, to inform the needed R&D programs. Within magnetic fusion it will be important to consider at least 1) tokamaks, since they are the most developed, 2) stellarators, since they offer the most direct access to steady-state non-disruptive operation, and 3) ST's, since they may offer the most cost-effective systems and possibly the easiest remote maintenance strategy. Within inertial fusion, it will be important to consider indirect *vs.* direct drive, and hot-spot *vs.* fast ignition, as well as different options for drivers and chamber technologies. As with magnetic fusion, the goal of the scoping studies would be to determine which issues should be resolved in advance of a Pilot Plant, and which issues should be resolved within the program of the Pilot Plant itself.

Conclusions

With the exciting possibilities of ignition in NIF and of high gain and high fusion power production in ITER, the U.S. fusion program should be developing plans for the most effective means for fusion energy to make the transition to commercial application. Considerable science and technology is needed to accomplish this, and there is strong synergy between the needs for magnetic and inertial fusion both in the areas of plasma-material interactions and neutron-material interactions. A fusion Pilot Plant with ~ 30% of the fusion power production of a commercial fusion system and $Q_{eng} > 1$ may be able to support the needed transition. Studies are needed to determine the split in R&D needs between activities prior to the Pilot Plant, and those to be addressed in the Pilot Plant program itself.

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Footnotes

[1] ARIES Program Public Information Site, http://www-ferp.ucsd.edu/ARIES/DOCS/final-report.shtml

[2] Cook *et al.*, 2004: European Fusion Power Plant Studies, Cook, I. et al., http://www.fusion.org.uk/techdocs/tofe16_cook.pdf

[3] Kikuchi, M., Seki, Y., Nakagawa, K., 2000, The Advanced SSTR, Fusion Engineering and Design, V. 48, p. 265

[4] FESAC, 2003, A Plan for the Development of Fusion Energy, DOE/SC-0074, http://www.ofes.fusion.doe.gov/More_HTML/FESAC/DevReport.pdf

[5] Tobita, K. *et al*., 2005, Design Stufy of Fusion DEMO Plant at JAERI, Fusion Engineering and Design, V. 81, p. 1151; Hiwatari, R. et al., Demonstration Tokamak Fusion Power Plant for Early Realization of Net Electric Power Generation, Nucl. Fusion V. 45, p. 96

[6] Feng, K.M., *et al*., Conceptual Design Study of Fusion DEMO Plant at SWIP, Fusion Engineering and Design, V. 12, p. 2109

[7] FESAC, 2007, "Priorities, Gaps, and Opportunities: Towards a Long-Range Strategic Plan for Magnetic Fusion Energy", http://www.ofes.fusion.doe.gov/fesac.shtml

[8] Most likely, as with recent proposals for new fission power plants in the U.S., some form of government participation such as loan guarantees would be needed for the first commercial fusion power systems.

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