Realizing the Promise of Fusion Energy

Final Report of the Task Force on Fusion Energy

August 9, 1999

Secretary of Energy Advisory Board
U.S. Department of Energy

Secretary of Energy Advisory Board
Washington, DC 20585

September 30, 1999

The Honorable Bill Richardson
Secretary of Energy
1000 Independence Avenue, SW
Washington, D.C. 20585

Dear Secretary Richardson:

On behalf of the Secretary of Energy Advisory Board, I am pleased to send you "Realizing the Promise of Fusion Energy," the final report of the Fusion Energy Task Force. At your request, the task force conducted a thorough review and analysis of all of the Department of Energy's fusion energy technologies, both inertial and magnetic, in order to recommend the role that each of those technologies should play in the national fusion energy research program. Since its first meeting in March 1999, the task force held four public meetings in connection with the preparation of this report.

Several government bodies and advisory panels have reviewed the nation's fusion energy programs and the task force sought to build on those efforts. Toward that end, the task force limited its scope to the Department's fusion energy program. Excluded from the review was the inertial confinement fusion program, which is being pursued as part of the Department's nuclear weapons stockpile stewardship program.

Given the growing energy demands worldwide, the eventual limits of fossil fuel supplies, and the scientific advances already achieved in fusion energy research, the task force recommends that the Department pursue fusion energy aggressively. In recent years, the Department has refocused and redirected its fusion energy program. After careful consideration, the task force endorses the revised focus of the program.

Among its key findings is a call to engage the Congress in a meaningful dialogue designed to establish a better understanding of fusion energy and the need to participate in a burning-plasma experiment. The task force concluded that the current funding level for fusion energy is subcritical. Funding on the order of $300 million per year will be required to support an appropriately balanced fusion energy program. The task force also concluded that the fusion energy program must be led by strong management, capable of directing the program towards its goals at a reasonable pace. In addition to a sufficient budget, it must have solid accountability and the availability of high-quality science and technology. In this connection, the task force recommended that the fusion energy program adopt new management techniques, including integrated program planning to better guide decisions, improve risk management, address problems and lower costs.

Although the Task Force has completed its review and analysis, several questions that were outside its scope of work will remain topics of public debate. The SEAB encourages the Department to consider these issues in a frank and open forum as the fusion energy programs proceed. As the leader in the development of this energy source, the Department must not allow the momentum of future projects cost and scale to jeopardize a full debate about the fusion energy program. The Department has a responsibility to take an active role in the future public discussions that are inevitable given the evolving scientific, technical and environmental complexities associated with fusion energy. At the forefront of this debate are questions about the environmental and national security impacts of the fusion energy program.

The Task Force warns that a strong management team must oversee the fusion energy program. As fusion energy requires progress on a variety of fronts including the scientific, engineering, and economic, it is premature to focus on one of many hurdles that must be overcome prior to realizing the potential of fusion. Although fusion holds the promise of a new and abundant source of power, the technology to harness and commercialize fusion energy has not yet been developed, leaving the actual environmental impact open for debate. Existing federal law requires that the environmental impact be assessed before the commitment of significant federal resources in the construction of a prototype. However, the management team must ensure that fusion energy's effect on the environment is considered in an open, public forum to incorporate and address environmental concerns at the early stages of research and analysis.

As DOE pursues parallel paths that encourage both classified weapons work of the Inertial Confinement Fusion (ICF) program and the unclassified research for commercial purposes which is the crux of the Inertial Fusion Energy program funded by the Office of Science, the Department must be ever mindful of classification guidelines, management controls, and openness with Congress. This level of attention must be sufficient to assure that the security of weapons aspects of ICF research are not compromised in the process of allowing open collaboration and exchange between the Defense Programs work and the non-classified research into inertial fusion energy. As always, DOE must also work with the appropriate Federal agencies to make sure that the ICF program is in compliance with all United States treaty obligations.

Finally, in light of recent revelations of cost overruns, SEAB intends to form a subcommittee to assess the technical and programmatic risks associated with the assembly and installation of the laser system of the National Ignition Facility (NIF). This subcommittee will provide recommendations on the best technical course of action to be undertaken to assure the timely and successful completion of the NIF project, the cornerstone of the Department of Energy's Stockpile Stewardship program. The results of this assessment will also have an impact on the Department's fusion energy program.

In summary, the Task Force on Fusion Energy concluded that fusion energy's promise is great and its potential should be pursued. However, in order to realize the promise of fusion energy, the task force sees the need for stronger and more coordinated program management for fusion energy to meet this promise. This is required to ensure that as the science evolves, the remaining issues will be considered in a public, frank and responsible manner.

Sincerely,

Andrew Athy
Chairman

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Task Force on Fusion Energy

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Preface

In December 1998, Secretary Richardson asked the Secretary of Energy Advisory Board to form a Task Force on Fusion Energy to conduct a review of the Department's fusion energy technologies, both inertial and magnetic, and to provide recommendations as to the role of these technologies as part of a national fusion energy research program. Specifically, the Task Force was requested to examine and, as appropriate, make recommendations concerning:

- The overall state of development and energy potential of the technologies;
- The structure of magnetic and inertial energy programs in the Office of Science;
- The appropriate balance between magnetic and inertial confinement fusion energy activities;
- The appropriate development path for fusion technologies; and
- The appropriate funding levels for these technologies.

(The full charge to the Task Force is set out as an appendix.) This report reflects the Task Force's response to the request.

The fusion program has had the benefit of many thoughtful reviews in recent years. For example, the President's Committee of Advisors on Science and Technology has examined the fusion program on several occasions, including the development of a budget-constrained fusion strategy in the mid-1990s that has served as the foundation for a redirection of the fusion program.[1] Similarly, the Fusion Energy Advisory Committee (now Fusion Energy Sciences

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[1] President's Committee of Advisors on Science and Technology, Panel on Energy Research and Development, *Report to the President on Federal Energy Research and Development for the Challenges of the Twenty-First Century* (November 1997); President's Committee of Advisors on Science and Technology, *The U.S. Program of Fusion Energy Research and Development: Report of the Fusion Review Panel* (July 1995).

Advisory Committee) has issued a variety of reports to assist the Department in defining and evaluating the program.[2] The Task Force has benefited from the insights that these reports, and others, have provided. In light of the fact that these other reports provide useful summaries of the fusion program, we have sought to achieve brevity by presuming that the reader is at least generally familiar with the program.

One challenge for the Task Force has been to define an appropriate role for itself in light of the past studies and other related activities that are now underway. The ongoing activities include further studies by the Fusion Energy Science Advisory Committee,[3] a study under the auspices of the National Academy of Sciences of the quality of science sponsored by the Office of Fusion Energy Sciences, and an ongoing effort by the community of fusion scientists to develop a "Roadmap for Fusion Energy" that will provide the community's views as to the appropriate strategy for the advancement of fusion energy. (This latter effort is underway in the period in which we are finishing our work.) The Task Force has sought to respond to its charge, while recognizing that these other efforts will provide important input that should affect the Department's actions. We have thus sought to provide an overarching framework that, we hope, will guide the Department's response to these other, more focused activities. Of course, the Task Force remains available to reconsider its conclusions and recommendations in light of the activities that are underway in these other fora.

The Task Force has had four public meetings in connection with its work – two in Washington, one at the Princeton Plasma Physics Laboratory (a center for magnetic fusion research) and one at Lawrence Livermore National Laboratory (a center for inertial confinement fusion research). We received thoughtful briefings and comments at each of our meetings from

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2 *E.g.*, Fusion Energy Sciences Advisory Committee, *Review of the Strategic Plan for International Collaboration on Fusion Science and Technology Research* (Jan. 23, 1998); Fusion Energy Advisory Committee, *A Restructured Fusion Energy Sciences Program* (Jan. 27, 1996). *See also* Fusion Policy Advisory Committee, *Final Report* (Sept. 1990).

3 *See, e.g.*, Fusion Energy Sciences Advisory Committee, *Opportunities in the Fusion Energy Sciences Program* (DRAFT Apr. 13, 1999).

a variety of individuals who are involved in the program and from others. These briefings were helpful to the Task Force and we very much appreciate both the hospitality of our hosts and the assistance that these discussions have provided us. We also have received able assistance from the SEAB staff that has facilitated our work. Needless to say, however, any errors in this report are our own.

SEAB Task Force on Fusion Energy

August 9, 1999

Executive Summary

The Department of Energy supports the study of fusion – the process by which energy is generated when light nuclei combine – to advance plasma science, to enhance the Nation's defense program, and to attempt to harness fusion as a commercially viable energy source. Fusion is attractive as an energy source because of the virtually inexhaustible supply of fuel, the promise of minimal adverse environmental impact, and its inherent safety. This study focuses on the Department's efforts to make this potential a reality.

The scientific progress on fusion has been remarkable. As a result, **it is the Task Force's view that the threshold scientific question – namely, whether a fusion system producing sufficient net energy gain to be attractive as a commercial power source can be sustained and controlled – can and will be solved.** The time when this achievement will be accomplished is dependent, among other factors, on the creativity of scientists and engineers, the skill of management, the adequacy of funding, and the effectiveness of international cooperation. **In light of the promise of fusion and the risks arising from increasing worldwide energy demand and from eventually declining fossil energy supply, it is our view that we should pursue fusion energy aggressively**.

Magnetic fusion energy ("MFE") is supported by the Office of Fusion Energy Sciences ("OFES"), which is part of the Office of Science. The MFE effort was significantly redirected in the mid-1990s so as to broaden the program from a focus on achievement of fusion energy in tokamaks to include an expanded exploration of scientific foundations and of other confinement approaches. **The Task Force endorses the revised focus of the program.** However, the preservation of a strong and balanced program does present a management challenge in a time of constrained budgets, particularly since a necessary next scientific step is the exploration of the physics of a burning plasma. A device to explore this regime might cost in excess of $1 billion. The fusion community is grappling with this challenge and is seeking to provide advice to the Department as to the logic and strategy for investment.

Very substantial MFE programs – programs with funding that exceeds that of the U.S. – are being undertaken abroad**. In light of the worldwide benefits of fusion, the large resource requirements for its development, and the significant MFE programs that exist outside the U.S., the case for the stable and meaningful engagement of the U.S. in international collaboration is compelling**. Although the U.S. is no longer a participant in the program to develop the International Thermonuclear Experimental Reactor ("ITER"), it should find appropriate means, in consultation with Congress, to continue to engage in international activities that complement and advance the U.S. fusion program. Moreover, over the longer term, the U.S. must involve itself in international experiments associated with burning plasmas. **In order to participate in a burning-plasma experiment while preserving the breadth of the restructured program, the Department and the community should engage the Congress at an early stage. In light of the fact that our political system generally does not accommodate firm long-term budgetary commitments, the development both of understanding of a significant new project and of solid support for it throughout the political system is essential.**

Inertial confinement fusion triggers burning fusion reactions by igniting a pellet containing fusion fuel using intense laser or ion beams as drivers. It is primarily funded by Defense Programs ("DP") to serve national security purposes. This same approach might be used to produce commercial power – inertial fusion energy ("IFE") – by igniting several pellets per second. As is the case for MFE, progress in inertial fusion has been remarkable, but very large extrapolations in performance in numerous areas must be achieved before its energy potential can be realized. **The Task Force concludes that IFE warrants continued exploration and development. Given the immature state of the technology, it is not appropriate at this time to select only one driver technology for continued exploration.**

Because OFES's efforts must necessarily supplement the work of others – international efforts in the case of MFE and the work of DP in the case of IFE – OFES alone can not define the overall direction of the total effort and, as a result, it should not be expected that the fusion program will be balanced in terms of the energy objective. Indeed, **in light of the promise of**

fusion, the Task Force concludes that the funding is now subcritical. The fusion community has estimated that overall funding for fusion energy on the order of $300 million per year will support significant enhancements of the program and will allow program balanced to be maintained.

The achievement of fusion's potential requires both careful planning and sophisticated management. The planning must encompass the identification and timely resolution of the important engineering, economic, and systems problems that must be overcome if fusion energy is to be a practical energy source. **The program must be directed by strong management – a management that leads the effort toward the fusion energy goal at reasonable pace, with sufficient budget, with solid accountability, and high-quality science and technology**. New management techniques, particularly integrated program planning should be applied. Moreover, because there is a separation of the magnetic and the main locus of the inertial confinement effort in different parts of the Department, some strengthened means for overall coordination should be established.

The Task Force noted a variety of other matters:

- Although OFES can not be a major funding source for materials research, it should remain sufficiently involved in such research as to allow it be an intelligent consumer and to maintain connection to the materials research community.
- The Department should see itself as a steward for plasma science, in the same sense that it is the steward for nuclear and high-energy physics. An insufficient number of universities are actively involved in research in plasma science and fusion research.
- Efforts to advance plasma science and to involve universities more fully in the fusion program are essential to assure the availability of talented young scientists and engineers to serve the fusion and the defense mission.
- While the program should now focus on developing the scientific underpinnings for fusion energy, the engineering challenges are immense and early planning for them is essential.

- The Task Force urges OFES to make a concerted effort to seek innovative ways to apply advances in computer technology to the fusion energy program.

The fusion program is in a state of transition, but, given the potential of fusion, enhanced support and efforts to strengthen the program are warranted.

Overview

The fusion program seeks to explore the fundamental energy source of the stars – the energy generated when the nuclei of light atoms, such as hydrogen and its isotopes, combine to form heavier atoms. The Department supports this program to serve three different purposes. First, the program supports the advancement of plasma science – advances that provide an understanding of the state of matter of 99 percent of the visible universe and that offer benefits in activities ranging from astrophysics to the production of microelectronic devices. Second, the inertial confinement fusion program is related to the Department's defense program. Inertial confinement fusion allows the exploration of the physics of materials under conditions like those created in a thermonuclear weapon, thereby enhancing stockpile stewardship. Finally, the program supports the advance of fusion as a possible energy source that might be harnessed by mankind. Although we are mindful of all aspects of the fusion program, the Task Force has been asked to focus on the latter aspect of the Department's program – that is, we have examined the strategy, scope, goals, and management of the Department's efforts to advance fusion as a possible energy source.

Fusion science holds the promise of leading the way to a remarkable energy source with several highly desirable characteristics:

- A Virtually Inexhaustible Fuel Supply. The basic fuels for fusion are deuterium and tritium. Both deuterium and lithium, from which tritium can be generated, are plentifully and inexpensively available.
- Minimal Environmental Impact. Fusion does not yield greenhouse gases or other significant effluents that threaten environmental harm.[4] Unlike some solar and wind

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[4] Even optimistic projections do not suggest that fusion energy will contribute significantly to energy supply until well into the next century. It thus will not be among the first set of technologies that will be deployed to respond to global warming. However, it may play a key role in the control of global warming beginning in the latter half of the century.

technologies, fusion energy would make minimal demands on land use. And, although the intense neutrons from the fusion reaction will result in activation of reactor materials, the materials would not require isolation from the environment for extended periods of time.

- Safety. The stored energy of the fusion fuel contained in the reactor would likely be equivalent to only a few minutes of power production in the case of magnetic fusion energy and fractions of a second in the case of inertial fusion energy. Accidents thus do not threaten wide-ranging impact.

These attractive characteristics have appropriately made fusion energy the holy grail of the energy field.

Scientific progress toward the fusion energy goal has been remarkable - in physics understanding, in development of new technologies needed for fusion, and in the achievement of plasma parameters close to those necessary for a fusion reactor. Indeed, controlled fusion power has increased over the years from less than one watt to more than ten million watts and we are in striking range of achieving a burning plasma in which a net energy gain will be observed**. It is the Task Force's view that the threshold scientific question – namely, whether a fusion reaction producing sufficient net energy gain to be attractive as a commercial power source can be sustained and controlled – can and will be solved**. The time when this achievement will be accomplished is dependent, among other factors, on the creativity of scientists and engineers, skill in management, the adequacy of funding, and the effectiveness of international cooperation.

Nonetheless, there remain significant barriers to the realization of fusion as a significant contributor to the world's energy supply. Progress requires advancing fundamental scientific knowledge (from controlling turbulence, to optimizing the magnetic-field configuration, to enhancing the fusion power gain), resolving very difficult materials issues (*e.g.*, developing a vessel that can withstand high temperatures and intense neutron flux while exhibiting favorable activation characteristics), finding answers to difficult engineering challenges (*e.g.*, constructing a reliable and repairable system), and proving economic feasibility (solving these problems in a manner that does not make fusion prohibitively expensive). Many years of persistent effort will be required to overcome these challenges. In spite of the extended effort and expense that will be required, the fusion program deserves continued support because of its unique energy potential. Constraints on supply and limits on the atmospheric loading of combustion products will eventually require that we diminish our reliance on fossil fuels. Because of this reality, the Department is wisely advancing a portfolio of energy technologies to meet future energy needs. **Indeed, in light of fusion's potential and the risks arising from increasing worldwide energy demand and from eventually declining fossil energy supply, it is our view that we should pursue fusion energy aggressively.**

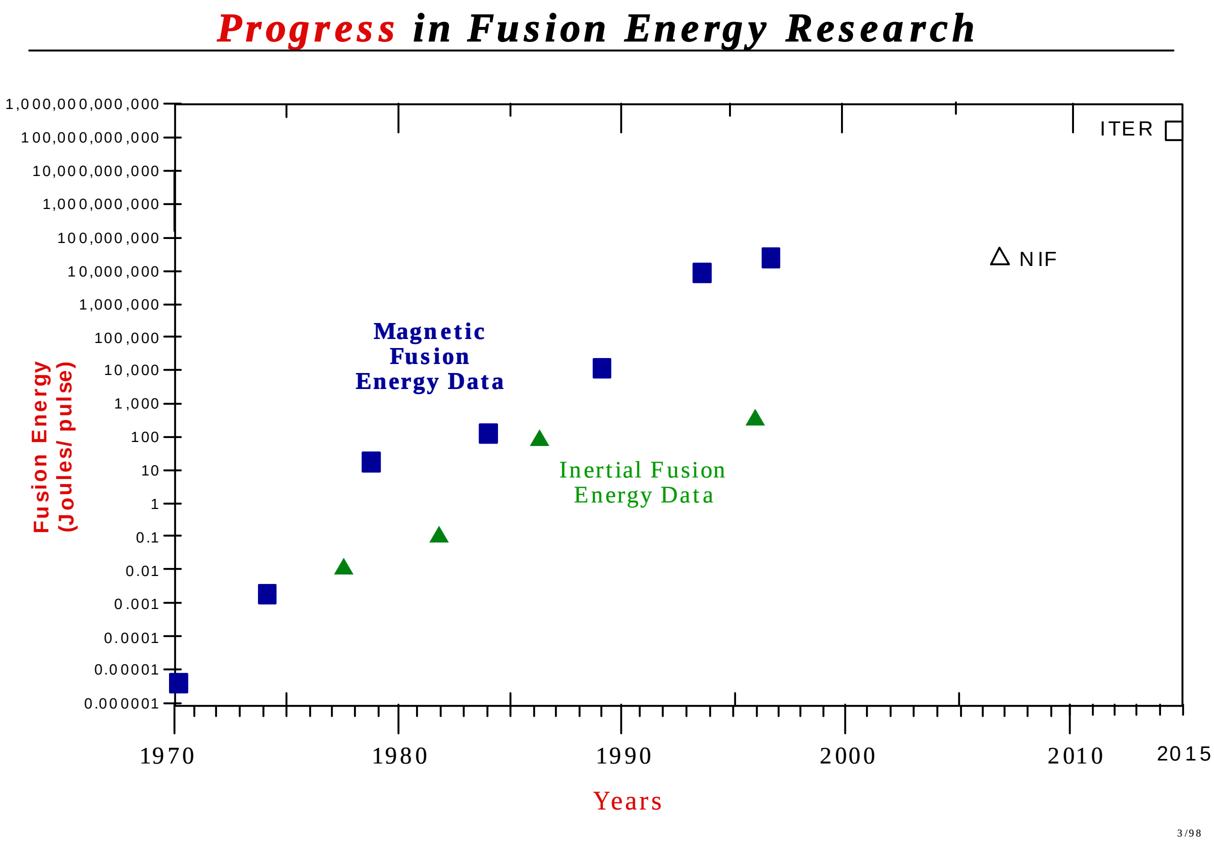
The Department's Fusion Energy Program

Magnetic fusion has been funded by the Office of Fusion Energy Sciences ("OFES"), which is part of the Office of Science. The principal funding for inertial fusion is by Defense Programs ("DP"), in recognition of the use of this technology to serve defense purposes, although in recent years some funds for inertial fusion energy have been provided by OFES. We shall discuss each of these activities and then certain of the issues that touch on both programs.

A. Magnetic Fusion

The magnetic fusion energy ("MFE") program seeks to establish the conditions to sustain a fusion reaction in a plasma that is contained by magnetic fields. As noted above, progress in the past decade has been remarkable – both in the significant progress toward a burning plasma and in the advance of scientific understanding. *See* Figure 1. Scientists have produced 10 million watts of fusion power in the laboratory and have studied the behavior of fusion products (alpha particles) in weakly burning plasmas. Underlying this progress are strides in fundamental understanding, which have lead to the ability to control aspects of plasma behavior. For example, scientists can now exercise a measure of control over plasma turbulence and resultant energy leakage, long considered an unavoidable and intractable feature of plasmas; the plasma pressure above which the plasma disassembles can now be made sufficiently large as to sustain a fusion reaction rate acceptable for a power plant. Electromagnetic waves can be injected and steered to manipulate the paths of plasma particles and then to produce the large electrical currents necessary to produce the magnetic fields to confine the plasma. These and other control capabilities have flowed from advances in basic understanding of plasma science in such areas as plasma turbulence, plasma macroscopic stability, and plasma wave propagation. Much of this progress has been achieved with a particular emphasis on tokamaks.

Focus. The MFE program was significantly redirected in the mid-1990s. The restructured program shifted from a nearly exclusive focus on the achievement of fusion energy in tokamaks to a broader program that would also explore scientific foundations and other



confinement approaches. The revised strategy involves support for the exploration of the science and technology of energy-producing plasmas, for basic plasma science, and for innovative confinement concepts. Expansion of the emphasis on basic plasma science reflects a recognition that this field is the foundation for the entire program and that its support provides benefits far beyond fusion energy. The investigation of a broader portfolio of confinement concepts advances plasma science and fusion technology in ways not possible in one system alone and thereby facilitates evolution toward an attractive fusion energy system.

The Task Force endorses the revised focus of the program. The tokamak is the most highly developed concept for fusion and has played a key role in the experimental study of fusion-relevant plasmas. But given the many barriers to achieving a practical energy source, it is essential to investigate other fusion concepts, which may either promise a more practical or attractive power reactor or provide scientific insights useful to fusion in general. The concepts should span a broad range from the advanced tokamak to configurations that are radically different from the tokamak. A set of criteria is being developed to evaluate the research emphasis to be placed on individual concepts and to formulate a well-balanced, cost-effective program. **OFES has begun to expand the fusion portfolio and it should be encouraged to continue this effort**.

We recognize, however, that the preservation of a strong and balanced program does present a management challenge, particularly in a time of constrained budgets. A necessary next major scientific step is the exploration of the physics of a burning plasma.   At the present time, only the tokamak is sufficiently advanced as to assure the necessary confinement in such an experiment.   But some estimates indicate that such a device would cost in excess of $1 billion. Given the cost, it is not practical to construct a variety of large-scale machines using different concepts to explore this scientific frontier. Thus, the program confronts a management and technical challenge in undertaking the study of burning plasmas – which necessarily involves a major investment in one particular confinement approach (probably a tokamak) – while not prematurely foreclosing less mature confinement approaches that may ultimately offer a better path to a practical fusion energy source.

The fusion community is grappling with this challenge and is seeking to provide advice to the Department as to the logic and strategy for investment.   The Task Force welcomes both the community's recognition of the challenge and its efforts to assist the Department in devising an appropriate strategy.

International Collaboration. Japan and Europe have lesser energy resources than the U.S. and greater concern about dependence on imported energy supplies.   Both have significantly larger programs in MFE than the U.S. – the Japanese budget for MFE is about 1.5 times that of the U.S. and the European budget is about 3 times that of the U.S.   Moreover, at a time when the U.S. has no machines operating or under construction in the billion-dollar class, both Japan and Europe are operating billion-dollar tokamaks (JET, JT60) that are advancing the scientific frontiers and both are operating or constructing billion-dollar stellarators**.   In light of the worldwide benefits of fusion, the large resource requirements for its development, and the**

significant MFE programs that exist outside the U.S., the case for the stable and meaningful engagement of the U.S. in international collaboration is compelling.

In fact, fusion scientists and engineers have operated as part of a worldwide network for decades. They share information with each other and their government sponsors through the Internet and through scientific exchanges. Indeed, international collaboration is and has been the norm for fusion experiments. The foundation for broadened and productive international collaboration for the benefit of all already exists.

Nonetheless, the restructuring of the U.S. program in the mid-1990s has created international friction. The philosophy guiding the European and Japanese programs is somewhat different from that of the U.S. because these other countries are still committed to an aggressive program leading to a demonstration reactor in the early decades of the next century. The U.S. had been a participant with them in the planning to construct an International Thermonuclear Experimental Reactor ("ITER") – a tokamak that was intended to constitute an aggressive intermediate step to a demonstration reactor. But, in connection with the redirection of the U.S. program, the U.S. withdrew from further participation in ITER. And Congress has directed that any collaboration on ITER is to be halted.

Although we have no criticism of the decision to redirect the U.S. program, it must be recognized that the redirection has increased the strains in international collaboration. In the best of circumstances, collaboration is difficult because of budgetary and cultural differences between the U.S. and our collaborators abroad. The Japanese and Europeans have longer (5-year) budgetary planning horizons and, once a course is set, are less likely to deviate from it. Because the U.S. program is more susceptible to year-by-year redirection – and, in fact, because it was recently refocused to a strategy that differs from that of the Europeans and Japanese – the U.S. is considered to be an unreliable partner.[5]

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[5] This perception of the U.S. no doubt threatens adverse consequences in other desirable areas of cooperation.

Given this context, the Department must carefully rebuild the foundations for international collaboration in fusion. In the short term, the Department must establish the ground rules for its ongoing activities. Because ITER has provided a vehicle for meetings and communications among other nations – even for aspects of the international effort that are not directly connected to ITER – the Department needs to find a way to couple itself to these activities without violating the letter or spirit of the Congressional directives. **It is our view that the Department must participate in international activities that enhance our fusion program. Communication with the Congress on these points is essential.**

For the longer term, the Department should develop a strategy as to how to integrate its activities in the global effort. There is general agreement that the next large machine should, at the least, be one that allows the scientific exploration of burning plasmas. Given the anticipated cost of such a venture, the case for international collaboration in its construction is strong. Thus, although the difficulties in siting a multi-billion dollar project are substantial, avenues for international long-range planning for instruments of this scale must be explored. If consensus cannot be developed, an alternative option is for a country or region unilaterally to launch a project and to invite collaborators to contribute after the fact. This is exactly the model that has been successfully applied in the construction of the Large Hadron Collider ("LHC") at CERN.

The ITER partners – the Japanese, the Russians, and the Europeans – are now considering whether to proceed with ITER or with a reduced-cost variant (the so-called ITER-RC). If they decide to go forward, the U.S. should seek to participate in some fashion. If they do not, the U.S. should pursue a less ambitious machine that will allow the exploration of the relevant science at lower cost. The U.S. might seek international collaborators on such a project from the outset, or, if the funding and political circumstances allow, the U.S. might launch the project and invite international collaboration (the LHC model). In any event, however, preliminary planning for such a machine should proceed now so as to allow the prompt pursuit of this option. **In order to participate in a burning-plasma experiment while preserving the breadth of the restructured program, the Department and the community should engage the Congress at an early stage. In light of the fact that our political system generally does**

not accommodate firm long-term budgetary commitments, the development both of understanding of a significant new project and of solid support for it throughout the political system is essential.

B. Inertial Fusion Energy

In inertial fusion the burning fusion reaction is ignited by illuminating and compressing a target – a pellet that contains deuterium and tritium – by the use of intense laser or ion beams. A power reactor would operate by igniting several such pellets per second. A favorable feature of inertial fusion energy ("IFE") is that the components (target factory, driver, fusion chamber) can be isolated from each other. In addition, the driver can be modular, thereby enabling a staged development.

As is the case for MFE, progress in inertial fusion has been remarkable. The scientific basis of inertial fusion has progressed to the point where the driver and pellet requirements to achieve ignition are known to high confidence and are within reach. Experimental diagnostics are capable of probing details of physical properties under extreme conditions. Knowledge of the laser-plasma interaction and implosion hydrodynamics has progressed from a rudimentary empirical level, with much uncertainty, to a current state in which there is good agreement between theory and experiment. Significant advances in computational power and technique, in concert with experiments, have led to good predictive capability. At the same time, laser driver technology has progressed from a few joules to megajoules, with sufficiently good beam control and pulse characteristics to implode ignition pellets. Likewise, advances in technology to fabricate complex targets with nearly sufficient surface smoothness to satisfy the program requirements have been remarkable. The United States is clearly the world leader in such research.

There is a high level of confidence that ignition-level performance will be achieved on the National Ignition Facility ("NIF"), now under construction at Lawrence Livermore National Laboratory. But the challenges that must be overcome to achieve a practical IFE reactor are at least as large as those before MFE. A practical fusion reactor would require large extrapolations of performance in numerous areas, including driver technology, pellet fabrication costs, and reactor wall technology. Nonetheless, **the Task Force concludes that IFE warrants continued exploration and development.**

A variety of drivers are being explored (several types of lasers, heavy ion beams, and z-pinch pulse power), as well as different means of coupling driver energy to the fuel pellet (direct and indirect drive). Some considerations favor heavy ion beams as the driver technology for IFE.[6] Because lasers have lower driver efficiency than an ion beam driver, a reactor employing a laser driver would require higher pellet gains than a reactor that uses an ion beam driver.   Moreover, the inherent high-repetition rate, high efficiency and high-current capacity of an induction linac, plus the reactor-compatible nature of the final focusing element, favor an ion-beam driver. On the other hand, because an ion beam driver would probably employ indirect drive, a reactor using an ion beam driver which would require the fabrication of more complicated targets than a reactor using a laser for direct drive.   **Given the immature state of the technology, it is not appropriate at this time to select only one driver technology for continued exploration.**   This is particularly the case since laser technology is the mainstay of the defense application and IFE should seek to obtain leverage from the large defense effort that relies on lasers.

As noted above, the achievement of IFE requires very significant technical progress in a wide variety of areas – in driver technology, in target design, in target fabrication, in chamber design – and the solutions must lend themselves to cost-effective application in a practical reactor.   Reactor studies can be useful in this connection by serving to reveal the practical barriers to the use of the technology for power generation – including the cost constraints within which such a system must operate.   Such studies should continue to be used as guides in

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6 The Z-pinch technology currently utilizes hardware in close proximity to the pellet and it is not apparent that the repetition rates necessary for an IFE application can be achieved with it. The principal candidates for a driver for IFE are thus various types of lasers and ion beams.

establishing the direction and balance of research efforts, as well as to establish goals that constitute thresholds for further investment.

The fusion community is seeking to develop a philosophy for fusion development that will apply to both IFE and MFE, including decision criteria for commencing and terminating programs. Our views on the overall strategy and management of the program are discussed below.

C. Balance and Funding

OFES should conceive of its basic mission as the advancement of fusion energy in either its magnetic and inertial form. But OFES's efforts must necessarily supplement the work of others. In magnetic fusion, international activities are likely to lead the way if only because the most significant funding is overseas. In inertial fusion, the bulk of the funding is for defense purposes and is not subject to control by OFES. (There also is some international activity, but it is more limited than in magnetic fusion.) In light of this reality, **OFES alone can not dictate the direction of the effort and, as a result, it should not be expected that the overall fusion program will be balanced solely in terms of the energy objective.** Rather, OFES should be expected to use its program to leverage activities undertaken elsewhere to assure effective collaboration and coordination and to establish world leadership in selected niche areas.

The fusion program has been on a downward funding trend – an unfortunate development at a time of remarkable scientific progress – although the funding appears to be stabilizing at a level of about $230 million. **In light of the promise of fusion, the Task Force concludes that the funding for fusion energy is now subcritical.** Proposed experimental programs in new innovative magnetic confinement concepts, which are central to the restructuring, have been reviewed very favorably, but await funding. We are not fully utilizing our lead tokamak facilities to push the science forward and to maintain links to the larger international community. Fusion is poised to benefit from opportunities to exploit new computational power, but the work is constrained by funding limits. At the same time, efforts to address materials problems and to invest in technologies to enable fusion experiments have atrophied. In short, it should not be anticipated that the restructured MFE program will be fully successful in all of its energy missions – simultaneously pursuing new concepts, supporting tokamak experimentation, and shepherding plasma science – unless some increment in funding is forthcoming. The community has estimated that overall funding for fusion energy on the order of $300 million per year will support significant enhancements in the program and will allow program balance to be maintained.

Given the large DP program in inertial fusion research, only a relatively modest increase in the OFES budget is needed to support the IFE activities that should be funded by the OFES program – endeavors which address issues of significance to the energy objective and which are not supported by DP. As noted above, the MFE program has suffered drastic funding cuts in recent years, and is now transitioning into a substantially restructured program. Since the present funding is barely adequate to sustain the restructured MFE program, and since OFES is the sole steward of MFE, any significant increases in IFE funding within OFES should come from an increment to the present budget. Moreover, DP should dedicate funds to dual-purpose activities, consistent with DP's mission statement, that exploit the synergy between the defense work and IFE science.[7] For example, DP might appropriately take the lead in the development of high-average-power lasers because of DP's very significant involvement and accomplishments in the laser field.

D. Strategy, Management, and Structure

While very significant progress in scientific understanding of plasma and fusion device behavior has been achieved, the DOE fusion program finds itself at a crossroads. The program is perceived to lack a strategy and programmatic focus. In fact, the restructuring may have created

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7 The involvement of weapons scientists in IFE helps to preserve a relationship to the open scientific community in fields closely related to defense work. Moreover, the funding of IFE by DP can be an attractive adjunct to defense work in the recruitment and retention of personnel.

an impression of ambivalence about whether energy or science should dominate the agenda. The frequent guidance by Congress to the Department should be seen as signs that Congress does not have confidence in the program management.

The Task Force believes fusion remains of critical importance for the future and that the scientific promise and the energy potential warrants its serious pursuit. As a result of the many thoughtful reviews of the program, augmented the community's efforts, progress on developing a programmatic strategy is underway. **Efforts to define a sensible path leading to a substantial energy contribution from fusion should be given continuing emphasis.** Such a strategy must inevitably allow considerable flexibility; the identification of precise long-term deadlines may be counterproductive because of the inevitability of scientific surprises and of possible instability in funding. **Nonetheless, it is crucial that this planning encompass the identification and timely resolution of the important engineering and economic problems that must be overcome if fusion energy is to be a practical energy source.** In particular, increased efforts should be made to identify downstream "show-stoppers" so as to allow early efforts to overcome or work around the problems or, failing that, to allow a redirection of the overall effort in the most fruitful directions, thereby avoiding the waste of funds on dead ends.

To achieve its goal, the program must be directed by strong management -- a management that leads the effort toward the fusion energy goal at reasonable pace, with sufficient budget, with solid accountability, and high-quality science and technology. Management should seek to restore credibility by articulating clear and sensible milestones and goals and to deliver on them.

We anticipate that the management challenges in the years ahead will be even more complex than those now confronting the Department. As the scientific obstacles relating to confinement and gain are solved, a host of underlying scientific and engineering issues must be addressed. These include developments that will ultimately enable the construction of a fusion power plant that is safe, reliable, durable, maintainable, and cost-effective.[8] Given constrained budgets, the wide variety of options, and the linkages of one issue to another,[9] increasingly sophisticated management of the program will be required.

Examining successful large-scale science programs and projects or successful high technology development projects provide possible models for future progress. Basic attributes of both are skilled, innovative and flexible leadership, integration of program and project planning, and true partnerships among all participants.

One common element of these models is the application of new management tools and techniques. Given the complex nature of the fusion effort, an integrated program planning process is an absolute necessity. Historically, the research, development and demonstration ("RD&D") process has been treated as a serial process.[10] However, in light of the interlinked scientific, engineering, and economic issues associated with progress toward fusion energy, each element of the program must affect the others. A more realistic model is to view the effort as matrix in which each element is strongly interactive with all the others.[11]

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[8] For example, new materials must be developed. Structural materials must be capable of operating over a wide temperature range, including extreme high temperatures, and of transmitting high heat fluxes. Moreover, they must have high reliability and long component lifetimes under circumstances that involve severe levels of radiation damage, dynamic and static mechanical loading, varying temperatures and heat loads, and exposure to coolants, tritium breeding materials, and plasma.

[9] For example, if vanadium alloys with satisfactory performance cannot be developed for the reactor vessel, concepts employing liquid lithium as the coolant/breeder may not be viable. *See* Summary of Fusion Materials Research and Development Activities, 1 (June 3, 1999) (White Paper prepared for the Task Force).

[10] *See* President's Committee of Advisors on Science and Technology, Panel on Energy Research and Development, *Report to the President on Federal Energy Research and Development for the Challenges of the Twenty-First Century* (November 1997).

[11] *See id*. at 7-14 to 7-20.

Proper management of the fusion program requires a comprehensive planning system that includes the following:

- Provides visibility of program activities
- Provides the means to manage by performance
- Encourages fundamental, innovative scientific research
- Drives resource planning
- Provides linkage of accomplishments to goals
- Establishes accountability
- Encourages the development of trained personnel
- Describes activity interrelationships, and
- Aids in integration among the base programs in OFES and DP and the fusion energy goal of practical fusion energy.

Integrated program planning, when properly instituted, should facilitate informed decision making, identify conflicts, and provide a vehicle for conflict resolution. Although each task could be initiated independently, conducting the tasks in parallel (through an integrated planning process) allows better cross-linking and integration of tools, understanding, and expertise. Overall, such an effort should enable DOE to address management problems and to develop guiding principles for better decisions, improved risk management, and lower cost.

Management of the fusion energy effort is complicated by the fact that there is a separation of the magnetic and main locus of the inertial confinement effort in different parts of the Department. This structure serves as an impediment to the establishment of a coherent and integrated program to pursue fusion energy. **Although practical constraints no doubt inhibit major shifts in structure, some strengthened means for overall coordination should be established**. One possible approach, for example, is to give both the responsibility and authority for integration of the "virtual" combined program to a Deputy Undersecretary (who might also have responsibility for integrating other energy technology programs as well). A single committee advisory to that individual might be established to represent all the fusion approaches, as well as the science, engineering, utility, and other affected sectors. Such a committee might be modeled on the High Energy Physics Advisory Panel; the group should be small enough to be efficient and should have leeway to define for itself the issues on which it reports.

E. Other Issues

Materials. The realization of fusion energy will require very significant advances in materials science and engineering. These matters deserve attention because, in the absence of solutions, the investment in other areas will be fruitless in terms of energy production. In recognition of this fact, OFES has allocated a small portion of its budget ($ 6.8 million in FY99) to materials research.

We recognize that materials research – a major and important national and international research area – is and will continue to be pursued for reasons largely unrelated to fusion needs. OFES should seek to exploit advances in materials that may be developed for other reasons. **Although OFES can not be a major funding source for the overall effort in materials research, it should remain sufficiently involved in such research as to allow it to be an intelligent consumer and to maintain connection to the materials research community**. Eventually, more aggressive funding of materials research for fusion will be required.

Plasma Science. As noted above, one of the missions of the OFES is to advance plasma physics. It is our view that **the Department should see itself as the steward for plasma science, in the same sense that it is the steward for nuclear and high-energy physics**. Like these other fields, plasma science has intrinsic scientific interest and has important connections to astrophysics, space physics, and materials sciences. Moreover, advances in plasma science have yielded practical accomplishments in areas such as microelectronics, lasers, switchgear, and microwave sources. Although the OFES goal of supporting plasma science can be fully justified by the fact that plasma science underlies the achievement of the fusion energy mission, this aspect of OFES's work has important other benefits.

An insufficient number of universities, particularly major research universities, are actively involved in research in plasma science and fusion research. This hampers the integration of plasma science into, and the appreciation of plasma science by, the larger scientific community. Indeed, in order to grow and advance, this scientific field, like others, must be fully embedded within the university system. OFES recognizes this issue and is taking some steps to address it (such as providing new funding opportunities for young faculty). OFES is encouraged to continue its efforts.

Manpower. The advancement of fusion will require sophisticated manpower. **Efforts to advance plasma science and to involve universities more fully in the fusion program are essential to assure the availability of talented, young scientists and engineers who can serve both the fusion energy and the defense mission**. This fact reinforces the importance of strong and stable support of plasma science and fusion research in universities.

Engineering. As noted above, extraordinarily complicated engineering issues are associated with fusion power. Indeed, the biggest challenge may well be the economic one – finding solutions to the problems that are not so prohibitively expensive as to make fusion unattractive in the marketplace. **While, given the state of knowledge, the program should now focus on developing the scientific underpinnings for fusion energy, the engineering challenges are also immense and early planning for them is warranted.** An integrated program plan, described above, should assist in this effort.

Computer Simulation. Computer simulation has always been an important component of both the MFE and IFE programs. Indeed, pioneering computational approaches to plasma dynamics have played a very significant role in the scientific progress that has been obtained in both MFE and IFE. The advent of terascale computing technology has opened the door for enhanced linkages of theory, experiment, and computation/simulation in ways that promise jointly to propel the scientific enterprise forward. The fusion program, in particular, would benefit from integrated approaches that couple complex physical models with experimental data, thereby facilitating insight into device behavior. For example, advances in computer hardware and software can enable very intricate three-dimensional calculations that allow the exploration of confinement schemes and of plasma phenomena, thereby providing a key guide and complement to experiments. Large-scale computing capabilities also offer the possibility of end-to-end simulations of complete fusion energy systems. OFES has appropriately sought to become a major participant in the Department's computer initiative**. The Task Force urges OFES to make a concerted effort to seek innovative ways to apply advances in computer technology to the fusion energy program.**

Conclusion

The fusion program is in a state of transition and extensive self-examination in the aftermath of the restructuring and as a result of declining funding. Nonetheless, the Task Force believes that the foundation for a vibrant and valuable program is being created. Given the promise of the technology and the significant scientific advances, enhanced support and efforts to strengthen the program are warranted.

Task Force on Fusion Energy

Appendix

Secretary of Energy Advisory Board
Terms of Reference
Task Force on Fusion Energy

Objectives and Scope

The SEAB Task Force is requested to conduct a thorough review of all the Department's fusion energy technologies, both inertial and magnetic. The review should analyze and provide recommendations on the role of each of those technologies as part of a national fusion energy research program. That analysis should address whether the current and planned resources within the Office of Fusion Energy Sciences budget are appropriately balanced among the concepts to provide the scientific basis for an informed selection of the best option for development as a fusion energy source.

In carrying out this review, SEAB Task Force should specifically take into account the relationship to international fusion energy programs, the connection of inertial fusion energy research to the stockpile stewardship activities in Defense Programs, and the broader science and educational goals that may be enabled by these fusion technologies.

Background Summary

The Department of Energy's Office of Fusion Energy Sciences manages a scientific research program, which has as its overarching mission to establish the knowledge base for an environmentally benign and economically competitive fusion energy power source. The greatest part of the research effort in this program has been applied to theory and experiments using magnetic fields to confine the plasma fuel so that fusion reactions can take place. These research efforts have played a critical role in the intellectual development of plasma science and technology, but the prime motivation of the Department's fusion energy program has always been the development of a new energy option.

The Department's Office of Inertial Fusion and National Ignition facility Project manages a research program to address high-energy-density physics issues for the science based stockpile stewardship program and to develop a laboratory microfusion capability. A major near term goal of the program is to demonstrate ignition in the laboratory, and the National Ignition Facility (NIP) is a cornerstone of this effort. Although the primary mission of the inertial fusion program is for defense applications, inertial fusion research will provide important information for the development of inertial fusion energy. This arrangement is consistent with the recommendations of the 1990 Fusion Policy Advisory Committee Report.

In their FY 1999 report language, both the House and Senate appropriations subcommittees noted chat, in addition to magnetic fusion technology, the Department also pursues related fusion energy technologies, primarily for national security purposes. Examples of such technologies are pulsed-power, lasers, and ion drivers, all variants of what is known as inertial fusion. These technologies may have bearing on the long term prospects for fusion ignition and/or energy. The Department's Office of Defense Programs has long pursued these technologies as a part of the weapons research program and more recently as a part of stockpile stewardship, and only secondarily because of any benefits to energy development.

Description of the Work

The Task Force should review the Department's present plans for research and development of the four fusion related technologies cited by the appropriations subcommittees -- pulsed-power, lasers, ion drivers, and magnetic fusion. The review should focus on the scientific quality of the programs, the goals and objectives of the programs, and the energy potential of each technology. The final written report should provide advice on how to structure the Department's fusion energy programs. The findings and recommendations of this Task Force should include comments on the goals and objectives of the Department's fusion energy related programs, a critique of the current development strategies, suggested changes in the overall roadmap (including major decision points), and recommended funding levels.

The Task Force should address at least the following questions:

1. What is the overall state of development and energy potential of the four fusion-related technologies?
2. How should the magnetic and inertial fusion energy programs in the Office of Science be structured to make maximum scientific progress in the development of fusion energy?
3. Recognizing that the inertial confinement fusion program in the Office of Defense Programs is driven by stockpile stewardship requirements, what is the appropriate balance between magnetic and inertial confinement fusion energy activities in the Office of Science?
4. What is an appropriate development path for each of the four fusion-related technologies?
5. What is the appropriate funding level for each fusion energy technology?

Reporting

The Task Force shall report to the Secretary of Energy Advisory Board.

Estimated Number and Frequency of Meetings

The Task Force is expected to meet approximately four times during its term. Meetings will be scheduled as the Task Force chair deems necessary for the Task Force to accomplish its duties and purpose.

Members

Subcommittee members shall reflect a balance of expertise and informed viewpoints. Approximately twelve members shall be selected from the fields of plasma science, energy, and the environment; the general scientific community; public interest organizations; and the Secretary of Energy Advisory Board.

Chairman

The Chairman of the SEAB shall designate a chair for the Task Force in consultation with the Secretary of Energy.

Working Groups

Working groups may be established as appropriate, to facilitate the functioning of the Committee. The objectives of the working groups are to make recommendations to the Task Force with respect to the activities described in the Description of Work section above.

Duration and Termination Date

This charter shall expire in five months from the date of the Task Force's establishment, subject to extension or dissolution by the Chairman of the Secretary of Energy Advisory Board.