Testimony of Dr. Stewart C. Prager
Director, Princeton Plasma Physics Laboratory
to the
Subcommittee on Energy and Environment
House Committee on Science and Technology
Hearing on
"The Next Generation of Fusion Energy"
October 29, 2009

Mr. Chairman and members of the committee, thank you for this opportunity to discuss fusion energy.

I am Director of the Princeton Plasma Physics Laboratory – a Department of Energy national lab, managed by Princeton University, dedicated to developing the scientific foundation for fusion energy. Prior to nine months ago, I was a practicing fusion plasma physicist at the University of Wisconsin.

There are two complementary, compelling approaches to fusion energy. In one, powerful lasers compress a tiny frozen pellet of fusion fuel, releasing fusion energy in a billionth of a second. The anticipated demonstration of ignition in the National Ignition Facility will tremendously advance the physics basis for this approach.

I am here today to discuss the approach known as magnetic fusion, in which a large, hot plasma (the hot gas that makes up the sun) is confined continuously by powerful magnetic fields. Fusion energy is perhaps one of the most challenging physics and engineering quests ever undertaken; its realization will be key to solving what is perhaps the most pressing problem confronting the world today – the absence of sustainable energy. By any measure, we are far along the road to commercial fusion power. My goal today is to talk about the future: the remainder of the journey to fusion energy.

My comments are informed by the just-completed study by the U.S. fusion community, commissioned by DOE and known as the ReNeW report. About 200 fusion scientists undertook this one-year study that articulates the scientific issues yet to resolve for fusion power, beyond those to be resolved in the landmark international ITER experiment. A fusion system consists of the hot plasma core – the "sun on earth" - in which fusion reactions occur, and the surrounding material structure. We are ready to move forward to better control the plasma and to develop new materials. The two problems are coupled in that the plasma affects the materials and the material affects the behavior of the plasma within.

Our ability to control the 100 million degree plasma core is quite amazing. Yet, we have more work to do to sustain the fusion plasma indefinitely and controllably. The sophistication of plasma science now offers new opportunities for fusion. For example, new designs of magnetic configurations are possible now that were nearly impossible even to conceive twenty years ago. They are possible only with modern computers, enabled by new principles in plasma physics. Building upon the substantial experimental foundation of the mainline tokamak approach, these cousins of the tokamak produce plasmas that persist indefinitely and are so well controlled as to reduce the severity of the materials challenges.

It is crucial that we establish a research program in materials for fusion. Materials must be developed to withstand the intense heat that emerges from the plasma. This requires a basic materials research combined with materials studies in plasma experiments.

But full solution of the materials challenge ultimately requires study of materials in a true fusion environment – with the intense flux of neutrons that are produced in the fusion reactions. It is time to lay the groundwork for such a U.S. facility, sometimes called a fusion nuclear science facility since it provides study of materials in the nuclear fusion environment. If this facility were designed somewhat more aggressively – to produce net fusion power as well as neutrons, it would demonstrate electricity production. Design studies are required to identify the wisest next step in these directions, considering our level of physics and engineering readiness.

The Princeton Plasma Physics Lab is dedicated to solving the broad range of fusion science challenges. Our key capability in plasma physics enables us to attack crucial problems in the fusion plasma core, the interaction between the plasma and materials, and the properties of materials exposed to the intense plasma heat.

The major experiment at our lab is developing the plasma physics basis for a fusion nuclear science facility, advancing physics broadly applicable to fusion and ITER, and investigating novel materials boundaries. We hope to play a key role in the physics and engineering design of a fusion nuclear science facility, which would not be located at our laboratory. We will continue our contributions to the design of ITER, and are preparing ourselves for participation in ITER research. And we are developing plans to realize experimentally, at our laboratory, the new steady-state approaches to fusion energy that could prove so essential to the feasibility of fusion.

When I began my research career the U.S. was the world leader in fusion. We had the best facilities and arguably the most innovative program. Scientists the world over flocked to our labs. The Japanese government sent research teams to then-modern U.S. facilities to learn the trade. An alarming reversal of that flow of scientists is now underway. The U.S. has not built a major new fusion facility in decades. The rest of the world is seizing the opportunities. Major facilities, more ambitious than anything in the U.S., are starting operation or are under construction in China, Japan, South Korea, Germany and France. The U.S. effort has dwindled to a fraction of that of the European Union and Japan. The time is ripe for the U.S. to reverse its slide. Opportunities abound to restore the U.S. to world leadership and move us aggressively toward carbon-free, abundant fusion energy.

Appendix I

Executive Summary

of the

Research Needs Workshop (ReNeW) for Magnetic Fusion Energy Science

Research Needs Workshop for Magnetic Fusion Energy Science

Executive Summary

Nuclear fusion–the process that powers the sun–offers an environmentally benign, intrinsically safe energy source with an abundant supply of low-cost fuel. It is the focus of an international research program, including the ITER fusion collaboration, which involves seven parties representing half the world's population. The realization of fusion power would change the economics and ecology of energy production as profoundly as petroleum exploitation did two centuries ago.

The 21st century finds fusion research in a transformed landscape. The worldwide fusion community broadly agrees that the science has advanced to the point where an aggressive action plan, aimed at the remaining barriers to practical fusion energy, is warranted. At the same time, and largely because of its scientific advance, the program faces new challenges; above all it is challenged to demonstrate the timeliness of its promised benefits.

In response to this changed landscape, the Office of Fusion Energy Sciences (OFES) in the US Department of Energy commissioned a number of community-based studies of the key scientific and technical foci of magnetic fusion research. The Research Needs Workshop (ReNeW) for Magnetic Fusion Energy Science is a capstone to these studies. In the context of magnetic fusion energy, ReNeW surveyed the issues identified in previous studies, and used them as a starting point to define and characterize the research activities that the advance of fusion as a practical energy source will require. Thus, ReNeW's task was to identify (1) the scientific and technological research frontiers of the fusion program, and, especially, (2) a set of activities that will most effectively advance those frontiers. (Note that ReNeW was not charged with developing a strategic plan or timeline for the implementation of fusion power.)

The Workshop Report

This Report presents a portfolio of research activities for US research in magnetic fusion for the next two decades. It is intended to provide a strategic framework for realizing practical fusion energy. The portfolio is the product of ten months of fusion-community study and discussion, culminating in a Workshop held in Bethesda, Maryland, from June 8 to June 12, 2009. The Workshop involved some 200 scientists from Universities, National Laboratories and private industry, including several scientists from outside the US.

Largely following the Basic Research Needs model established by the Office of Basic Energy Sciences (BES), the Report presents a collection of discrete research activities, here called "thrusts." Each thrust is based on an explicitly identified question, or coherent set of questions, on the frontier of fusion science. It presents a strategy to find the needed answers, combining the necessary intellectual and hardware tools, experimental facilities, and computational resources into an integrated, focused program. The thrusts should be viewed as building blocks for a fusion program plan whose overall structure will be developed by OFES, using whatever additional community input it requests.

Part I of the Report reviews the issues identified in previous fusion-community studies, which systematically identified the key research issues and described them in considerable detail. It then considers in some detail the scientific and technical means that can be used to address these issues. It ends by showing how these various research requirements are organized into a set of eighteen thrusts. Part II presents a detailed and self-contained discussion of each thrust, including the goals, required facilities and tools for each.

This Executive Summary focuses on a survey of the ReNeW thrusts. The following brief review of fusion science is intended to provide context for that survey. A more detailed discussion of fusion science can be found in an Appendix to the Report, entitled "Fusion Primer."

Fusion science

Fusion's promise

The main advantages of producing power from fusion reactions are well known:

• Essentially inexhaustible, low-cost fuel, available worldwide.

• High energy-density of fuel, allowing straightforward base-load power production without major transportation costs.

• No production of greenhouse gas, soot or acid rain.

• No possibility of runaway reaction or meltdown that could pose a risk to public safety.

• Minimal proliferation risk.

• Only short-lived radioactive wastes.

Few of these benefits are unique to fusion; what is exceptional is their simultaneous achievement in a single concept. For example, fusion's freedom from greenhouse-gas production and chemical pollution is shared with, among other energy sources, fission nuclear power; in this regard the relatively mild radioactivity of fusion, whose waste is thousands of times less radioactive and long-lived than fission, is significant. On the other hand, compared to the non-proliferating renewable energy sources, fusion offers a steady, predictable energy source with low land use.

To be weighed against these advantages is the long and relatively expensive development path for fusion. Achieving the conditions necessary for appreciable fusion reactions to occur invokes substantial physics and engineering challenges. Yet the impressive progress achieved in addressing these hurdles must be acknowledged. One measure is the exponential increase in fusion power produced in laboratory experiments, amounting to some eight orders of magnitude (a factor of 100,000,000) since the mid-1970's. Indeed some fusion experiments have approached scientific "break-even," producing roughly as much fusion power as was externally supplied for heating the fuel. A more important if less easily measured avenue of progress lies in scientific understanding. Fusion scientists have developed a broad and sophisticated, if still incomplete, picture of what is happening in a magnetically confined fusion plasma. This advance now allows routine control of key plasma properties and behavior.

Magnetic confinement

Magnetic confinement (more accurately termed "magnetic insulation") allows the fusion fuel, which is necessarily in the form of ionized gas, or plasma, to retain sufficient heat to maintain fusion reactions. It acts by enforcing a relatively low plasma density at the plasma boundary, where vessel walls would otherwise cool the gas, and by inhibiting heat flow from the interior to the wall region. The essential ingredient is a magnetic geometry in which the magnetic field lines abide in a closed, bounded region.

During the last decades of the twentieth century, fusion research gained important scientific victories in plasma confinement: major advances in both the control of instability and the amelioration of heat transport. While significant confinement issues remain to be solved, and while most of the fusion scientific community looks forward to substantial further improvements, the present demonstrated level of confinement is sufficient to impart confidence in the future of fusion energy. One indicator of this scientific advance is the rapid confinement progress mentioned above. Perhaps a more significant consequence is the decision by the international fusion community to embark on the ITER project.

Breadth of fusion research

Fusion progress requires scientific research of the highest quality and originality. Such science is not an activity to be balanced against the energy goal, but rather an essential component of the quest for that goal. This Report emphasizes the goal-directed nature of the program, but it is also appropriate to mention that, like any deep investigation, fusion research has enjoyed broad connections with other domains of science.

Many connections are mentioned in the Theme chapters of Part I. Examples are:

• gyrokinetic simulation, used to understand transport and stability in magnetized fusion plasmas, has become an important tool in astrophysics and magnetosphere physics;

• magnetic reconnection, a key phenomenon in the stability of magnetically confined plasmas, has central importance in numerous solar, magnetosphere and astrophysical contexts;

• turbulent heat transport across the magnetic field, which plays a role in modern fusion experiments very similar to its role in the equilibrium configuration of the sun and other stars;

• unstable Alfvén waves, whose effects in fusion experiments are closely similar to observed perturbations in the earth's magnetosphere;

• the high-strength, ductile materials being developed for fusion should have wide application in industry, including aerospace and chemical manufacturing.

Research requirements

In the next two decades, the "ITER era," magnetic fusion will for the first time explore the burning plasma regime, where the plasma energy is sustained mostly by its own fusion reactions. We expect ITER to expand our understanding of fusion plasma science and to be a major step toward practical fusion energy. It will also, as the first burning plasma experiment, pose new requirements, including advanced diagnostics for measurement and control in a burning-plasma environment, and analytical tools for understanding the physics of self-heating.

To benefit fully from its investment in ITER the US must maintain a broad research program, attacking fusion's scientific and technical issues on several fronts. We need in particular to acquire knowledge that ITER cannot provide: how to control a burning plasma with high efficiency for indefinite periods of time; how to keep a continuously burning plasma from damaging its surrounding walls–and the walls from contaminating the plasma; how to extract the fusion energy from a burning plasma efficiently and use it to produce electricity and a sustained supply of tritium fuel; and ultimately how to design economical fusion power plants. These requirements motivate a multi-disciplinary research program spanning such diverse fields as plasma physics and material science, and advancing a range of technologies including plasma diagnostics, magnets, radiofrequency and microwave sources and systems, controls, and computer simulation.

The key scientific and technical research areas whose development would have a major effect on progress toward fusion energy production were systematically identified, categorized and described in the three resource documents that form the starting point for ReNeW: the report of the Priorities, Gaps and Opportunities Panel, chaired by Martin Greenwald; the report of the Toroidal Alternates Panel, chaired by

David Hill; and the report of the Energy Policy Act task group of the U.S. Burning Plasma Organization.

In Part I of the ReNeW Report the full panoply of fusion issues are summarized, and then examined from the point of view of *research requirements*: the facilities, tools and research programs that are needed to address each. The research thrusts presented in Part II are essentially integrated combinations of these research requirements. [NOTE: This paragraph is similar to the first paragraph on page 2.]

The ReNeW thrusts: a research portfolio

Thrust definition

The ReNeW thrusts listed below are the key results of the Workshop. They constitute eighteen concerted research actions to address the scientific and technological frontiers of fusion research. Each thrust attacks a related set of fusion science issues, using a combination of new and existing tools, in an integrated manner. In this sense each thrust attempts a certain stand-alone integrity.

Yet the thrusts are linked, both by scientific commonality and by mutual dependence. The most important linkages–for example, requirements that a certain thrust be pursued and at least in part accomplished before another is initiated–are discussed in Part II of the main Report. Here we emphasize that fusion advances along a broad scientific and technological front, in which each thrust plays an important role.

The thrusts span a wide range of sizes, from relatively focused activities to much larger, broadly encompassing efforts. This spectrum is expected to enhance the flexibility of OFES planning.

ReNeW participants consider all the thrusts to be realistic: their objectives can be achieved if attacked with sufficient vigor and commitment. Three additional elements characterize, in varying degrees, the ReNeW thrusts:

• Advancement in fundamental science and technology–such as the development of broadly applicable theoretical and simulation tools, or frontier studies in materials physics.

• Confrontation with critical fusion challenges–such as plasma-wall interactions, or the control of transient plasma events.

• The potential for major transformation of the program–such as altering the vision of a future fusion reactor, or shortening the time scale for fusion's realization.

Thrust organization

The resource documents used by ReNeW organized the issues into five scientific and technical research areas. Correspondingly, the ReNeW organizational structure was based on five Themes, each being further sub-divided into three to seven panels. The thrusts range in content over all the issues delineated in the five Themes.

Many of the ReNeW thrusts address issues from more than one Theme. For this reason the scientists contributing to most thrusts are from a variety of research areas, and key elements of a given thrust may stem from ideas developed in several Themes. In other words, the content of a typical thrust transcends that of any single Theme. Nonetheless, it is convenient to classify each thrust according to the Theme that contains its most central issues.

The ReNeW thrusts are:

Theme 1: Burning plasmas in ITER.

ITER participation will be a major focus of US fusion research during the time period considered by ReNeW. The opportunities and challenges associated with the ITER project are treated in Theme 1.

Thrust 1: Develop measurement techniques to understand and control burning plasmas. This thrust would develop new and improved diagnostic methods for measuring and controlling key aspects of burning plasmas. The desired measurement techniques must be robust in the hostile burning-plasma environment and provide reliable information for long time periods. While initially focused on providing critical measurements for ITER, measurement capability would also be developed for steady-state burning plasmas beyond ITER.

Thrust 2: Control transient events in burning plasmas. This thrust would develop the scientific understanding and technical capability to predict and avoid disruptions and to mitigate their consequences, in particular for ITER. Also, tools would be developed to control edge plasma transport and stability, to minimize instability-driven heat impulses to the first wall.

Thrust 3: Understand the role of alpha particles in burning plasmas. Key actions would be developing diagnostics to measure alpha particle properties and alpha-induced fluctuations, incorporating validated theories for alpha particle behavior into integrated burning-plasma simulation tools, and expanding the operating regime of burning plasma devices through the development of control techniques for alpha-driven instabilities.

Thrust 4: Qualify operational scenarios and the supporting physics basis for ITER. This thrust would address key issues in forming, heating, sustaining, and operating the high-temperature plasmas required for ITER's mission. An integrated research campaign would investigate burning-plasma-relevant conditions with the use of upgraded tools for heating and current drive, particle control and fueling, and heat flux mitigation on existing tokamaks, along with a possible new facility.

Theme 2: Creating predictable, high-performance, steady-state plasmas

An economic fusion reactor will require a steady state with higher fusion density and greater fraction of self-heating than ITER. This Theme addresses a broad range of issues, including both plasma physics and engineering science, needed to demonstrate that plasmas with the needed conditions can be achieved and controlled. Predictive capability to enable confident extrapolation to a demonstration reactor is emphasized.

Thrust 5: Expand the limits for controlling and sustaining fusion plasmas. This thrust would integrate development of the diagnostic, auxiliary heating, current drive, fueling systems and control systems needed to maintain the nonlinear tokamak plasma state, seeking to maximize performance. The thrust will exploit existing experiments to test and develop new ideas and proceed with increased integration in upcoming steady-state experiments and alpha-heated plasmas in ITER, ultimately enabling the self-heated and self-driven plasmas needed for a fusion power plant.

Thrust 6: Develop predictive models for fusion plasmas, supported by theory and challenged with experimental measurement. Advances in plasma theory and simulation would be combined with innovative diagnostic methods and experiments to improve and validate models of confined plasma dynamics. Assessment of critical model elements would be provided by dedicated analysts, acting as bridges between theorists, code developers and experimentalists.

Thrust 7: Exploit high temperature superconductors and other magnet innovations to advance fusion research. Magnets are crucial for all MFE concepts. This focused thrust would perform the research necessary to enable revolutionary new high temperature superconducting materials to be used in fusion applications. Key activities include development of high-current conductors and cables, and integration into components of fusion research experiments, with great potential to improve their design options.

Thrust 8: Understand the highly integrated dynamics of dominantly self-heated and self-sustained burning plasmas. This thrust would explore scenarios where, as in a reactor, most heat comes from fusion alphas and most current is self-driven by plasma gradients. It would start by assessing potential advanced plasma scenarios and upgrades on ITER which could enhance its performance. In parallel, scoping/design studies would be done for a new US facility to explore the high fusion gain DEMO plasma regime. The studies would support actions to proceed with ITER enhancements, the construction of a US DT facility, or both.

Theme 3: Taming the plasma-material interface

Magnetic confinement sharply reduces the contact between the plasma and the vessel walls, but such contact cannot be entirely eliminated. Advanced wall materials and magnetic field structures that can prevent both rapid wall erosion and plasma contamination are studied in Theme 3.

Thrust 9: Unfold the physics of boundary layer plasmas. Comprehensive new diagnostics would be deployed in present confinement devices to measure key plasma parameters in the boundary region, including densities and temperatures, radiation, flow speeds, electric fields and turbulence levels. The results could vastly improve numerical simulation of the edge region, allowing, in particular, reliable prediction of wall erosion and better radiofrequency antenna design.

Thrust 10: Decode and advance the science and technology of plasma-surface interactions. Measurement of complex interaction of plasma with material surfaces under precisely controlled and well-diagnosed conditions would provide the information needed to develop comprehensive models to uncover the basic physics. These measurements would be made on both upgraded present facilities and new boundary plasma simulators capable of testing irradiated and toxic materials.

Thrust 11: Improve power handling through engineering innovation. Heat removal capability would be advanced by innovative refractory power-exhaust components, in parallel with assessment of alternative liquid-metal schemes. Materials research would provide ductile, reduced-activation refractory alloys, which would be developed into prototypes for qualification in high-heat flux test devices. Practical components would be deployed on existing or new fusion facilities.

Thrust 12: Demonstrate an integrated solution for plasma-material interfaces compatible with an optimized core plasma. Understanding of interactions between a fusion plasma core region and its boundary would be advanced and validated in a new facility. The facility would combine high power density, long pulse length, elevated wall temperature and flexibility regarding boundary systems, in a limited-activation environment. Knowledge gained from thrusts 9-11 would help guide the design of this facility.

Theme 4: Harnessing fusion power

Fusion energy from D-T reactions appears in the form of very energetic neutrons. Theme 4 is concerned with the means of capturing this energy, while simultaneously breeding the tritium atoms needed to maintain the reaction.

Thrust 13: Establish the science and technology for fusion power extraction and tritium sustainability. Fusion must create the tritium fuel it uses, and do so in the same systems that capture and extract the fusion energy. This thrust develops the scientific foundation and engineering of practical, safe and reliable processes and components that harvest the heat, create and extract the tritium, and rapidly process and contain the tritium. The thrust will culminate in a fuel and power handling capability on a scale needed for a demonstration energy system.

Thrust 14: Develop the material science and technology needed to harness fusion power. The objective of this thrust is to create low-activation, high-performance materials that effectively function for a long time in the hostile fusion environment. An essential requirement to fulfill the mission of this thrust is the establishment of a fusion-relevant neutron source to perform accelerated characterization of the effects of radiation damage to materials.

Thrust 15: Create integrated designs and models for attractive fusion power systems. Advanced design studies focused primarily on DEMO, but also on nearer term fusion nuclear facilities is one element of this thrust. These would lay out the scientific basis for fusion power and provide focus to the research efforts required to close the knowledge gap to DEMO. The other element comprises science-based predictive modeling capabilities for plasma chamber components and related systems.

Theme 5: Optimizing the magnetic configuration

Currently most large fusion experimental devices are based on the tokamak magnetic configuration, a design using a strong, axisymmetric external magnetic field to achieve operating parameters close to those in a fusion reactor. Alternative magnetic configurations are studied to investigate physics and technology principles that could optimize the design of future fusion devices. The most developed alternate toroidal magnetic configurations are considered in Theme 5.

Thrust 16: Develop the spherical torus to advance fusion nuclear science. Experiments on the small aspect-ratio tokamak, or Spherical Torus, would be extended to regimes of lower collision frequency, approaching values needed for fusion nuclear science applications. Plasma start-up, power handling, controlled stability, and sustainment issues in this regime would be studied in long-pulse experiments using stronger magnetic fields, improved heating and current drive, and advanced diagnostics, with strong coupling to theory and modeling..

Thrust 17: Optimize steady-state, disruption-free toroidal confinement using 3-D magnetic shaping, and emphasizing quasi-symmetry principles. Magnetic quasi-symmetry in 3-D configurations is expected to lead to excellent plasma confinement while ensuring stable steady-state burning plasma performance with minimal need for control. This thrust would conduct new quasi-symmetric experiments, which would, together with theory, engineering design, and targeted international collaboration, validate extrapolation to burning plasma applications.

Thrust 18: Achieve high-performance toroidal confinement using minimal externally applied magnetic field. This thrust advances a multi-faceted program of theory, simulation, and well-diagnosed experiments to resolve critical issues of confinement, stability, and current sustainment in magnetic configurations with minimal toroidal field. New devices with heating and current drive systems would enable scaling to high temperature and small ion gyroradius.. Fusion system studies will guide productive directions for present and future research.

Appendix: A Fusion Primer

Just as the heaviest elements, such as uranium, release energy when fission allows them to become smaller, so the very lightest elements release energy when they fuse, joining together to produce larger nuclei. (The dividing line between nuclei that are too light and want to fuse and those that are too heavy occurs at iron, the most stable nucleus.) The reaction that occurs most readily is the fusion of two isotopes of hydrogen: deuterium (D), whose nucleus consists of a proton and a neutron, and tritium (T), whose nucleus contains a proton and two neutrons. Fusion of these nuclei–the so-called D-T reaction–yields helium, an inert, non-radioactive gas whose nucleus has two protons and two neutrons. This helium nucleus or "alpha particle" carries 20% of the fusion energy production. It is contained by magnetic fields, and provides the plasma self-heating that sustains the very high plasma temperature. The remaining neutron is released at very high energy–energy whose capture provides 80% of the energetic profit of the reaction.

A reactor based on D-T reactions would have to breed tritium from lithium (which is plentiful), using the neutrons liberated in the D-T fusion process. More advanced fuel cycles would not require tritium breeding, but the D-T reaction has advantages with regard to accessibility and energy production. It is expected to be used in at least the first generation of fusion power reactors.

Because all nuclei are positively charged, they electrically repel each other. This "Coulomb repulsion" can be overcome only by bringing the reactants to very high temperatures; in the case of D-T the required temperature exceeds one hundred million degrees.

Far below thermonuclear temperatures the electron on each hydrogen atom breaks free from its nucleus, yielding independent ion and electron fluids. The resulting electrically active gas, called *plasma*, can carry enormous electric currents; it is strongly responsive to electromagnetic fields, while at the same time able to produce strong fields on its own. Thus the operating fluid in any fusion device is plasma, a form of matter more electrodynamically active than any conventional liquid, solid or gas.

In summary, the key features of D-T fusion are:

1. an operating temperature in the hundred-million degree range, with the result that the working gas is necessarily in the plasma state;

2. an energy release primarily in the form of very fast alpha particles and neutrons, whose energy must be captured to provide the thermal output of the reactor;

3. the need to breed tritium from the D-T neutron and lithium.

Heating and confinement
Evidently the most basic tasks in constructing a fusion reactor are to heat a hydrogen gas to thermonuclear temperatures, and then to confine the resulting plasma for a time long enough for fusion reactions to take place, thus maintaining the high temperature. In most reactor designs heating is provided by a combination of driving electric currents through the plasma, directing energetic particle beams at the plasma, and energizing plasma particles by means of radiofrequency electromagnetic radiation, similar to the heating mechanism of a microwave oven.

Confinement is measured by the so-called energy confinement time, denoted by τ_E. Since both reaction rates and energy loss rates depend upon the plasma density *n*, the required value of τ_E depends on plasma density. It turns out that the critical parameter is the product $n\tau_E$; when density is measured in ions per cubic centimeter and τ_E in seconds, sufficient confinement has been achieved if the product exceeds about 10^{14} sec/cm^3 (the "Lawson criterion"). [NOTE: This paragraph is a little technical for a general primer, but it seems to work.]

One way to satisfy the Lawson criterion is to compress a hydrogen pellet to extreme density values, exceeding the density of conventional solids, while allowing relatively short confinement times. This is the approach taken by the *inertial confinement* program. The main arm of international fusion research uses much lower densities–lower even than the density of air at the earth's surface. Thus the working fluid is a rarefied plasma, whose low density is part of the reason for the intrinsic safety of the device. The relatively long confinement time thereby required is supplied by magnetic fields, taking advantage of the plasma's strong response to such fields. This line of research is called *magnetic fusion*, although the phrase "magnetic confinement for fusion" would be more descriptive.

Magnetic confinement
Neon signs confine cold plasma in glass tubes. But a very hot, rarefied plasma–a fusion plasma–could not maintain thermonuclear temperatures if it had substantial contact with a material wall. At the densities used in magnetic fusion, plasma resting against a wall will quickly cool, bringing fusion reactions to a halt. So the confining magnetic field must protect the plasma from being quenched by contact with its bounding vessel. A magnetic field configured to provide this confinement is traditionally called a "magnetic bottle."

A magnetic bottle can work because charged particles–the ions and electrons that constitute a fusion plasma–spiral around the local field direction in helical orbits; the stronger the field, the tighter the helix. Thus, while motion parallel to the field is unaffected, motion perpendicular to the local field direction is strongly inhibited.

This inhibition of perpendicular motion has two effects. First, it allows the magnetic force to act against plasma pressure, pushing plasma away from the vessel wall. This profile control is especially effective when a *divertor*–a magnetic geometry in which the outermost field lines are diverted into an external chamber–is employed. In this case the layer of plasma near the vessel wall has especially low density, imposing a near vacuum between the inner plasma core and the wall.

The second insulating effect of the magnetic field pertains to dissipative transport. The inhibition of perpendicular motion affects plasma diffusion and heat conduction: transport in directions transverse to the field is sharply reduced, while transport parallel to the field is unaffected. For an appropriate field configuration this anisotropy markedly slows the conduction of heat from the fusion plasma core to the boundary region. Notice that this effect acts throughout the plasma volume, not only near the wall.

It is significant that while a magnetic bottle can reduce plasma contact with material boundaries, such contact is not eliminated. The residual contact is sufficiently tenuous to maintain a hot plasma interior, but still problematic because the wall material can be scarred. Aside from the obvious lifetime aspects of such erosion, plasma-wall interaction can allow impurities from the wall to enter the confinement region, with deleterious effects on both confinement and fusion reaction rates. Thus, significant materials-physics issues arise in the fusion quest.

A centuries-old theorem in topology shows that any closed surface on which the magnetic field does not vanish must have the topology of a torus: a magnetic bottle must be *toroidal*–donut-shaped. All the devices consider by ReNeW resemble donuts in this sense. (So-called "magnetic mirrors" get around the topological theorem by "plugging" the ends of a cylindrical field configuration; the mirror approach to confinement was not part of the purview of this ReNeW.) Since the only source of a magnetic field is electric current, magnetic confinement is based on electric currents flowing around or within some toroidal surface.

Most confinement devices employ a combination of external currents, in wire-wound coils, and internal currents, flowing within the plasma itself, to maintain the toroidal field structure. A prominent example is the *tokamak*, in which external and internal currents combine to yield a confining field that is symmetric with respect to a central axis. Other confinement schemes have yet to achieve the tokamak's level of performance but could bring operating advantages. For example, the stellarator deliberately breaks the field symmetry in order to simplify steady-state operation. And there are schemes under investigation that require relatively weak (and therefore less expensive) external magnetic fields.

Constructing a magnetic bottle does not solve the problem of confinement; there are essentially two additional hurdles. First, plasma currents, arising spontaneously from electromagnetic and fluid instability, can create magnetic fields that open up the bottle. Second, even when the magnetic configuration is stable with regard to gross distortion, localized "micro-instabilities" can produce fluctuations that degrade confinement. Common versions of such accelerated transport resemble boiling water on a stove: the water remains in the pot, but its turbulent motion rapidly conducts heat from the hot bottom to the cooler upper surface.

In the last decades of the twentieth century fusion research gained important scientific victories in plasma confinement: major advances in both the control of instability and the amelioration of turbulent transport. While significant confinement issues remain to be resolved, and while the fusion scientific community looks forward to substantial further improvements, the present demonstrated level of confinement is sufficient to impart confidence in the future of magnetic fusion energy.

Heating and confinement are the central, but not the only, challenges that must be faced before fusion power can be realized. Even a perfectly confined plasma at thermonuclear temperature must be fueled with reactant, it must be promptly cleansed of the helium that fusion produces, its thermal energy yield must be effectively retrieved, and so on. Such challenges occupy increasing research attention as the fusion program matures; they are the subject of major attention by ReNeW.

APPENDIX II

BIO

Stewart Prager

Stewart Prager is director of the Princeton Plasma Physics Laboratory, a Department of Energy national laboratory, and professor of astrophysical sciences at Princeton University. He received his Ph.D. degree in plasma physics from Columbia University in 1975. Following two years performing fusion energy research at General Atomics in San Diego he joined the University of Wisconsin – Madison as an assistant professor of physics. Prager remained at the University of Wisconsin, as a professor of physics, until 2009 when he assumed his position at Princeton.

Prager's research focuses on basic plasma physics, including applications to fusion energy and, more recently, applications to astrophysics. He has worked to advance the understanding and control of spontaneous plasma processes, such as turbulence, transport, and processes characterized under the umbrella of magnetic self-organization. While at Wisconsin, Prager was director of the Madison Symmetric Torus (MST) experimental facility supported by DOE. He also served as director of the Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas, established through the National Science Foundation program of "physics frontier centers."

Prager has participated in numerous scientific planning and advisory processes, including service as the chair of the DOE's Fusion Energy Sciences Advisory Committee, as chair of the Division of Plasma Physics of the American Physical Society (APS), and as President of the University Fusion Association. He is also a co-recipient of the APS Dawson Prize for Excellence in Plasma Physics, a fellow of the APS, and a recipient of the Leadership Award of Fusion Power Associates.