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THE U.S. ADVANCED TOKAMAK FUSION SCIENCE PROGRAM

A White Paper

Executive Overview

Tokamak research shows that magnetic fusion energy deserves serious consideration as a viable baseline electric power source for the future. The challenge remaining is to optimize the concept and pursue greater understanding of the new advanced-tokamak (AT) regimes to increase the economic and environmental attractiveness of both tokamaks and magnetic fusion energy more generally. The advanced tokamak mission is to further the knowledge and performance of advanced tokamak plasmas—as an attractive power plant, as a vehicle for the demonstration and exploration of burning plasmas, and for the broader contribution to fusion energy science and technology.

In pursuit of this broader objective, tokamak research is the most capable vehicle available today for advancing magnetic fusion science. The tokamak's ability to produce high temperature plasmas, its extensive diagnostics instrumentation, and its coupling to maturing simulation capabilities are accelerating the deepening foundation of high temperature plasma physics. Research in the 2000 decade will emphasize understanding and optimization through experiment-theory interaction across a wide spectrum of fusion plasma physics: transport processes, magneto-hydrodynamic stability and control, wave-particle interaction, plasma-wall interaction, and to a very limited degree, alpha-particle physics. A central U.S. tokamak research thrust during this decade will be aimed at enhancing and extending advanced tokamak performance. This far reaching effort of integrating the above physics issues will contribute to a broad range of fundamental plasma science, including optimization of other toroidal confinement concepts, as well as further improve advanced tokamak power plant projections.

The U.S. advanced tokamak program is focused on fundamental toroidal confinement physics, developing the scientific basis for the innovative advanced tokamak concept. This cutting edge research is being carried out within U.S. existing tokamak facilities—Alcator C-Mod, DIII-D, HBT-EP, and ET. Even with smaller facilities than those operating in Europe and Japan, the U.S. facilities can, with modest upgrades, maintain a vital cutting-edge role during the next decade by means of its facilities' flexibility and diagnostic capability, by its tradition of innovation, and by U.S. strengths in theory and modeling.

In addition to concept optimization, tokamaks are now ready to begin the study of burning plasmas, the unexplored frontier of fusion plasma physics. The present U.S. strategy is to pursue burning plasmas internationally. Two potential alternatives exist. The more ambitious alternative—preferred by the major international parties—as measured by the capability of the resulting device, would have the U.S. participate in an appropriate manner in an international ITER-class facility. While the U.S. is no longer an ITER partner, the remaining ITER partners—Europe, Japan and Russia—intend to make a construction decision before 2002 on a facility with lesser technical objectives and lower cost than the original ITER design. A reduced ITER-class device will enable researchers to address ignition physics, long pulse burning plasma physics, and many fusion-nuclear technologies in one facility. The U.S. would have much to gain by rejoining such a new collaboration.

A second strategy would have the U.S. collaborate with one or more international partners in the construction and operation of a compact, high-field, short pulse facility targeting ignition alone. An example would be collaboration with Italy in the Ignitor, now under prototype fabrication. Another example would be construction of a high-field ignition tokamak incorporating advanced-tokamak concepts, e.g., an advanced evolution of the former U.S. BPX design. In parallel, the U.S. would collaborate internationally on a steady-state superconducting advanced tokamaks similar to the former U.S. TPX design (e.g. KSTAR under construction in Korea and HT-7U in design in China). This research would address both steady-state AT plasma performance and important power and particle handling issues. A third element of this second strategy would be a volume neutron source to address fusion nuclear technologies. These three next-step facilities could be implemented nationally with international coordination, but current national budgetary caps dictate any large next-step facility be implemented through international collaboration.

THE U.S. ADVANCED TOKAMAK FUSION SCIENCE PROGRAM

I. ADVANCED TOKAMAK RESEARCH DEVELOPS FUSION SCIENCE AND EXPLORES A PATH TO AN ATTRACTIVE FUSION ENERGY SOURCE.

A. Fusion—the ultimate energy source of the universe.

Harnessing the energy source of the sun and stars is a grand challenge with enormous potential payoff for future generations: an environmentally attractive energy source with essentially inexhaustible fuel with no carbon emissions. The required fuels are the deuterium isotope of hydrogen and lithium, both abundantly available to all nations. In pursuit of this vision, the mission[1] of the Fusion Energy Sciences Program is:

To advance plasma science, fusion science, and fusion technology—the knowledge base needed for an economically and environmentally attractive fusion energy source.

Fusion research has developed much of the discipline of plasma physics, the ubiquitous fourth state of matter, in order to understand the complex collective behavior of fusion systems. Fusion research has application to fields of science such as space and astrophysics, spawns technologies for the commercial and defense sectors, and pioneers physics and technologies for related magnetic fusion concepts. Now, the understanding of plasma confinement systems, particularly of tokamaks, has developed to the point where an ignition and sustained-burn experiment can be built.

The tokamak is today’s most successful vehicle for producing high temperature plasmas with a wide range of dimensionless and dimensional parameters. Equipped with extensive and mature diagnostics systems, the U.S. tokamaks Alcator C-Mod and DIII-D are national user facilities to test new ideas as well as validate and verify increasingly sophisticated simulation capability. Tokamak research is deepening the foundation of high temperature plasma physics with benefits to a broad range of scientific disciplines, including optimization of other toroidal confinement concepts.

Tokamaks are the leading magnetic plasma confinement concept. In separate experiments, tokamaks produce plasmas with 40 keV ion temperature, 15 keV electron temperature, and confinement triple product (the product of plasma density, plasma temperature, and plasma energy confinement time) of 1×10^{21} m^{-3}•s•keV, plasma betas of 13%, and discharges lasting two hours. Today’s large tokamaks have produced in single pulses a fusion power density of 2.8 MW/m^3 (in the U.S. TFTR), 21.7 MJ of fusion energy and 16 MW fusion power approaching scientific breakeven (in the European JET), and studies of high performance plasmas (in the Japanese JT-60U). The advanced tokamak research mission, within the U.S. fusion program[2-4], may be summarized as follows:

Advanced Tokamak mission: To further the knowledge and performance of advanced tokamak plasmas—as an attractive power plant, as a vehicle for the demonstration and exploration of burning plasmas, and for the broader contribution to fusion energy science and technology.

B. The advanced tokamak concept addresses concerns of tokamak critics.

As the best understood fusion concept, the conventional tokamak has been subject to a number of criticisms. Having achieved by far the highest fusion performance, the critics now grant that the conventional tokamak could generate fusion power. They now argue that tokamak power plants will be too large, will be uneconomical, and face large engineering obstacles. These valid concerns, however, ignore recent experimental and theoretical physics progress pointing toward new opportunities offered by the innovative advanced tokamak concept. Through higher physics performance, the advanced tokamak power plant is projected to be smaller and more economical, by a factor two. Through steady-state operation the advanced tokamak reduces many engineering obstacles such as high plasma current and cyclic fatigue.

Critics single out plasma disruptions as the major tokamak issue. Indeed disruptions set several engineering design constraints. Their mechanical forces are comparable to potential magnet quench and seismic events. However, disruptions are not unpredictable random events. They occur when the plasma pressure or current exceeds known theoretical limits. Thus, with control of the plasma pressure and current profile and plasma shape, they can be avoided and mitigated. Advanced tokamak research addresses disruptions in two ways. First, AT research emphasizes stability physics and plasma control so disruption understanding, avoidance, and mitigation is developed. Second, the AT concept requires lower plasma current so disruption forces and associated wear and tear are reduced to a lower level.

C. Recent physics progress points the way toward attractive advanced tokamak power plant concepts and next-step burning plasma experiments.

Recent years have seen striking worldwide progress in tokamak fusion research[5-8]—in diagnostic capability, plasma performance, theoretical understanding, and computational simulation and modeling—through application of established principles and through new discoveries that point the way for future research. This progress includes:

- Developing fundamental understanding and demonstrated suppression of turbulence-driven energy transport by sheared electric and magnetic fields—the control of ion turbulence and the evolution to a Laminar state. Current research is aimed at better understanding and control of these internal transport barriers.

- Achieving plasmas with self-generated (bootstrap) plasma currents to sustain steady-state tokamak plasmas—the self organization of a multi-dimensional fluid system. Research in this area now aims to achieve steady-state plasmas with high beta equilibrium and a high fraction of bootstrap current simultaneously.

- Demonstrating understanding, through detailed diagnostics and modeling, of practical methods to disperse plasma power exhaust—the physics of power flow from long to short mean-free-path media with atomic and molecular recombination. Ongoing research is dealing with divertor erosion from pulsations of energy and particles.

- Initiating ground breaking alpha-particle physics experiments with deuterium-tritium plasmas—energetic particle binary classical energy transfer. A burning plasma facility will be needed to advance alpha physics to the next level.

- Integrating such composite progress has resulted in improved tokamak performance for short pulses. Ongoing research is aiming at extending the duration of high performance tokamak operation.

Such advances have impacted tokamak power plant concepts, generating a new research strategy called the advanced tokamak program[5-7], impacted other toroidal fusion concepts, stimulated further innovation, and contributed to a broad general scientific knowledge base.

Power plant system studies[9-12] which incorporate new advanced tokamak concepts show the possibility of a power plant having competitive cost-of-electricity, steady-state operation, maintainability, low level waste, and public and worker safety. Examples include the U.S. ARIES-RS study and the Japanese SSTR study. Owing to the thickness of nuclear shielding and the limits on magnet current density, ARIES-RS power plant system studies indicate that cost effective tokamak plants will have ~5m major radius, power outputs of ~1000 MW and cost-of-electricity in the range of 6–8 ¢/kW-hr, with advanced tokamak physics performance. While such a power plant could not compete with today’s natural-gas-driven turbine generators, it could be cost competitive in a mid-21st century energy economy having scarcer fuel supplies and greater environmental restrictions. This long range view, combined with the historic tokamak scientific tradition of innovative research and improvement, the tokamak's unique ability to explore burning plasma, and its ability to contribute to fusion plasma science, justifies a strong national tokamak effort. These studies identify areas of high pay-off research and define quantitative technical objectives. These designs can be expected to further evolve and improve with emerging R&D results, e.g. neo-classical ion energy confinement (the lowest theoretically possible), reductions in electron transport, detachment of surface plasma from material walls to decrease concentrated heat loads on vessel components, and with new technologies such as higher-temperature/higher-field superconductors for magnets and advanced wall concepts for power exhaust.

[3-D drawing of ARIES-RS tokamak]
(the file is enormous)

Figure 1. The attractive ARIES-RS power plant conceptual design utilizes advanced tokamak physics and desired utility operator features. The eventual commercial tokamak power plant will incorporate further physics and technology innovations from ongoing research and development world-wide.

D. Tokamak research is ready to begin the study of burning plasmas—the unexplored frontier of fusion science.

Burning plasma physics, a topic common to all fusion concepts, is the unexplored plasma physics frontier. This frontier includes the study and control of self-heated plasmas, excitation of energetic alpha particle effects, exhaust of high power fluxes, and maintenance of high plasma purity.

In 1996, the Fusion Energy Advisory Committee[1] and the President's Advisory Committee on Science and Technology[2] recommended that as fusion research moves into the stage of energy-producing plasmas it move into the international arena. In 1998, the Fusion Energy Sciences Advisory Committee recommended that:

In concert with our international partners, a burning plasma facility should be built at the earliest possible time.

Collaboration on an ITER class facility would represent such a unique opportunity for international collaboration (Europe, Japan, Russia, and the U.S.) on the physics of burning and ignited plasmas, as well as developing reactor-scale fusion energy technology with broad benefits and implications[18-19]. The original ITER EDA design had ambitious scientific and technical objectives—assured ignition, 1,500 MW fusion power, 1000-second inductive burn, 1 MW/m^2 neutron flux, and 1 MW-yr/m^2 neutron fluence achieved with pulses lasting many days conditions—resulting in an 8m major radius tokamak costing roughly twice that of a nuclear plant of comparable power. Given today's fiscal constraints and perceived lack of urgency for new energy sources (resulting from low fuel cost and lack of both supply and environmental concerns), the resulting cost proved too high for an experimental device, even for one having the capability of the original design. Currently, the remaining

ITER partners are targeting a design having somewhat reduced technical objectives, but at about half the original cost. However, by Congressional action in FY99 the U.S. suspended participation in these new design activities and the U.S. is now engaged only in sharing results of our science programs and carrying out work aimed at generic low-cost next-step approaches to burning plasma physics for a possible new arrangement for international collaboration on fusion science. In the next few years if the remaining ITER partners proceed with RTO/RC-ITER construction, the U.S. should be prepared to seek to collaborate.

To target ignition or high gain in a smaller reduced cost D-T superconducting RTO/RC-ITER requires high performance for long duration in “advanced tokamak” regimes which have been produced for short pulses and now being extended in duration in both DIII-D and Alcator C-Mod, as well as other world tokamaks. At larger size, experiments are underway at JET and JT-60U to demonstrate increased and prolonged fusion power performance to reduce the extrapolation to a burning plasma facility. The features required for an advanced tokamak—the degree of plasma shaping, current profile control, rotation, and the role of a conducting wall—is being established as a major theme of world-wide tokamak research.

An alternate modularized approach might feature a high-field copper-magnet burning plasma machine[17] (DTAT) in combination with a superconducting steady-state machine (SSAT) to develop steady-state physics and technology. The value of copper-magnet designs would be greatly enhanced if they are also capable of exploring AT physics by operating for sufficiently long pulses with power-handling and current-drive capability. These modular elements would subsequently be integrated in an ITER-class facility. A 14 MeV neutron irradiation facility for developing fusion blankets and qualifying new low-activation materials and components would be required in any strategy as illustrated in the Fig. 2 roadmap.

This tokamak roadmap leverages off substantial international investments so expenditures for the U.S., as well as other parties, are within perceived financial constraints. To maintain international leadership in advanced tokamak research with the U.S. fiscal constraints of the past four years, the U.S. was forced to shut down six productive tokamak facilities (MTX, PBX-M, Phaderus, TEXT, TFTR, and Versator). TFTR was the lead U.S. tokamak facility.

A feature of such roadmaps is that facilities also do research at lower exploratory levels. For example, a large fraction of Alcator C-Mod and DIII-D research deals with Proof-of-Principle (e.g. advanced tokamak confinement, stability, current drive, and divertor principles) as well as Concept Exploration (e.g. new current drive or divertor concepts which require high temperature plasmas to explore).

The next tokamak research step is either a single facility (e.g. RTO/RC-ITER) or a set of multiple facilities, including a burning plasma experiment (DTAT) and a superconducting tokamak (SSAT). Either strategy would be imbedded in a world program of tokamak innovation and optimization, fusion technology development, and one of exploring alternate confinement concepts to broaden physics understanding and options. While next-step tokamak research will be determined in an international context, we share a common exciting and challenging vision:

> *In the 2010 decade a burning tokamak plasma capable of exploring advanced and steady-state physics will be operating to provide the scientific basis for an economically attractive, and environmentally benign fusion power source.*

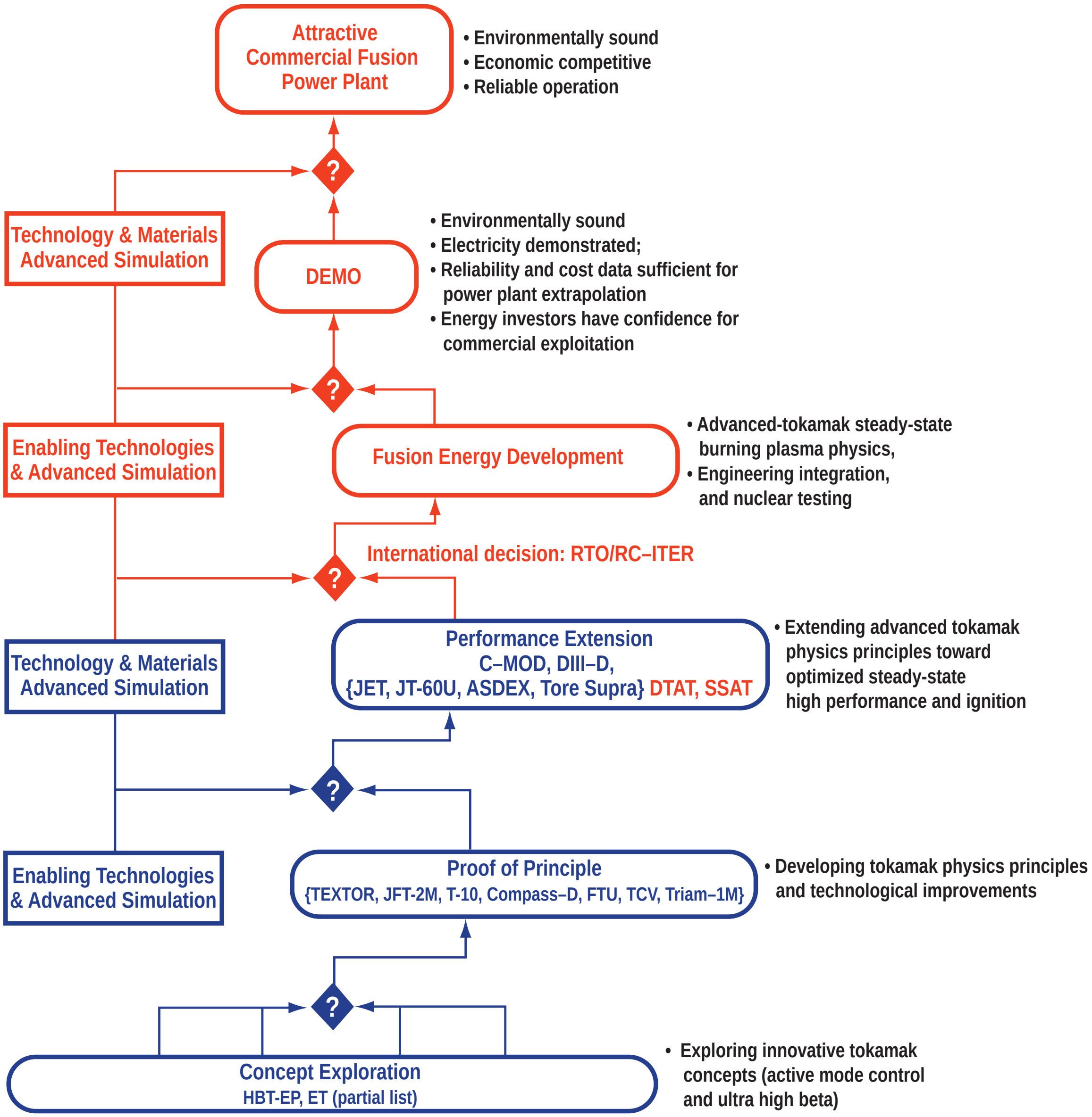

Figure 2. The Tokamak Fusion Energy Development Roadmap.

E. The advanced tokamak concept offers opportunities for significant optimization of toroidal magnetic fusion configurations.

The advanced tokamak concept uses the magnetic field more efficiently than a conventional tokamak. It holds up to twice the plasma pressure with the same magnetic field. Correspondingly the required magnetic field energy would be four times less for the same fusion power as a conventional tokamak. The advanced tokamak operates ultimately in steady state, unlike the pulsed conventional tokamak. To do so it relies primarily on its self-generated current, requiring a far lower fraction of its total current to be driven by recirculating power. Thus, the advanced tokamak concept is indeed revolutionary, and not business as usual. More generally, the AT illustrates the enormous opportunities available from multi-parameter optimization of toroidal magnetic fusion configurations. Advanced tokamak physics has much in common with other toroidal confinement concepts such as the spherical tori, stellerators, reverse field pinches, and spheromaks. For example, like the AT, the spherical torus and compact stellarator both rely on self-generated plasma current.

The toroidal magnetic geometry is optimized through higher plasma shaping and by optimizing the plasma current profile. The two hallmarks of the advanced tokamak are: (1) higher plasma performance (through higher plasma stability and energy confinement), and (2) steady-state operation (through efficient current drive, disruption-free operation, as well as power and particle handling). The integration of these two elements is achieved by self-consistently optimizing plasma physics through magnetic geometry (plasma shape and current profile) together with plasma profiles (pressure, density, rotation, radiation). This challenging and rich scientific research of optimizing toroidal confinement requires a strong coupling between theory, simulation, and experiments.

Metrics are useful to characterize and measure progress of the advanced tokamak concept. Advanced tokamak metrics can be referenced to established metrics of the ARIES power plant studies[9], compared to the conventional tokamak (the ITER-EDA design[8]) as indicated in Table 1. The values of such metrics depends on the specific ARIES-RS design. Other combinations would be acceptable for other specific designs. The conventional tokamak concept leads to a credible power plant, although with electricity costs above today's market. Nevertheless, it provides a baseline option if warranted by future market demands. The ARIES system design leads to lower electricity costs by optimizing physics and engineering technologies available within the reasonable future. To first approximation, the advanced tokamak has twice the performance and half the cost of electricity of a conventional tokamak. It has other advantages, such as operating steady rather than in pulses.

For comparison, the best experimentally-achieved values are given in the third column. These values come from different world-wide experiments and are not simultaneous. The ITER demonstration discharges and database indicate a firm basis for the conventional tokamak. The advanced tokamak database is being established world-wide, especially in terms of simultaneous and long pulse experiments. Examples of simultaneous achievements in DIII-D and TFTR are given in Table 1. While individually, many parameters can be achieved in today's facilities, integrated performance with copious levels of fusion power will require a new next-step facility. The DIII-D and TFTR high performance examples indicate the challenges facing existing facilities to develop the scientific basis for ARIES-RS. The future big challenge is to achieve these values simultaneously and to extend their performance toward steady state.

Table 1. Advanced Tokamak Metrics *

Attribute	Conventional Tokamak (ITER-EDA[8])	Advanced Tokamak (ARIES-RS[9])	Best Achieved Values (not simultaneously)	DIII-D AT Shot 96686[25]	TFTR D-T Shot 80539[26]
• **MHD Stability**					
Plasma pressure relative to magnetic field pressure: $\beta = 2\mu_O<p>/B^2$, %	3	5	12 (DIII-D)	4.8	1
Normalized plasma stability factor: β_N = B/(I/aB), % m·T/MA	2.3	4.8	5 (DIII-D)	3.8	1.8
• **Energy Confinement**					
Confinement improvement relative to 1989 standard: $H_{89} = \tau_E/\tau_{89L}$	1.8	2.4	3.5 (AUG, DIII-D, TFTR)	3.2	2.1
AT parameter: $\beta_N H_{89}$	4.1	11.5	17 (DIII-D)	12	3.4
• **Current Drive**					
Plasma duration	Pulsed (1000sec)	Steady-state	2 hours (TRIAM)	1 sec	peak
Percent bootstrap current, %	30	89	80 (JT-60U, TFTR)	50	23
Current drive efficiency: $n/_{CD}R/P_{CD}$, 10^{20}A/W·m^2	—	2	0.4 (JT-60U)	—	—
• **Heat and Particle Exhaust**					
Divertor upstream normalized heat flux: q, MW/m^2	1.0	2.0	0.5 (C-Mod)	0.1	—
Helium ash removal: τ_{He*}/τ_E	10	10	10 (DIII-D, JT-60U, TFTR)	?	?
• **Integrated Performance**					
Fusion Power, MW	1,500	1,800	16 (JET)	—	10.7
P_{fusion}/P_{aux}	Ignition	29	0.6 (JET)	—	0.27
Ion/electron Temperature: Ti/Te, keV	30/35	21/22	40/15 (TFTR/JET)	10/6	36/13
Density: ne (10^{20} m^{-3})	1.0	2.5	10 (C-Mod)	0.6	1.0
Triple product: $n\tau T$, 10^{21} m^{-3}s keV	10.0	5.0	5.0 (JET, JT-60U, TFTR)	0.1	0.4

* These metrics and values are tentative pending further community dialog.

F. The advanced tokamak concept poses new challenging scientific research issues.

The advanced tokamak concept is based on physics building blocks grounded in experimental and theoretical results. Research is now needed to develop deeper understanding of physics scaling to larger systems and to determine the ultimate physics potential, to develop the necessary enabling control tools, and to demonstrate the simultaneous integrated optimization of the advanced tokamak capability. The resolution of these scientific issues will have broad general application to the optimization of other toroidal configurations. The broadest level research question is:

At what performance level can the advanced tokamak configuration be sustained in steady-state with a largely self-driven burning plasma?

Answering this question requires resolving a number of critical advanced tokamak physics issues which must be resolved:

- Maintain high beta (pressure) plasma while avoiding neoclassical tearing modes, resistive wall modes, edge modes, and disruptions.

- Understand and control of internal transport barriers to optimize plasma pressure profile to maximize stability and self-driven plasma current alignment.

- Develop off-axis plasma current profile control to maintain high beta plasma stability and sustain steady-state operation.

- Demonstrate compatibility of radiative divertor design between plasma shape, impurity control, confinement as well as power and particle control.

- Show compatibility of AT operation with energetic alpha particle modes and self heating equilibrium.

The ultimate scientific challenge is to simultaneously resolve the above issues in a burning plasma. This will require a new integrated facility of the nature of ITER.

II. THE U.S. HAS UNIQUE FACILITIES AND CAPABILITIES TO BE AN INTERNATIONAL ADVANCED TOKAMAK RESEARCH LEADER

The U.S. has tokamak facilities with unique characteristics and strong diagnostic capabilities. These facilities are complemented with exceptional theory and modeling capabilities within the U.S. This combination provides an opportunity to improve the tokamak concept that will benefit a range of possible tokamak development paths and enable extending AT research results to wider classes of toroidal magnetic configurations.

U.S. advanced tokamak research is carried out with extensive international collaboration. World-wide tokamak facilities have characteristics (listed in Appendix A) and have research programs which differ and complement each other to provide opportunities for scientific confirmation, collaboration, and joint experiments. International expert groups provide a valuable role in developing common databases, comparing results of experiments and theory, and coordinating research. The combination of results from the smaller flexible U.S. machines and from the larger higher-temperature foreign devices will form the basis for a major next international step along the tokamak line. Since the U.S. intends to have a significant role in developing next-step tokamak activities, the U.S. tokamak program collaborates on tokamaks abroad. Two large tokamaks now operate: the European JET can operate with D-T plasmas, while the Japanese JT-60U research focuses on steady-state high-performance plasmas. Since the close of TFTR, the U.S. now has no large tokamak so it is even more important to collaborate internationally to test ideas in joint experiments.

There are three mid-size divertor tokamaks in the world equipped with sufficient plasma heating, control, and diagnostic systems to advance tokamak research on a broad front. The U.S. tokamaks, DIII-D[20] and Alcator C-Mod[21] operate as national collaborative programs with users from many laboratories and universities. DIII-D is a low-field tokamak with high power heating including ECH for high-beta advanced tokamak research. DIII-D is unique world-wide with its poloidal field magnet capability for very strong plasma shaping and its ability to emulate other tokamak shapes for coordinated joint experimental studies. Alcator C-Mod is the world's highest-field tokamak, capable of very high-density operation with equal electron and ion temperatures, with plasma pressure equal to that expected in a reactor. Its compact size and closed divertor configuration offer unique capabilities for studying high power-density plasma exhaust problems. Together DIII-D and Alcator C-Mod provide data from two plasmas with very different physical parameters but similar dimensionless parameters. The German ASDEX-Upgrade has external plasma shaping control coils with less shape flexibility than DIII-D and different divertor geometry. In addition to the divertor tokamaks, Textor and FTU are European tokamaks addressing pumped limiter and high field physics respectively. The French Tore-Supra is a circular superconducting tokamak investigating the physics of steady-state current drive and heat removal with an ergodic-magnetic-limiter. The U.S. collaborates with all the international tokamaks listed in Appendix A. Korea is constructing superconducting advanced tokamaks (KSTAR), and China is engineering the design of a superconducting tokamak (HT-7U) both targeting to begin operation circa 2003. Italy is building prototypes for a high field ignition experiment (Ignitor). Appendix B lists parameters of these and other tokamak designs.

Two smaller U.S. experiments contribute to tokamak concept exploration. The Columbia University high beta tokamak (HBT-EP)[22] is addressing wall stabilization and active mode control, issues critical for advanced tokamak operation. The UCLA Electric Tokamak (ET) is a low-curvature electric tokamak[23] under construction to explore the possibility of achieving classical confinement and unity beta in tokamaks. The U.S. also collaborates with other exploratory and proof-of-principle tokamaks abroad.

It is urgent to utilize and upgrade the U.S. tokamaks to continue to make vitally needed contributions to the world tokamak physics program. The U.S. tokamaks' programs focus on concept innovation and optimization: sustaining enhanced performance advanced tokamak operation for pulses beyond current relaxation time scales (5 to 10 sec) dominately with self-driven bootstrap current, augmented by off-axis current drive. Both Alcator C-Mod and DIII-D require auxiliary off-axis rf current drive systems—essential tools to carry out their advanced tokamak research. DIII-D is implementing 6 MW of ECH power, C-Mod is in need of 3 MW of LHCD power. New diagnostics continually need to be implemented and methods to control transport barriers, divertor improvements, and MHD feedback stability need to be developed. Key to the HBT-EP program is upgrading the active plasma feedback and rotation control system for high beta experiments. The ET electric tokamak requires heating and diagnostics to carry out its innovative research on ultra high-beta omnigenic tokamak equilibrium with possibly classical confinement. The pace of research progress is now heavily constrained by annual funding levels. Increased operation time, facility upgrades, and new diagnostics will enable scientific users to sooner address the innovative cutting-edge issues of the next decade. At the same time, it is important to strengthen international collaboration through joint experiments to extend U.S. results and ideas to unique foreign facility capabilities. Such a more optimum research pace can be accomplished by increasing FY00 tokamak funding from 75 to 80 M$. In a decade, however, these facilities will become outdated, and the research focus will naturally shift to new more capable burning-plasma and steady-state facilities described earlier towards the end of the next decade.

U.S. theory and modeling is the world leader in many forefront areas. International multi-machine data bases now provide opportunities for evaluating theories as well as benchmarking and cross comparing simulation codes. While good progress is being made in predictive capability, the development of comprehensive modeling and simulation must be given more emphasis. The Department of Energy is starting a Scientific Simulation Plan, and the fusion program aims to be a major participant to significantly increase its computational capability. The challenge in fusion theory research is that fusion systems are highly complex, highly nonlinear and strongly coupled in many areas of physics and technology; the physical effects which must be simultaneously modeled span many decades in space and time scales. To advance requires a multi-faceted experimental program with extensive diagnostics to generate the data, a strong theory program to develop models, and a comprehensive predictive simulation capability with widespread use of modern computing techniques.

Major tokamaks are generally well equipped with space and time-resolved diagnostics to measure local plasma parameters: ion and electron temperatures and densities profiles, and more recently, motional Stark effect instruments to measure the plasma current profile. It is notable that the recent development of the new advanced tokamak concept relied critically on the development of the ability to measure this current profile. Such profile diagnostics, coupled with fluctuation diagnostics, critically test theories and improve tokamak plasma performance. There is a need to continuously improve, modify, and implement revolutionary new diagnostics to address key new theoretical issues and provide needed data to the scientific simulation plan.

III. U.S. ADVANCED TOKAMAK PHYSICS RESEARCH OBJECTIVES

U.S. advanced tokamak research emphasizes fusion science with a central theme of innovative concept improvement aimed at delivering [2]:

- Marked progress in scientific understanding and optimization of toroidal plasmas, and

- Comprehensive predictive advanced tokamak physics models which will be benchmarked with data from domestic and international tokamaks.

A number of different advanced tokamak operating modes are being investigated at DIII-D, Alcator C-Mod, and world-wide. A major thrust is to extend the duration of high performance modes with different methods for plasma current, flow, and pressure profile control. Collaborative research is being carried out with JET and JT-60U with common researchers participating in joint experiments to optimize and facilitate scientific progress. In the next decade, this cross-cutting research will extend to further innovations, strengthen the understanding and integration of fusion science, and explore a path to an attractive fusion energy source. During the 2010 decade, tokamak research with a burning plasma facility will address for the first time the integration of all previous scientific understanding in a burning plasma. Such a plasma will rely mainly on self-driven processes, alpha heating, bootstrap current, with relatively small external sources of power, momentum, and current drive. This entirely new regime will require comprehensive scientific understanding and efficient plasma control methods now only beginning.

The knowledge that will be developed from advanced tokamak research serves several complementary purposes. First, as a reliable way of creating high temperature plasmas which are carefully diagnosed, basic plasma physics as a discipline will be built up. Second, no matter which confinement configuration ultimately proves to be the most satisfactory, the progress in understanding magnetic plasma confinement will underpin the long-term quest to establish the feasibility of fusion energy. Third, the improved understanding of advanced tokamak plasmas will support the construction and operation of a next-step plasma experiment and a steady-state advanced tokamak. Finally, the inclusion of universities and students in this endeavor maintains a cadre of the highest-quality plasma experts in the US, as a future national resource.

Advanced tokamak power plant system studies and the ITER process have identified long-range and near-term priority physics research needed to be carried out. The consensus of the international physics community have established physics research objectives which we discuss in terms of different scientific topics.

A. Transport and Turbulence Physics

The processes by which heat and particles transport across the magnetic field and thus degrade confinement and limit performance.

Research objective:

Improve the understanding of energy and particle transport processes and physics-based predictive scaling to next step tokamaks.

Transport “barriers,” regions of very low turbulence and slow diffusion, have for some years been observed. The “H-mode” edge and the “PEP mode” arising from pellet fueling are long-standing examples. A unifying interpretation based on the idea that sheared plasma flow decorrelates and stabilizes the turbulence involved has shown remarkable ability to explain the observations. More recently, observations indicate that such barriers are strongly influenced by the internal magnetic configuration shear and by flow shear in the plasma due to the application of external torque or generation of flows from the plasma pressure. These various approaches for controlling turbulence present an outstanding opportunity to develop a deep understanding of the basic mechanisms of turbulent transport in magnetized plasmas, as well as to obtain improved confinement for fusion. Control of transport provides the means to optimize the plasma pressure profile to improve the tokamak concept. Transport physics is largely generic to all magnetic confinement, but presently tokamaks have the detailed diagnostics, simplicity of configuration, and low-collisionality plasmas needed to study it.

The study of transport barriers and what they tell us about the principles of plasma transport is a key part of proposed research on DIII-D and on Alcator C-Mod. DIII-D has established core transport barriers as well as the widely observed edge barriers and begun to study their dependence on magnetic configuration, beta, rotation, and so on, in dynamically changing plasmas, with outstanding diagnostic detail. C-Mod, in addition to its own unique observations of enhanced confinement and spontaneous rotation, is able to extend the study of transport physics to high magnetic fields and plasma pressures so that the scaling of the physics can be verified. Theoretical models of transport, based on computational simulation of the basic plasma particle or fluid equations, have shown substantial promise for a first-principles calculation of the transport behavior of tokamaks, and are being further developed and actively compared with experiment.

Many intriguing physics puzzles remain to be understood. For example the observation of a non-local thermal response to transient temperature perturbations, which may be related to developing theories of non-linear dynamics, or the difference observed between the electron and ion heat transport.

B. MHD Stability and Disruption Physics

The macroscopic plasma behavior determining the maximum equilibrium plasma pressure and its stability to large-scale instabilities which might disrupt confinement.

Research objective:

Develop understanding of high beta ideal and nonideal magnetohydrodynamic (MHD) stability limits through detailed theory-experiment interaction. This includes disruption avoidance and mitigation.

The ultimate performance limits of magnetically confined fusion plasmas may well be set by MHD stability. Therefore, a major part of advanced tokamak research is devoted to understanding and increasing the plasma beta (the ratio of plasma pressure to magnetic field pressure) limits by plasma current and pressure profile control, by real time feedback control, and by wall stabilization effects and rotation.

Many fundamental aspects of tokamak MHD stability behavior are well understood theoretically. Areas of active research include stability improvement through wall-stabilization and feedback stabilization as well as the study of the consequences of plasma modification of the magnetic configuration (called neoclassical MHD). Critical to MHD stability physics are “disruptions” in which MHD instabilities lead to a sudden termination of the plasma current. Disruptions introduce engineering constraints on the design of next-step tokamak experiments, and ultimately power plants. Advanced tokamak research has a strong emphasis on understanding and developing these stability limits and mitigating the consequences of disruptions. This justifies a high priority being placed in experiments on mitigation and avoidance of disruptions, as well as developing a fundamental understanding of their physics mechanisms. DIII-D research focuses on understanding and increasing high beta stability limits. Alcator C-Mod focuses on understanding disruption characteristics. HBT-EP focuses on demonstrating wall and feedback stabilization physics.

Although MHD theory is well able to calculate equilibria and has been able to explain a great many experimental observations, important fundamental questions remain. For example the important effects of neoclassical MHD and other non-ideal effects on stability are active research areas. Three-dimensional modeling of MHD effects is benefiting from modern computational techniques.

MHD stability is sometimes intimately related to transport issues. For example the edge transport barrier of H-modes is thought to be governed by pressure driven instabilities. Therefore an important part of the MHD research is devoted to understanding edge instabilities, the underlying causes of “Edge-Localized-Modes,” and the limits such considerations impose. In addition, the observed “density limit” though not understood, may be an example of an interaction the other way around, in which large changes in transport phenomena lead to adverse stability consequences.

C. Wave-Particle Interaction Physics

The processes by which energetic beams or radio frequency waves can be used to heat or drive current in the plasma and the process by which the plasma can be fueled.

Research objective:

> ***Demonstrate efficient current profile control, utilizing external sources to complement the intrinsically driven bootstrap currents, benchmarked with predictive modeling***

Basic questions remain in wave-particle interactions. In the area of ion-cyclotron heating and current drive, mode conversion and direct fast-wave interactions can drive current, as has been verified by initial experimental observations. Electron cyclotron heating is being employed for transport studies, MHD stability control, and for locally controllable current profile control. Upcoming advanced tokamak experiments will utilize these mechanisms to investigate their applicability to burning plasma experiments and power plants. Moreover, waves are proposed as a way of controlling the plasma rotation thought to determine the transport barriers. Therefore, wave interactions may also prove to be the key to controlling transport in a burning plasma.

Alcator C-Mod employs ICRF as its main auxiliary heating and current drive scheme and will explore a number of these questions. In addition to high power neutral beam heating and fast-wave ICRF current drive, DIII-D has a major thrust in ECH and current drive. Highly localized ECH power deposition is a critical tool for transport studies and for current drive profile control. This ECH capability is just coming into operation and will be enhanced in succeeding years. Theoretical understanding of the current drive efficiencies and rotation drive is crucial to establishing more reliable predictive models.

D. Boundary and Divertor Physics

The science of the transition between the confined plasma core and the wall, plasma/atomic physics, plasma flows, and neutral particle interactions.

Research objective:

> ***Demonstrate, and predictively model, the divertor dissipation of intense power fluxes, plasma flow, pumping of helium ash, and the baffling of recycling neutral particles.***

Boundary physics includes the very important investigation of divertors, in which the plasma scraped off the plasma edge is diverted into a chamber where helium ash can be removed and the plasma-wall interactions controlled by atomic physics processes. The scrape-off layer itself also involves fascinating highly anisotropic physics of parallel plasma flow and perpendicular transport. All these topics are generic to any toroidal magnetic confinement scheme, but tokamaks have made outstanding progress recently both in understanding the physics and in demonstrating the possibilities for meeting the practical challenges of power and particle handling, which are very severe for any next-generation fusion experiment. For example, we now have strong experimental evidence from Alcator C-Mod and DIII-D confirming the theoretical prediction that volumetric recombination is important in the divertor. Both U.S. (and overseas) tokamaks have demonstrated detached divertor operation, where the plasma particle and heat flows are predominantly dissipated by atomic processes before reaching the solid divertor targets. These radiative divertors reduce the power-handling requirements.

Future divertor experiments need to establish a practical, and preferably fundamental, basis for predicting cross-field transport in the scrape-off layer. This is a scientific topic even more challenging than core transport. In addition, the parallel and perpendicular plasma flows are known to be crucial effects for energy and particle transport, but are not well understood at this time.

Experiments to address these and the related atomic flows and interactions are planned for DIII-D and Alcator C-Mod, with different divertor geometries and diagnostics. Together with outstanding diagnostics and with extensive divertor theory and modeling efforts, these experiments will help to put divertor and boundary physics on a sound footing and demonstrate the feasibility of constructing practical configurations for the edge of a magnetic confinement fusion system.

Plasma boundary control is important to enable effective radiative divertor operation while simultaneously having high core plasma confinement and a high plasma purity to optimize fusion reactivity. Tritium retention in the wall is an in-situ concern for all toroidal confinement systems. DIII-D is studying this issue with a divertor in-situ materials evaluation system (DiMES). Alcator C-Mod operates with non-graphite (molydenum) plasma facing components.

E. Alpha-particle Physics

The processes that the energetic charged fusion products encounter while transferring their energy to the confined plasma.

Research objective:

> ***Carry out experiments with D-T fusion reaction products and with energetic ions to benchmark alpha particle physics.***

Alpha-particle physics can be studied in full only in an ignited fusion plasma, in which fusion power dominates the plasma heating. Therefore, extensive studies await the construction of an ignition experiment. Meanwhile, some alpha-particle physics is either studied in sub-ignition D-T plasmas (as in TFTR and JET), or by using energetic particles produced by RF or neutral beam injection to simulate fusion-produced energetic alpha particles. The energetic particle approach is also possible in DIII-D, Alcator C-Mod, and JT-60U, which have observed the Alfven eigenmodes that are one of the key concerns with energetic particle interactions. Theoretical work will emphasize understanding of the stability and the non-linear consequences of the alpha-driven modes.

A burning plasma experiment would extend these studies to alpha-particle pressures equal to power plant levels. Also, the plasma self-heating will enable the first investigations of plasma pressure and transport control. By varying the plasma current profile, the magnetic geometry can be varied to investagate physics associated with conventional and advanced tokamak as well as features of physics of other toroidal magnetic confinement configurations.

F. Integrated Plasma Physics

Integration of the above research topics forms the basis for advanced tokamak research which focuses on investigating the feasibility of reducing the size of a steady-state tokamak power plant. This requires optimization of all the above composite fusion science elements, such as incorporated in ARIES-RS and SSTR power plant concepts. Smaller size requires simultaneous achievement of high-beta and good confinement. Steady-state requires sustaining the plasma current, dissipating the fusion plasma power exhaust and extracting alpha particle ash, and avoiding disruptive plasma termination. Plasma burn is regulated by control of fueling and exhaust as well as control of the localized plasma current profile and transport barrier profile. Advanced tokamak research addresses disruption concerns by lower current operation, by raising the central safety factor above unity, and by raising the stability limits.

BACKGROUND

This white paper was initiated on December 17, 1997 at a tokamak community meeting and subsequently updated through numerous internet exchange of drafts and comments. Tokamak facility research plans and needs, and U.S. program international tokamak programs are described elsewhere[20-24]. This white paper was pulled together by Richard Hawryluk (PPPL), Ian Hutchinson (MIT), Ned Sauthoff (PPPL), and Thomas Simonen (GA). Direct your comments to simonen@gav.gat.com. This is version 14 (4/30/99).

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Appendix A. Characteristics of Operating World Tokamaks

	Major Radius R(m)	Magnetic Field B(T)	Plasma Current I(MA)	COMMENT
PERFORMANCE EXTENSION TOKAMAKS				
JET	3.0	4.0	6.0	E.U.
JT-60U	3.3	4.4	3.0	Japan
TFTR	2.5	5.8	3.0	U.S. (shutdown)
DIII-D	1.7	2.1	3.0	U.S.
Alcator C-Mod	0.65	9.0	2.0	U.S.
Tore Supra	2.3	4.0	1.7	France (superconducting)
ASDEX Upgrade	1.7	3.1	1.6	Germany
PROOF OF PRINCIPLE TOKAMAKS				
FT-U	0.93	8.0	1.6	Italy
TCV	0.88	1.4	1.2	Switzerland
TEXTOR	1.75	3.0	1.0	Germany
T-10	1.5	3.0	0.4	Russia
Compass-D	0.55	2.1	0.4	England
Triam-1M	0.84	8.0	0.15	Japan (superconducting)
CONCEPT EXPLORATION TOKAMAKS (partial list)				
JFT-2M	1.3	2.2	0.5	Japan
Tuman-3M	0.5	1.2	0.18	Russia
HBT-EP	0.95	0.35	0.025	U.S./Columbia U.
ET	5.0	0.25	0.3	U.S./UCLA (1999 startup)

Appendix B. Characteristics of Tokamak Design Studies

	Major Radius R(m)	Magnetic Field B(T)	Plasma Current I(MA)	COMMENT
POWER PLANT CONCEPTUAL DESIGNS				
ARIES-RS	5.5	8.0	11.3	U.S.
SSTR	7.0	9.0	12.0	Japan
FUSION ENERGY DEVELOPMENT FACILITY DESIGNS				
(ITER-EDA)	8.1	5.7	21.0	Superconductor (cancelled)
RTO/RC-ITER	~6.4	~4.2	~17.0	Evolving ITER design
BURNING PLASMA EXPERIMENT DESIGNS (DTAT variants)				
IGNITOR	1.3	13.0	12.0	Italian-Copper proposal
DTAT	~2.0	~10.0	~8.0	Evolving U.S. next-step study (FIRE)
(BPX)	2.6	9.0	12.0	U.S. Copper (cancelled)
STEADY-STATE SUPERCONDUCTING ADVANCED TOKAMAK DESIGNS (SSAT variants)				
KSTAR	1.8	3.5	2.0	Korea (under construction)
HT-7U	1.7	3.5	1.0	China (under design)
(JT-60SU)	5.0	6.25	10.0	Japan (inactive design)
(TPX)	1.8	4.0	2.0	U.S. (cancelled)