# An Accelerated Plan to Develop Practical Magnetic Fusion Energy

A White Paper Submitted to the Fusion Energy Sciences Advisory Committee

Charles Baker, David Baldwin, Robert Goldston,
Thomas Jarboe, Stanley Milora, Miklos Porkolab

## Abstract

Recent events have increased national attention to the need for clean, new domestic energy sources. At the same time, scientific results have greatly increased confidence that fusion can be harnessed as a practical large-scale energy source. A plan is presented for the accelerated development of magnetic fusion energy. The first major step in this plan is the construction of a new international facility, called ITER, in which magnetically confined fusion fuel will be sustained at high temperature through its own internal fusion process. Additional critical elements of the plan are described, as required to achieve the goal of producing electrical power for the grid within approximately 35 years.

## Introduction

A number of factors have contributed to the recent increased attention to the possibility of accelerating the development of fusion as a practical energy source. Energy policy in general has risen in visibility with the development of the President's National Energy Policy, as well as with Energy Bills passed in both houses of Congress. All three documents call attention to fusion as an abundant, safe and clean energy source. The fuel for fusion is abundantly available to all nations for thousands of years, the fusion process is intrinsically safe and waste from fusion is relatively short-lived. Climate change has also received considerable public attention, and the timescale for accumulation of $CO_2$ in the atmosphere suggests that attractive new energy sources such as fusion should be developed aggressively in the next few decades.

In parallel with these policy developments, progress in magnetic fusion energy scientific research has been rapid. Fusion power in the range of 10 - 20 MW for duration of about one second has been produced in experimental facilities in both the U.S. and Europe. The understanding and predictability of fusion systems have developed to the point where Europe, Japan, Russia and Canada are currently negotiating to construct a 500 – 700 MW(th) fusion test facility, capable of operation for pulse lengths of up to one hour. The scientific data are now available to support a U.S. decision to join these negotiations.

It is in this context that this "Accelerated Plan to Develop Practical Magnetic Fusion Energy" is presented. We have taken as guidelines for this plan that

a) At least a modest amount of electrical power from fusion should be available to be put onto the electrical grid within approximately 35 years
b) Soon thereafter a well-optimized power system should be available for large scale commercial application

The largest new component of the plan presented here is the construction of a burning plasma experiment. Such an experiment will permit the first investigation of a magnetically confined plasma, or hot ionized gas, producing hundreds of megawatts of fusion power, and largely sustaining its high temperature through its own internal fusion reactions. This is a critical and necessary step for the development of fusion energy. Such an experiment alone, however, will not supply sufficient information to allow the rapid deployment of practical fusion energy. To achieve the stated goals will also require strengthening of key strategic elements of fusion energy research: fundamental understanding, configuration optimization and development of materials and technology.

As formulated this plan will position the U.S. to develop practical, highly attractive fusion power systems and so to be a supplier, rather than only a consumer, of fusion systems on the world market.

The scientific results of the last decade open a pathway to the demonstration of practical fusion electric power. With commitment of effort and focus on critical issues and well-identified milestones, this goal should be achievable on the requisite timescale.

## The Proposed Plan

A new plan for the development of magnetic fusion energy must meet a number of criteria. It must penetrate deeply into the new regime of self-sustaining “burning” plasmas, since self-sustained operation is a prerequisite for fusion power production. It must recognize the central role of fundamental understanding in supporting both the decision to proceed now with a burning plasma experiment and also the innovations that will ultimately make fusion energy practical. It must accelerate the investigation of key scientific issues for fusion’s practicality in order to assure that viable and cost-effective fusion energy systems are brought to market. Finally it must recognize the importance of advanced materials and fusion energy technologies to the realistic implementation of a commercial fusion power plant. In all areas this effort must be managed tightly such that only well-conceived projects fitting closely into the overall plan are funded, and project teams are held accountable against well-defined milestones and deliverables. Metrics of quality, relevance to the plan and performance must be key.

The plan presented here addresses the development path for magnetic fusion energy, in which magnetic fields continuously confine the plasma used to produce fusion energy. An alternative approach, inertial fusion energy, uses repetitive pulses of energy to heat dense plasma rapidly to high temperature, during the brief period that it is held in place by its own inertia. Plans for the development of inertial fusion energy are also being formulated, and the significant synergies between these technologies should allow a unified plan to be developed, taking full advantage of a mutually supportive development process.

### A Burning Plasma

A burning plasma is one in which the fusion process itself will provide most of the heat to sustain the high plasma temperature. This will be required in any practical fusion system, and as such is a major and necessary step towards fusion power, as affirmed by all recent reviews of the fusion energy sciences program. An experiment of this class will also advance the science of fusion plasmas across a very broad frontier. A number of magnetic fusion facilities have been proposed for this purpose, but none is under construction yet. Europe, Japan, Russia and Canada are currently negotiating over construction of the ITER device, which would serve as a burning plasma facility. Owing to its relatively long pulse, superconducting coils and large duty factor, ITER would also serve as an engineering test facility, adding considerably to its value for fusion energy development. Test modules on ITER could be used to demonstrate the production of a small amount of electricity, although less than required to operate the device.

International collaboration in large-scale science is an attractive vehicle for sharing costs and drawing on worldwide expertise. Success requires commonality, or at least complementarity, of goals and serious commitment, so such collaboration should not be undertaken lightly. The question whether to pursue something as critical as fusion energy development through international collaboration is an important policy decision, as it raises issues of intellectual property rights, infrastructure development and management efficacy. International agreements are slow and difficult to achieve. Currently, however, the ITER cooperation appears to present a unique, attractive opportunity for the U.S. It represents a critical pre-competitive step in the development of fusion energy, the need for which is widely recognized for the benefit all humanity. The ITER design has been optimized to reduce cost and increase flexibility, ameliorating earlier U.S. concerns. Joining the ongoing ITER negotiations would enable the U.S. to influence the outcome of those negotiations to its benefit. Later, substantial opportunities will likely arise regarding other needed large-scale facilities dealing with low-activation-materials and component testing, as noted below, and a positive first step with ITER will facilitate future progress.

The plan described here, and illustrated in Figure 1, assumes U.S. participation in ITER. In this plan ITER functions as a long-pulse burning plasma experiment, providing scientific data on self-sustaining plasmas and allowing the development of the needed improved operating regimes for a demonstration power plant, DEMO. ITER's long pulses and high duty factor allow investigation of a wide range of scientific issues critical to fusion energy development. ITER will also function as an engineering test facility, providing practical experience with the engineering components of a fusion power plant, at full scale.

Domestic studies have been made of a lower-cost copper-magnet device called FIRE, which would also allow studies of burning plasma physics, but for much shorter and fewer pulses. Because of its low duty factor and copper coils, FIRE could not address certain long-pulse scientific issues, and would not function as an engineering test facility in the same sense as ITER. A smaller device, called Ignitor, has also been proposed in Italy. It shares some properties with FIRE, but is even more compact and supports shorter pulses. In the event that ITER does not move forward, an alternative strategy would be to proceed with the domestic FIRE experiment. An experimental test reactor which followed after FIRE would likely have lower availability than one which followed after ITER, since it would represent the first integration of full-scale technologies such as superconducting magnets, and might require an additional 5–10 years to come to full-power operation.

### Fundamental Understanding

Fusion requires the control of very high temperature ionized gases, called plasmas. Dramatic advances have been made in the last decade in the understanding of the physics of high-temperature plasmas confined by magnetic fields, both through more sophisticated plasma diagnostic measurements and through the greatly enhanced computational power now available to researchers. These efforts are critical because the innovations required for practical fusion energy can only arise from accurate physical understanding, and ultimately only a well understood and fully controlled plasma can function as a reliable fusion power source. Furthermore the scientific progress represented by this work has its own fundamental value. A recent emphasis has been to strengthen the connections between fusion research and other related areas of science, such as astrophysics and accelerator design. This effort is beginning to bear fruit as scientific ideas and techniques help to cross-fertilize research. In its recent review of the fusion energy sciences program, the NAS/NRC endorsed the high quality of the scientific research in fusion and particularly emphasized the critical importance of science in attaining the goal of practical fusion power.

A major thrust is required in the area of advanced computing, involving on the one hand a strengthening of underlying plasma theory and on the other increased involvement of computer scientists, mathematicians and possibly computer architects. Access to rapidly increasing computing power is needed as part of this effort. A strengthening of plasma measurement systems (included in the configuration optimization effort discussed below) is critically coupled to this element of the strategy. Deepening of scientific insights and integration of scientific results pointing to important innovations are the key deliverables of this strategic element.

While the fusion energy sciences program concentrates additional resources on the above goals, it would be appropriate for the DOE Office of Science Basic Energy Sciences program and the National Science Foundation to strengthen their activities in basic plasma science, since the product of this research is valuable not only for fusion energy but also as an element of basic research.

### Configuration Optimization

The ITER design is based on the tokamak (see glossary) configuration, which is the only magnetic configuration for plasma confinement currently sufficiently developed to allow confident extrapolation into the burning plasma regime. However there are significant remaining technical questions as to how effectively a tokamak-based fusion power plant can operate in steady state with low recirculating power, high neutron wall loading and very infrequent off-normal heat flux events (called “disruptions”). Thus it is necessary to strengthen efforts at configuration optimization to be prepared for the step to a practical DEMO after ITER. This optimization is based on, and contributes to, the fundamental understanding of high temperature plasmas.

Topologically toroidal (doughnut-shaped) magnetic systems are currently understood to have the best prospects for fusion power production. This stems from the fact that plasmas flow easily along magnetic field lines, and the closure of these lines onto toroidal surfaces is extremely beneficial for plasma confinement. The configuration of the magnetic torus (*e.g.,* the internal profiles of the magnetic fields, the ratio of the major to minor radii, the ratio of the magnetic fields pointing the long compared with the short way around the torus, and the degree of symmetry of the torus) can have important implications for the achievable fusion power density, the overall plasma stability, the cost of the requisite magnets and the amount of recirculating power required for plasma sustainment. Investigations to study these variations are needed on a timely basis to have confidence that a practical fusion system can be fielded. The Secretary of Energy Advisory Board, in its recent review of the fusion program, gave particularly strong support to this approach to assuring the practicality of fusion energy.

A framework has been developed for studying confinement configurations at increasing depth, starting with initial studies at the "Concept Exploration" (CE) level, progressing to more scientifically complete studies at the "Proof of Principle" (PoP) level, and allowing studies of plasmas approaching fusion parameters at the "Performance Extension" (PE) level. In addition to developing specific improved fusion systems, scientific results from a portfolio of configurations deepen understanding by providing strong tests of theoretical ideas and so provide benefit across the spectrum of configurations. All transitions from the CE to the PoP and then PE level, however, require strict peer review against criteria of scientific quality, relevance to the plan, and performance.

Existing PE class tokamak devices in the U.S. are scientific workhorses producing critical results for the final design and then operation of a burning plasma experiment. It is important to strengthen plasma measurement diagnostics, tools for plasma control, and run time on these facilities as well as on those at the CE and PoP level, and the cost-effectiveness of increments in these areas is high. It is anticipated that the present PE class tokamak experiments could be operated very productively until shortly before a burning plasma experiment begins operation, with a strong focus on developing for ITER the improved performance operating mode called "Advanced Tokamak" operation, in which a large fraction of the plasma current is self-sustained at high plasma pressure by the internally driven "bootstrap" current. This mode offers the potential to resolve key issues for the tokamak, to allow it to progress to the DEMO stage. During this time period there will also be important near-term opportunities for international collaboration on more powerful tokamak facilities abroad, and later in the decade a long pulse superconducting device is anticipated to come on line in South Korea, while a second such device is under consideration in Japan. These would provide particularly important new opportunities for collaboration.

Because an optimized fusion plasma cannot be designed through theory and computation alone, the plan must also provide for more detailed experimental examination of configurations that promise attractive resolution of the key issues for DEMO. A PE class Spherical Torus (ST) (see glossary) might serve as the first new PE class device in the U.S. program for many years, if thorough review concludes that this is warranted by results from the present very promising PoP class devices and the projected capability of the ST configuration for fusion power application. A second new PE class device, perhaps of the Reversed Field Pinch (see glossary) or Compact Stellarator (see glossary) type, could operate on a timescale such that, coupled with results from PE class experiments abroad, either configuration could ultimately be chosen for DEMO. The Compact Stellarator is particularly well positioned to benefit from results of the large superconducting stellarator PE experiments in Japan and Europe.

It is important that the pipeline of introductory CE experiments remains open, as indicated in figure 1, since innovative approaches continue to be generated. Configurations currently in the CE class would most likely need to point towards improvements in power plants beyond DEMO, although the possibility of very attractive ideas taking the lead should not be excluded by the structure of the plan. Thus selected activities within the CE line should be strengthened to support the possibility of their rapidly moving forward.

### Materials and Technology

Because ITER cannot provide all of the experience with materials and technologies required to provide confidence in environmentally attractive, high availability operation of DEMO, additional facilities at a range of scales will be required to develop the needed low-activation, long-life materials and highly reliable technologies.

Fusion's environmental and economic attractiveness requires materials that can withstand high neutron fluxes for long periods of time, resulting in only moderate and short-lived radioactivity. Very considerable progress has been made by modifying steels that were developed for fission applications. In tests using neutrons from fission reactors, these steels appear to have adequate properties for initial fusion applications. Vanadium alloys show promise of lower activation levels, and higher temperature (and so higher efficiency) operation, but these materials are less well developed. Most attractive, but least developed, are silicon carbide composites. Nanoscience techniques and advanced computation are leading to the development of materials modifications such as dispersion strengthening which may allow, for example, higher temperature operation. While fission neutrons provide valuable information on materials properties for fusion, it will be necessary to test the most promising materials with the spectrum of higher-energy neutrons created by fusion.

Advanced computing is making major contributions to materials nanoscience in many areas, including fusion materials development. This effort needs to be considerably strengthened, and highlighted as a mission of the DOE Office of Science Basic Energy Sciences program. Materials development and testing in fast fission reactors needs to be strengthened as well. Investigations are now under way as to whether the U.S. Spallation Neutron Source can provide appropriate energetic neutrons for some aspects of fusion materials testing. Both Europe and Japan are designing new neutron sources, and perhaps with fusion materials testing considered during the design stage such facilities could contribute more strongly.

There is a widespread view that a small-volume "point" neutron source such as the International Fusion Materials Irradiation Facility (IFMIF) is needed to qualify materials for DEMO. The conceptual design of this facility is now complete, and it awaits the beginning of engineering design. IFMIF should begin operation within five years of ITER in order to provide timely information.

The major technologies required for fusion can be read outwards from the plasma: plasma-facing components to manage high heat and particle fluxes, blankets to capture neutrons, breed tritium fuel and provide heat for electricity generation, and large superconducting magnets to form the requisite magnetic fields. The first of these is actually an interlocked science and technology problem, as some fusion systems such as tokamaks are prone to off-normal heat flux events (disruptions) and/or repetitive heat loads that can be concentrated in space and time, called edge localized modes. Technologies are also needed to heat and fuel the plasma, and in some configurations to sustain an electrical current in the plasma. A critical issue is that these high technologies must be integrated in a manner that results in high reliability, availability and maintainability in a practical energy-producing system.

A facility will be needed to enable testing fusion system components at sufficient neutron flux and fluence to assure high availability of the DEMO power plant. Various studies of such a facility have appeared with the names "Volume Neutron Source", "Fusion Development Facility" and "Component Test Facility". Here we adopt the name Component Test Facility (CTF), used in the U.K. study, as expressive of its primary goal. It would be a compact device constructed using steady-state resistive magnets for the main coils, most likely based on the database accumulated from the Spherical Torus and Advanced Tokamak programs. The purpose of such a facility would be to test fusion energy technology components such as the blankets for tritium breeding and heat extraction, at realistic neutron fluxes and fluences for DEMO. It would serve, for example, to shake out design concepts and test materials, coatings and coolant compatibilities, establishing reliability, availability, and maintainability of fusion energy technologies. With conservative physics performance the CTF could have a steady-state driven plasma with a low fusion gain value, 1 – 2, but still with enough neutron flux and fluence for the required component testing. With success in advanced performance physics in the Advanced Tokamak and Spherical Torus lines of research, this device could support higher fusion performance, gain, and neutron fluxes for accelerated testing. Furthermore there would be incentive to add electric power conversion equipment to offset the electric power required for this facility. With full utilization of advanced physics possibilities a small net electric production might even be possible. A CTF device could be internationally funded, but led by the U.S. and sited domestically, providing the critical test bed for component optimization and application of long life, low activation materials.

In addition to the individual major facilities described above, several smaller supporting technology facilities will be required as well. Their main functions will be subsystem and component development and separate-effects testing, in non-nuclear environments. These will be used to develop the required engineering and materials science, and screen design options for reliability under extended and off-normal conditions, before testing in CTF or ITER.

## A Demonstration Power Plant

*On the basis of the program outlined here, it should be possible to begin operation of a practical demonstration power plant in approximately 35 years*. If, in parallel with a burning plasma experiment, the U.S. has sustained a strong program of fundamental understanding, configuration optimization and materials and technology development, it should be well positioned to develop an optimized design for a U.S.-led DEMO. This device should be capable of reliable full-power operation, and should be sufficiently cost-effective that rapid market penetration will ensue.

**Cost**

The plan presented here is a staged one, with costs increasing at a moderate rate over time. As each project is initiated there must be a very careful evaluation of the database supporting the project, of the project plan, and of the overall level of progress in fusion energy development. Quality, relevance and performance remain as critical criteria. Thus at each stage in fusion energy development, and for each project, there is a clear "exit ramp".

The costs for the domestic magnetic fusion program are based on earlier planning documents, such as the Fusion Energy Sciences Advisory Committee 1999 Knoxville assessment, with increments for the facilities described. The cost for ITER is based on the ITER team's estimate, and so requires further review, particularly since the ITER team did not factor in estimates of contingency in the manner employed in the U.S. The cost of participation in ITER construction in $FY2002, assuming the cost developed by the ITER team, could be as low on average as $50M/year for 10 years were the U.S. to participate as a limited 10% partner or as high as $115M/year were the U.S. to participate as a full non-host partner. Full partnership would allow a greater involvement of U.S. industry in ITER construction, and greater influence of U.S. scientists and engineers in the ITER program. The cost for FIRE construction is based on a pre-conceptual design study, so requires further review as well, but on a similar 10-year basis would correspond to $120M/year. Costs for IFMIF and CTF are based on available studies and assume equal three-party collaboration. Decisions on these additional international facilities would be phased behind the decision to construct ITER.

Table 1 – Estimated Cost in FY2002 $M

| | Domestic | ITER | IFMIF | CTF | Total |
|---|---|---|---|---|---|
| FY 2006 | 315 | 50 – 115 | – | – | 365 – 430 |
| FY 2010 | 370 | 50 – 115 | – | – | 420 – 485 |
| FY 2020 | 355 | 30 – 75 | 20 | 70 | 475 – 520 |
| FY 2030 | 330 | 30 – 75 | 20 | 50 | 430 – 475 |

In FY 2030 DEMO would also be under construction. If this were done with one partner, the annual cost would be in the range of $350M/year.

This plan is optimized to minimize costs, without sacrificing likelihood of success. It also provides a slow growth in expenditures, which can be keyed to programmatic reviews and possible future optimizations.

The most important feature of this plan, however, is that it will provide fusion energy to the grid on a practical timescale, and it will ensure that the fusion systems which are developed are environmentally attractive and marketable both in physics performance: power density, steady-state operation and plasma stability, as well in engineering performance: reliability, availability and maintainability. This plan will put the U.S. in a position to be a supplier rather than only a consumer of fusion power systems in the future.

**Summary**

The priority of fusion has risen considerably in public discourse, as illustrated in the President's National Energy Policy and in Energy Bills passed in both houses of Congress.

The investigation of self-sustained "burning" plasmas is a critical next step in the development of practical fusion energy. Participation in ITER is an attractive means for the U.S. to access the new regime of self-sustained burning plasmas, and will provide both steady-state science and engineering testing beyond what can be achieved in a domestic experiment.

The advancement of the science of high-temperature plasmas is a key success factor for the development of fusion energy, and provides fundamental value to the nation.

Because it remains uncertain how effectively the tokamak configuration on which ITER is based will be able to operate in steady state with high neutron wall loading and low disruptivity, a strong parallel program in configuration optimization is required to assure that a practical demonstration power plant (DEMO) can be constructed after ITER.

Because ITER will not provide the full range of technology testing to assure high reliability, availability and maintainability of DEMO, other facilities will be needed to qualify materials and technologies for fusion. Of particular interest for the U.S. might be an integrated component test facility.

The accelerated plan to develop practical magnetic fusion energy presented here saves costs through international collaboration. It provides for careful review at each step, with exit ramps within every aspect of the program. Most importantly, however, this plan assures that fusion power systems developed by the U.S. will be environmentally attractive and marketable, making the U.S. a supplier rather than only a consumer of such systems.

# Glossary

- **CE:** Configuration Exploration experiment providing initial investigation of a new plasma configurations.
- **CS PoP:** Compact Stellarator of the “Proof of Principle” class, which adds compactness and higher power density to the advantages of the conventional stellarator. NCSX to begin construction in FY2003 in U.S.
- **CTF:** Component Test Facility. A small steady state fusion facility to test components at neutron fluxes close to first-wall values in fusion power systems, with the possibility of small net electric production. Funded internationally.
- **DEMO**: A full-size fusion power plant with as high as possible availability, and as competitive as possible cost of electricity. Likely multiple DEMO’s in the world program, built by consortia.
- **FIRE:** A limited-pulse burning plasma physics facility, funded nationally.
- **IFMIF:** International Fusion Materials Irradiation Facility, funded internationally. Point neutron source for testing small material samples at fluxes close to first-wall values in fusion power systems.
- **ITER:** A long-pulse burning plasma physics and engineering test facility, funded internationally.
- **PE:** Performance Extension experiment studying a configuration at near-fusion parameters
- **PoP:** Proof of Principle experiment investigating a plasma configuration in an integrated manner.
- **RFP PoP:** Reversed Field Pinch of the “Proof of Principle” class. The RFP is a configuration with a very low magnetic field the long away around the torus, leading to low-cost magnets in a fusion power plant. MST in U.S., RFX in Italy.
- **S/C Tok PE:** Superconducting tokamak facility of the “Performance Extension” class. KSTAR is currently under construction in Korea as well as HT-7U in China, JT-60SC has been proposed in Japan.
- **S/C Stellarator PE’S (non-US):** Superconducting stellarators of the “Performance Extension” class. A stellarator is a toroidal configuration whose cross-sectional shape varies around the torus, allowing increased stability (little or no disruptions) and no need for external sustainment of plasma current. LHD currently operating in Japan, W7-X under construction in Germany.
- **ST PoP:** Spherical Torus facility of the “Proof of Principle” class. An ST is a toroidal configuration in which the minor radius approaches the major radius, resulting in capability to sustain high plasma pressures and so fusion power density for a given magnetic field. NSTX and MAST are currently in operation in the U.S. and England respectively.
- **Tok PE:** Tokamak facility of the “Performance Extension” class. A tokamak is an axisymmetric toroidal system characterized by a ratio of the major to the minor radius of ~ 3, with a much stronger magnetic field directed around the torus the long way than the short way. Copper-coil machines in this class include DIII-D and C-MOD in U.S., JET and ASDEX in the U.K. and Germany, and JT-60U in Japan.

Fig.1, Magnetic Fusion Energy Facilities Operation Timeline