FOREIGN APPLIED SCIENCES ASSESSMENT CENTER
TECHNICAL ASSESSMENT REPORT

COMPARATIVE ASSESSMENT OF WORLD RESEARCH EFFORTS ON MAGNETIC CONFINEMENT FUSION

R.C. Davidson
R.D. Hazeltine
M.A. Abdou
L.A. Berry
J.T. Hogan
P.H. Rutherford

February 1990

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FOREIGN APPLIED SCIENCES ASSESSMENT CENTER

PURPOSE

The Foreign Applied Sciences Assessment Center (FASAC) is operated for the Federal Government by Science Applications International Corporation (SAIC) to improve U.S. knowledge of foreign applied science and to increase awareness of new foreign technologies with military, economic or political importance. Such knowledge can reduce technological surprise, can support estimates of the consequences of technology transfer, and can provide a background for U.S. research and development decisions.

The Center directs leading U.S. scientists in the preparation of technical assessment reports and provides continuity as a national forum for periodic reviews of foreign science research activities.

REPORTS

Although FASAC examines world applied science, emphasis is placed on research in the Soviet Union. The Center reports on what the Soviets call exploratory research (akin to Department of Defense 6.1 and 6.2 research), which seeks to translate developments in fundamental research into new technology. The Center generally does not report on technology already being incorporated in engineering applications.

In addition to an assessment of the quality and emphasis of foreign research, a Center report provides milestones for monitoring subsequent progress. It also provides elements of a net technical assessment of the balance with U.S. science, without being an out-and-out comparison.

ORGANIZATION

The permanent Center staff includes the Center's Director, two Senior Scientists, a Senior Editor, a Technical Information Specialist, and an Assistant Editor. FASAC panels consist of expert consultants from academia, industry, and government, typically six to eight members per panel.

Each panel assesses the status and potential impacts of foreign applied science in a selected area. Panel members are selected by the following criteria: leading authority in the field; recent "hands-on" experience; knowledge of foreign research; and knowledge of the direction of U.S. research programs.

The panels review broad areas of applied science and then focus on particular activities of interest to their assessment. At intervals, panels are convened to revisit some of the same topics. Periodically, an Integration Report effort draws together the Panel Chairmen, Center staff, SAIC scientists and engineers, and government representatives. Together they produce a comprehensive report that describes the trends in foreign research including pervasive issues, such as instrumentation, which affect research capabilities.

The Director and Senior Scientists help select the topics to be assessed, select the Panel Chairmen, guide and assist in the preparation of panel reports, and write the Integration Report, which provides a comprehensive multidisciplinary assessment of foreign applied science.

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1710 Goodridge Drive, McLean, VA 22102 (703) 734-5528
10260 Campus Point Drive, San Diego, CA 92121 (619) 546-6353

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R. C. Davidson
R. D. Hazeltine
M. A. Abdou
L. A. Berry
J. T. Hogan
P. H. Rutherford

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Science Applications International Corporation
1710 Goodridge Drive, P. O. Box 1303, McLean, VA 22102
10260 Campus Point Drive, San Diego, CA 92121

ABSTRACT

This report presents a comparative assessment of the world's four major research efforts on magnetic confinement fusion, including a comparison of the capabilities in the Soviet Union, the European Community (Western Europe), Japan, and the United States. A comparative evaluation is provided in six areas: tokamak confinement; alternate confinement approaches; plasma technology and engineering; fusion nuclear technology and materials; plasma confinement theory; and fusion computations. The panel members are involved actively in fusion-related research, and have extensive experience in previous assessments and reviews of the world's four major fusion programs.

Although the world's four major fusion efforts are roughly comparable in overall capabilities, two conclusions of this report are inescapable. First, the Soviet fusion effort is presently the weakest of the four programs in most areas of the assessment. (Electron cyclotron heating, plasma confinement theory, and mirror research are notable exceptions.) Second, if present trends continue, the United States, once unambiguously the world leader in fusion research, will soon lose its position of leadership to the West European and Japanese fusion programs. Indeed, before the middle 1990s, the upgraded large-tokamak facilities, JT-60U (Japan) and JET (Western Europe), are likely to explore plasma conditions and operating regimes well beyond the capabilities of the TFTR tokamak (United States).

In addition, if present trends continue in the areas of fusion nuclear technology and materials, and plasma technology development, the capabilities of Japan and Western Europe in these areas (both with regard to test facilities and fusion-specific industrial capabilities) will surpass those of the United States by a substantial margin before the middle 1990s.

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FOREWORD

This report, *Comparative Assessment of World Research Efforts on Magnetic Confinement Fusion,* is one in a series of technical assessment reports produced by the Foreign Applied Sciences Assessment Center (FASAC), operated for the Federal government by Science Applications International Corporation (SAIC). These reports assess selected fields of foreign basic and applied research, evaluate and compare the foreign state of the art with that of the United States, and identify important trends that could lead to future applications of military, economic, or political importance. This report, like others produced by the Center, is intended to enhance US knowledge of foreign applied science activities and trends for reducing the risk of technology transfer, and also to provide a background for US research and development decisions, including the possibility of cooperative programs with foreign countries. Appendix C of this document provides a list of titles of FASAC reports completed and in production.

This report presents a comparative assessment of the world's four major research efforts on magnetic confinement fusion, including a comparison of the capabilities in the Soviet Union, the European Community (Western Europe), Japan, and the United States. A comparative evaluation is provided in the following six areas:

- tokamak confinement;
- alternate confinement approaches;
- plasma technology and engineering;
- fusion nuclear technology and materials;
- plasma confinement theory; and
- fusion computations.

The report was prepared by a panel of six internationally recognized US scientists and engineers who are active participants in magnetic confinement fusion research and have extensive experience in previous assessments and reviews of the world's four major fusion efforts:

- Dr. Ronald C. Davidson (Co-Chairman) — Professor of Physics, Plasma Fusion Center, Massachusetts Institute of Technology

- Dr. Richard D. Hazeltine (Co-Chairman) — Professor of Physics, Institute for Fusion Studies, University of Texas at Austin

- Dr. Mohamed A. Abdou — Professor, Department of Mechanical, Aerospace, and Nuclear Engineering, University of California at Los Angeles

- Dr. Lee A. Berry — Research Staff Member, Fusion Energy Division, Oak Ridge National Laboratory

- Dr. John T. Hogan — Research Staff Member, Fusion Energy Division, Oak Ridge National Laboratory

- Dr. Paul H. Rutherford — Associate Director, Plasma Physics Laboratory, Princeton University

On a part-time basis, over the period September 1989 to January 1990, each panel member devoted time toward assessing the published research literature, preprints, international conference proceedings, and laboratory reports on Soviet, West European, and Japanese activities on magnetic confinement fusion, and to evaluating the underlying research and development activities in light of their own experience, including their interactions and collaborative activities with Soviet, West European, and Japanese colleagues. In addition, each panel member has participated in at least one of the three prior FASAC assessments of magnetic confinement fusion (directed at one of the three foreign programs of interest).

For important, detailed information on the assessments contained in this report, the reader is referred to the three earlier FASAC technical assessment reports: *Soviet Magnetic Confinement Fusion Research* (October 1987), which is updated in Chapter II of this report, *West European Magnetic Confinement*

Fusion Research (January 1990), and *Japanese Magnetic Confinement Fusion Research* (January 1990).

EXECUTIVE SUMMARY

This report presents a comparative assessment of the world's four major research efforts on magnetic confinement fusion, including a comparison of the capabilities in the Soviet Union, the European Community (Western Europe), Japan, and the United States. A comparative evaluation is provided in six areas: tokamak confinement; alternate confinement approaches; plasma technology and engineering; fusion nuclear technology and materials; plasma confinement theory; and fusion computations. In addition, extended summaries of the present capabilities and outlook for future accomplishments are presented for the individual fusion programs in the Soviet Union, Western Europe, and Japan. The panel members are involved actively in fusion-related research, and have extensive experience in previous assessments and reviews of the world's four major fusion programs.

By way of background, the Soviet invention of the tokamak confinement approach and the very encouraging experimental results obtained on the T-3 tokamak at the Kurchatov Atomic Energy Institute in the late 1960s resulted in the vigorous pursuit of tokamaks on a worldwide basis during the 1970s and 1980s. As a consequence, this report places particular emphasis on the tokamak approach, which naturally dominates the assessments of large-size and medium-size experimental facilities, plasma confinement theory, fusion computations, including both scientific and engineering computations, and plasma technology and engineering development related to auxiliary heating systems, magnets, and plasma fueling capabilities. Nonetheless, considered on a worldwide basis, there are also sizeable research efforts on alternate confinement approaches, which may offer potentially more attractive reactor features than the tokamak. The alternate confinement approaches examined in this report include stellarators, reversed-field pinches, and mirrors. Pursued at a much lower level of effort than tokamaks, the alternate approaches are correspondingly at an earlier stage of development.

Although the world's four major fusion efforts are roughly comparable in overall capabilities, two conclusions are inescapable from a close examination of this report. First, the Soviet fusion effort is presently the weakest of the four programs in most areas of the assessment. (Electron cyclotron heating, plasma confinement theory, and mirror research are three notable exceptions.) Second, if present trends continue, the United States, once dominant in fusion research, will soon lose its position of leadership to the West European and Japanese fusion programs.

Japan and Western Europe have assigned fusion R&D relativity high priority during the decade of the 1980s. Before the middle 1990s, the upgraded large tokamak facilities, JT-60U (Japan) and JET[1] (Western Europe), are likely to explore plasma conditions and operating regimes well beyond the capabilities of the TFTR tokamak (United States). In addition, if present trends continue in the areas of fusion nuclear technology and materials, and plasma technology development, the capabilities of Japan and Western Europe in these areas (both with regard to test facilities and fusion-specific industrial capabilities) will surpass those of the United States by a substantial margin before the middle 1990s.

INTERNATIONAL THERMONUCLEAR EXPERIMENTAL REACTOR (ITER)

As a prelude to the Reagan-Gorbachev Geneva Summit Meeting in November 1985, the Soviet Union submitted a proposal to build a tokamak engineering test reactor on a collaborative basis with US and Soviet leadership. The ensuing discussions led to the establishment, under the auspices of the IAEA, of the ITER Conceptual Design Activity as a quadripartite activity involving the European Community, Japan, the Soviet Union, and the United States.

The major roles and responsibilities within the Conceptual Design Activity were apportioned as evenly as possible among the four parties. Thus, the United States supplies the Chairman of the ITER Council, the Soviet Union provides the Chairman of the International Scientific and Technical Advisory Committee (ISTAC), the Managing Director from Japan chairs the Management Committee, and the European Community provides the site for joint design work, Garching-near-Munich.

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1 Joint European Torus

The major scientific and technical roles in the ITER Design Team have also been apportioned evenly. There is a matrix structure of four Project Units and eight Engineering Design Units, and each party provides the leadership of one of the Project Units and two of the Engineering Design Units. Each party spends the equivalent of $16-18 million annually on the ITER activity—split about equally between design and R&D. The contribution to ITER from the Soviet Union represents a much larger fraction of its national fusion budget than do the contributions from the other three parties.

Since the formal structure of the ITER Activity is so symmetrical, an assessment of the relative contributions of the four parties must be based on the impressions of Design Team participants or ISTAC members from the United States, and these are necessarily somewhat subjective. The European Community has established a dominant position in almost all aspects of the engineering design of ITER, partially due to the proximity of the highly regarded NET team. Both Japan and the Soviet Union have contributed strongly to the joint design activity, and they have also taken steps to ensure that their national programs are readily responsive to ITER's R&D needs. All four parties have contributed about equally to physics aspects of the design activity, although the United States has the formal lead in this area; the contributions from Soviet physicists are also particularly noteworthy.

Among the four ITER parties, the European Community maintains the strongest design effort on an equivalent national device, the Next European Tokamak (NET). Although political considerations will require that all reasonable possibilities for an international ITER-like project are pursued first, the European Community can be expected to authorize construction of NET in about 1995 if ITER is not progressing into construction by that time. To reduce costs, the European Community may encourage some level of international participation in NET.

Although the Japanese seemed lukewarm at first toward participation in ITER, perhaps because they still expected early authorization of their national Fusion Engineering Reactor (FER) project, their enthusiasm for ITER appears to have increased markedly. Japan is now seen as likely to join a future phase of the ITER Activity, even to the extent of joining a multinational construction project if this were to materialize. Should ITER not go forward, it is probable that successful results on the JT-60U tokamak will lead to authorization of the national engineering test reactor, FER, but this device will be somewhat less ambitious—and less costly—than the present ITER design.

The main thrust of Soviet strategy for future fusion development has, for many years, been the internationalization of the design and construction of a tokamak engineering test reactor. Thus, ITER represents the major element in long-range fusion planning in the Soviet Union. Failing a continuation of the present quadripartite agreement, it seems likely that the Soviet Union will seek a bilateral or trilateral arrangement under which an ITER-like device could be built.

INTERNATIONAL ASCENDANCY OF TOKAMAK RESEARCH

The Soviet invention of the tokamak confinement approach and the very encouraging experimental results obtained on the T-3 tokamak at the Kurchatov Atomic Energy Institute in the late 1960s resulted in the vigorous pursuit of tokamaks on a worldwide basis during the 1970s and 1980s. By the middle 1970s, the favorable early results on the Soviet T-3 tokamak had been followed by the successful demonstration of techniques for auxiliary plasma heating in a number of medium-size tokamak devices in the United States and Western Europe. As a result, projects to construct large tokamaks, whose plasma parameters could approach reactor-like values, were initiated in Western Europe (JET), the United States (TFTR), Japan (JT-60), and the Soviet Union (T-20/T-15). By 1985, three of these large tokamaks, TFTR (1982), JET (1983), and JT-60 (1985) had become operational. The T-15 tokamak, which was a smaller substitute for the more ambitious reactor-prototype device, T-20, achieved an initial plasma in late 1988, but is still not in full experimental operation. In the late 1970s, the Soviet Union also initiated a project to build a deuterium-tritium tokamak, T-14/TSP, that uses adiabatic compression to reach peak plasma parameters.

The development of closer ties among the countries of the European Community in the early 1970s came at a time of grave concerns regarding future energy supplies. It coincided also with the realization that tokamak performance scaled favorably with size to the reactor level. Accordingly, Western Europe chose fusion as a vehicle for enhanced cooperation in science and technology and decided, in 1973, to construct jointly the large JET tokamak. By offering an attractive project on a scale larger than any single nation was prepared to undertake, the European Community minimized national competition and made cooperation advantageous. The overall resources available for fusion in Western Europe were sufficient, however, to maintain strong national tokamak programs in all of the main participating countries. By maintaining strong support for the tokamak program throughout the late 1980s, Western Europe has now taken a slight lead over the United States, both in the scope of its program and in the usual measures of plasma performance in the large devices.

The Japanese tokamak program began in the early and middle 1970s, but the Japanese devices did not make any major or fundamental contributions to world tokamak research during this period. By 1975, the development of fusion had become a major objective of Japan, and the focus of a rapidly-expanding program was a large tokamak, JT-60, to be constructed at the new Naka site of the Japanese Atomic Energy Research Institute (JAERI). To prepare for JT-60, Japan executed an agreement with the United States for collaborative experimental work on the Doublet III tokamak at General Atomics. The tokamak program in Japan has lacked the breadth of the programs in either Western Europe or the United States; it has been focused quite narrowly on operation of a single large device, the JT-60. An upgraded machine, called JT-60U, will operate in 1991, and its operation will place Japan in a leading role in world tokamak research.

Soviet leadership in experimental tokamak physics declined during the decade of the 1970s, and by the early 1980s, the Soviet effort was not at the forefront of world tokamak research. Despite hardware limitations, however, the mainline Soviet tokamak program continues to be pursued vigorously by a highly competent experimental staff with superb theoretical support. Through a combination of constrained budgets for hardware expenditures, bureaucratic inefficiencies, engineering difficulties, and questionable quality control, the Soviet fusion program has experienced significant delays in bringing the T-15 and TSP tokamak facilities into operation. Japan, Western Europe, and the United States, with their broad industrial capabilities, have suffered fewer and less severe delays. Nonetheless, it would be a serious error to underestimate Soviet capability to develop fusion as a practical energy source, particularly in view of the significant human and intellectual resources committed to fusion research in the Soviet Union.

TOKAMAK CONFINEMENT

The relative standing of the United States, Western Europe, Japan, and the Soviet Union in tokamak research during the 1990s will be determined largely by the results obtained on the large tokamaks TFTR, JET, JT-60, and T-15, respectively. In the case of the United States, the results from TFTR will be augmented importantly by those from the medium-size tokamak DIII-D, which has major programs in the confinement and stability of strongly elongated plasmas and in high-power neutral-beam and electron cyclotron heating, and from the Alcator C-MOD tokamak (to be operational in late 1990), with major programs in the confinement and heating of dense, shaped plasmas at high magnetic field. In the case of the Soviet Union, results from hydrogen operation in T-15 may be supplemented by those from adiabatic compression of deuterium-tritium plasmas in the TSP tokamak, although the outlook for tritium operation in TSP is clouded by technical and political uncertainties. The West European tokamak program on JET will be supplemented by strong efforts on several medium-size tokamaks, including ASDEX-U, Tore Supra, FT-U, and TEXTOR, each with different technological capabilities and areas of scientific emphasis. The Japanese tokamak program on JT-60U will be supplemented by relatively small programs on the JFT-2M and TRIAM-1M facilities. In addition, as described in the main text of this report, there are several other medium-scale tokamaks in the world program that will continue to contribute to the advancement of the tokamak confinement approach on a broad front during the 1990s.

Returning to the large tokamaks, both JET and JT-60 will benefit from major machine upgrades and enhancements of auxiliary capabilities that are being implemented in the early 1990s. In the case of JT-60, an enlarged vacuum vessel is being constructed to accommodate the largest D-shaped plasma that can be fitted within the existing toroidal-field coils; the upgraded machine is called JT-60U and will operate in 1991.

The outlook for JET is very favorable. Many of the performance-enhancing items are already well into fabrication, such as beryllium divertor plates, a lower hybrid current drive system for sawtooth control, increased ion cyclotron heating power, and an increase in the neutral-beam energy to 140 keV. The proposed extension of JET's operating lifetime through 1996 apparently has been approved, thereby not only providing time for the orderly completion of JET's existing activities, but also creating an opportunity for further additions to its program. These additions are likely to exploit JET's long-pulse capabilities, to test novel modes of plasma operation that are prototypical of ITER, especially in the area of impurity control. The introduction of tritium will presumably be postponed until the final period of JET's operating lifetime, that is 1995-1996.

The principal features of JT-60U are a doubling of the plasma current, and provision (and approval) for operating in deuterium. Upgraded waveguide launchers will maintain JT-60's position at the forefront of research in lower hybrid current drive. It seems likely that negative-ion beams will be selected for "second-stage" heating and current drive in JT-60U, and there is every indication that the present negative-ion-beam development program in Japan will be successful in producing a 20-MW system by the middle 1990s. If so, there is a distinct possibility that JT-60U will take a clear lead in world tokamak research, especially in ITER-prototypical heating and current drive experiments, by 1994-1995.

Both the upgraded JET and JT-60U should be capable of accessing the more favorable H-mode of confinement in divertor operation, but the improvement in confinement will be partially offset by having to work at slightly lower plasma current. In certain regimes, the deuterium-tritium-equivalent Q-value could be in the range 1.0 to 1.5, with more than half of the fusion reactivity coming from reactions among thermal ions. Eventually, JET will be able to explore this regime in actual deuterium-tritium plasmas.

Enhancements of TFTR's capabilities will be limited to an increase in the ion cyclotron heating power, installation of carbon-carbon composite tiles in high-heat-flux regions, and relatively early introduction of tritium. The near-term program will emphasize confinement studies with upgraded diagnostics. If its favorable confinement regime can be extended to higher plasma currents, the TFTR has the capability to achieve the first demonstration of fusion breakeven ($Q \sim 1.0$) in deuterium-tritium plasmas.

The investigation of plasma confinement on T-15, using a combination of high-power electron cyclotron heating at 83 GHz and neutral-beam injection, presently planned for the period 1991-1992, will provide significant information that cannot be closely matched in non-Soviet experiments. (The DIII-D program at General Atomics comes closest.) If the Soviet Union is successful in developing higher-frequency (124 GHz) gyrotrons, the T-15 device, operated at higher toroidal field, would provide a truly unique test of the application of electron cyclotron heating at reactor-like plasma parameters.

Looking beyond the present generation of large tokamaks, the outlook is clouded by political uncertainties and by the very high cost of "next-step" devices, that is, engineering test reactors. Both Western Europe and Japan have the technical resources—and clearly also the financial means—to construct their respective engineering test reactors, NET and FER, without external participation. On the other hand, the poor performance of industry on construction of T-15 casts doubt on Soviet capability to construct the next-step national device, the OTR. The United States has discontinued design work on a purely national engineering test reactor.

In even the best of circumstances, there will be a long hiatus in mainline experimental tokamak research from the middle 1990s, when the large tokamaks of the present generation are scheduled to complete their programs, to the early 2000s, when an engineering test reactor could become operational. The United States is considering an intermediate-scale device, the Compact Ignition Tokamak, which would explore the ignited-plasma regime at short pulse length and which could be operational before the end of the century.

ALTERNATE CONFINEMENT APPROACHES

Alternate confinement approaches differ from the tokamak in their magnetic field geometries, and they offer potentially more attractive reactor features. On an international basis, all of the alternate approaches are pursued at a much lower level than tokamaks and are consequently at an earlier stage of development. Among the alternate approaches, stellarators are pursued most vigorously. Stellarators and reversed-field pinches use toroidal magnetic field geometry, whereas mirrors use a linear (open-ended) confinement geometry.

The world's largest operating stellarator is the Advanced Toroidal Facility (ATF) at the Oak Ridge National Laboratory. A planned Japanese stellarator, the Large Helical Device (LHD), will have roughly twice the linear dimensions and magnetic field strength of ATF. R&D work in support of the LHD project has already begun; it will be built at the new Institute for Fusion Studies near Toki. Meanwhile, the next-step Wendelstein stellarator device (W-VII-X) in the West European program (Institute for Plasma Physics, near Munich, West Germany) remains a paper study, and its future is linked to decisions to be made regarding the ITER and the NET. However, the W-VII-X project could be carried out independently by the West Germans, and would be competitive with the Large Helical Device in Japan if approved in a timely manner. At present, the US fusion program has no approved successor to the Advanced Toroidal Facility. The Soviet Union's next-step stellarator device (Uragan-3M at the Khar'kov Physical-Technical Institute) is only comparable in capability to the present generation of devices elsewhere in the world.

To summarize, the Japanese stellarator program, taken as a whole, must be regarded as the world leader despite the near-term strength of the US effort. This view is based both on the success of present Japanese stellarator devices (Heliotron-E and CHS), as well as on the ambitious nature of the Large Helical Device.

In the reversed-field pinch area, two new devices, comparable in size and current, are being built. These are the RFX at Padova (Padua) University in Italy, and the ZT-H at Los Alamos National Laboratory. Because the RFX is scheduled to begin operation in 1990, several years before ZT-H, its commissioning could move the West European program well ahead of the United States. Collaboration between the United States and Western Europe will be especially important to further progress in developing the reversed-field pinch approach. Scientifically, the RFX and ZT-H are complementary facilities: the former is subject to slow loss of equilibrium, and the latter may be subject to instabilities. Their differences will make collaboration beneficial. While the TPE-IRM-15 reversed-field pinch facility at the Electrotechnical Laboratory in Japan will remain competitive in the short term, it will be overshadowed by the larger RFX and ZT-H facilities in the middle 1990s.

Mirror-based fusion research suffered a major international setback when the United States decided to end this line, mothballing the MFTF-B experiment at Lawrence Livermore National Laboratory and terminating the TARA experiment at Massachusetts Institute of Technology. At the time of this decision, the United States had the leading mirror program, the only other competitors being the GAMMA-10 tandem mirror at Tsukuba University in Japan, and Soviet experiments at the Kurchatov Institute and the Nuclear Physics Institute in Novosibirsk. The US decision, perhaps predictably, has not affected the level of effort on mirror research in the Soviet program. New results have been reported from AMBAL, the multiple-mirror GOL device, and the Gas Dynamic Trap in Novosibirsk, and from the OGRA-4 and PR-8 machines at Kurchatov. The results from the Gas Dynamic Trap are cited as providing support for a possible compact fusion neutron source. The Japanese GAMMA-10 group is pursuing optimization of tandem mirrors, and the work is of high quality. However, significant new results have not been reported for several years, and the long-term outlook is unclear because of the large capital costs of the LHD stellarator project.

PLASMA TECHNOLOGY AND ENGINEERING

Fusion research facilities require sophisticated components in a broad range of areas from superconductivity to high-energy particle beams. Capability in a given area is determined by specific laboratory and/or industrial expertise and by the infrastructure which is needed to design and manufacture high-performance, reliable components and systems.

Future progress in neutral beam development depends on the commitment to a national or international project. ITER will advance accelerator and negative-ion beam technology if construction is approved. Apart from ITER, negative-ion beams with energies up to 500 keV are being discussed for all of the large tokamaks as well as for the Large Helical Device in Japan. With the commitment to the Large Helical Device and the JT-60U, and the lack of definitive plans to construct ITER, the Japanese could take a lead in negative-ion-based neutral beams. The necessary development of MeV-range accelerators, not required for these projects, is likely to remain at the present level of effort until a major facility commitment is made to an engineering test reactor.

In the area of radio frequency source technology, high-power ion cyclotron experiments for plasma heating (and often for current drive) play a major role in the US, West European, and Japanese fusion programs, and in each case there is a strong industrial base. Continued progress, as allowed by physics development, and program support are expected. Ion cyclotron experiments do not play a major role in Soviet plans. Soviet industry, while not up to Western standards, is less limited in ion cyclotron source technology than in other heating technologies.

The assessment for lower hybrid source technology parallels that for ion cyclotron technology except that, while a reasonable industrial base exists, there are no large fusion experiments planned in the United States that require further lower hybrid source development. The experience gained in developing and operating launchers in Western Europe and Japan is an important step towards the more demanding requirements of ITER (a second-generation 24-waveguide array has already been used on the JT-60 tokamak in Japan).

In the near term, the United States (Varian Associates) will likely remain the principal supplier of gyrotrons for electron cyclotron heating experiments in the West and Japan. Competitive suppliers may develop as a result of sustained funding for the gyrotron programs recently initiated in Western Europe and Japan, for Tore Supra and the Large Helical Device, respectively.

In the past five years, substantial work on plasma fueling technology was started in Western Europe and has contributed to advancing the technology. However, with continued support, the United States is likely to retain its present leading position in plasma fueling technology, but with significant contributions also coming from the West European program.

Progress in superconducting magnets will be in part determined by the need for that technology in future facilities. Present magnet programs in the West and Japan have proposed major magnet test facilities. Decisions on these facilities will likely require a decision on ITER construction and on the respective national roles in that project. The lack of a civilian high-tech industrial capability in the Soviet Union is a substantial handicap in its ability to make further advances in this area.

FUSION NUCLEAR TECHNOLOGY AND MATERIALS

Fusion nuclear technology and materials research includes those technical disciplines and components of a fusion reactor related to fusion energy conversion and recovery, tritium fuel breeding and processing, and radiation protection. Research on fusion nuclear technology and materials can be divided conveniently into five areas: blankets (where fusion energy conversion and the breeding of tritium fuel takes place); neutronics; tritium processing systems; neutron-interactive materials; and plasma-interactive materials (plasma-facing components).

At present, the level of effort on fusion nuclear technology and materials research is largest in the West European program and second-largest in the Japanese program. The level of effort in both of these programs is two or three times that of the US program. The US level of effort and the capability of US facilities in the fusion nuclear technology and materials area are no longer in the position of international preeminence held in the late 1970s and early 1980s. Nevertheless, the sizeable US investment in R&D made in the late 1970s and early 1980s, the broad technological base, and the efficient use of resources, all help the United States to maintain relatively competitive programs in certain areas. US research on tritium systems and neutron-interactive materials are two notable examples. The manpower level in the Soviet program is comparable to that in Japan and Western Europe, but the Soviet funding is lower than that in the United States.

During the past several years, the West European and Japanese programs have increased their efforts several-fold and have embarked on new R&D initiatives, including the commissioning of new facilities, while there has been a sharp decline in funding with no new facilities in the United States. If this trend continues, world leadership in fusion nuclear technology and materials research will be a competition between Japan and Western Europe, with the United States a distant third. This will affect adversely the ability of the United States to be viewed as a desirable partner in international collaborative efforts. In addition, established high-technology development policy in Western Europe and Japan may place the United States at a disadvantage for long-term industrialization of fusion.

The Soviet effort, despite its breadth and large manpower pool, has been fragmented and relatively weak in many critical areas. Commitment of new resources (both funding and facilities), access to fast computers, as well as a sharpening in focus and an improvement in management, are necessary for the Soviet program to become effective. It is unlikely, however, that the Soviet program will rise to a position of international prominence in the fusion nuclear technology and materials area in the near future.

PLASMA CONFINEMENT THEORY

At present, the strongest theory program in the international magnetic fusion effort is that of the United States. The fusion theory effort of Western Europe is in second place; it is close to the United States and rapidly getting closer. Confinement theory in the Soviet Union, once the world leader, has lost five or more years to the West, although the skill of individual Soviet theorists remains striking. Japan's theory effort is clearly the smallest and weakest, despite pockets of strength. This ranking, broadly consistent with previous FASAC reports, essentially reflects productivity—the quality and importance of theoretical research as revealed in the published literature. Not surprisingly, it agrees with an estimated ranking based on numbers of personnel; by this measure, the West European theory effort is comparable in size to that in the United States, while the Soviet effort is about 65 percent, and that of Japan is 20 percent, the size of the US theory program.

With regard to outlook for the future, the quality of West European theoretical research, and especially its unequalled rate of growth, suggest that Western Europe will become the world leader in plasma confinement theory during the next five years. Japanese confinement theory will make important gains in certain areas—computer simulation is an example—but the Japanese program will remain small and far from world leadership for the foreseeable future. Assessing the outlook for Soviet theory is problematic. Strong underlying capabilities and improved computational hardware, together with the exciting general changes in Soviet mobility and communication, could portend a dramatic intellectual flowering—as is now apparent with regard to Soviet nonlinear dynamics. On the other hand, the absence of a world-class experimental program would surely inhibit Soviet theory in coming years as much as it has in the past.

FUSION COMPUTATIONS

Fusion computations can be divided into three main areas: scientific computations; data acquisition; and engineering computations.

Fusion scientific computations are carried out along similar lines in the four major programs. The United States has, by far, the strongest fundamental computational studies program, and no other group is comparable. Research in this area is expected to lead in the long term to the development of first-principles models for plasma performance, which should be superior to the semiempirical models presently employed. The US contributions in the fields of nonlinear, multidimensional simulation, and particle simulations are unequalled, with several centers of excellence. In contrast, there are isolated examples of similar work in Western Europe, Japan, and the Soviet Union. Fusion-related computational activities in Western Europe, the Soviet Union, and Japan are directed more toward device-related questions.

One area that can give an indication of relative ranking is experimental interpretation based on predictive and data analysis codes. In this area, the United States is in a leading position, with the TFTR group at Princeton Plasma Physics Laboratory, and the DIII-D group at General Atomics. The Princeton TRANSP data analysis code has been imported by Western Europe to analyze data on JET and other West European tokamaks. Both the DIII-D and JET groups have studied configurational effects, but the DIII-D group has been the more active in detailed data analysis. The Soviet program (Kurchatov Institute) is intellectually very strong in this area, but has been unable to fully exploit even the existing computational resources. While these resources are not at the level of other groups, they are adequate for the analysis of data from the T-10 and T-15 tokamaks. The Japanese program is the weakest in fusion computations related to experimental interpretation.

In the area of data acquisition, the experimental data acquisition systems in the US, West European, and Japanese fusion programs are comparable, and superior to those in the Soviet Union. However, the Soviet data acquisition systems appear to be adequate for present and next-step experiments. The majority of data acquisition systems (both Eastern and Western Bloc) used in fusion experiments are based on DEC hardware. Data from experiments in the United States and Western Europe are easily accessible and heavily used by participants in joint experiments. The hardware exists for such collaboration with the JT-60 group in Japan, but it is not used as heavily. The US and West European experimental data acquisition systems are mostly VAX-based. The major exceptions are the systems for the JET and Tore Supra tokamaks in Western Europe, which use NORSK systems. Japan has acquired a VAX for communications and data transfer among ITER participants.

The Soviet fusion program has developed a link with the Central Research Institute for Physics in Budapest, for "reverse engineered" DEC clones, below the VAX level (PDP 11/780). A part of the T-15 data acquisition system is now in use by the T-10 group and by theorists at the Kurchatov Institute. The system appears to be adequate for T-15 experimental needs, although its first real test will come with the integrated operation of all T-15 subsystems. The T-15 data acquisition system has been developed as part of the civilian research activity, and no connection with military or illicit technology transfer has been found.

With regard to engineering computations, a useful comparison here is based on contributions to the ITER joint design work. Overall, the United States and Japan have the highest capabilities in this area, because many neutronics, mechanical, thermal analysis, and CAD codes are available from non-fusion laboratory and commercial sources, and the computational resources available to the US and Japanese participants are the best of the ITER parties. The West European (NET) group has made comparable contributions in engineering computations, whereas the Soviet Union clearly lags. However, the Soviet Union has made considerable progress, and is believed to contribute its share in this area because of its dedication of a higher level of "home-team" effort to the ITER project than the other parties.

Finally, while the availability of computational hardware has an important effect on fusion-related performance, the most important determinant appears to be the dedication to solving fusion-related problems. Thus, Japan, which arguably has (or soon will have) access to the most advanced computers, does not perform as well as might be expected when compared with the other fusion participants. The United States has the lead in the fusion computations area, and this should continue, with Western Europe, the Soviet Union, and Japan all contributing effectively. The Soviet contribution has been improving steadily for the past five years, and this is expected to continue.

CHAPTER I
COMPARATIVE ASSESSMENTS

A. INTRODUCTION AND BACKGROUND

Research in magnetic fusion is one of the most demanding measures of a nation's capabilities in advanced technology and the physical sciences. This report presents a comparative assessment of the world's four major research efforts on magnetic confinement fusion, including a comparison of the capabilities in the Soviet Union, the European Community (Western Europe), Japan, and the United States. Important background material for this assessment includes the three recent FASAC reports:

- *Soviet Magnetic Confinement Fusion Research;*[1]
- *West European Magnetic Confinement Fusion Research;*[2] and
- *Japanese Magnetic Confinement Fusion Research.*[3]

In Chapters II-IV of this report, updated summaries of the present capabilities and outlook for future accomplishments are presented for the individual fusion programs in the Soviet Union, Western Europe, and Japan, respectively. In Section B of Chapter I, a comparative assessment is made of the capabilities of the four world efforts, including the US magnetic fusion program funded by the US Department of Energy (DOE). Although a separate chapter is not presented on the US fusion program, the panel members are involved actively in related

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1 R. C. Davidson, L. A. Berry, R. A. Ellis, Jr., R. D. Hazeltine, J. T. Hogan, R. S. Post, and W. M. Stacey, *Soviet Magnetic Confinement Fusion Research,* Foreign Applied Sciences Assessment Center, Science Applications International Corporation, McLean, Virginia, October 1987.

2 R. D. Hazeltine, K. W. Gentle, J. T. Hogan, M. Porkolab, D. J. Sigmar, D. Steiner, and K. I. Thomassen, *West European Magnetic Confinement Fusion Research,* Foreign Applied Sciences Assessment Center, Science Applications International Corporation, McLean, Virginia, January 1990.

3 R. C. Davidson, M. A. Abdou, L. A. Berry, C. W. Horton, J. F. Lyon, and P. H. Rutherford, *Japanese Magnetic Confinement Fusion Research,* Foreign Applied Sciences Assessment Center, Science Applications International Corporation, McLean, Virginia, January 1990.

research, and are very familiar with the accomplishments and capabilities of the US program. The comparative evaluation in Section I.B is provided in the following six areas:

- tokamak confinement;
- alternate confinement approaches;
- plasma technology and engineering;
- fusion nuclear technology and materials;
- plasma confinement theory; and
- fusion computations.

By way of background, in view of the ascendancy of the tokamak confinement approach to a position of dominance in world fusion research during the 1970s and 1980s, this report necessarily places particular emphasis on tokamak development. This is true in the areas of large-size and medium-size experimental facilities, plasma confinement theory, and fusion computations, including both scientific and engineering computations. Because the plasma technology and engineering development related to auxiliary heating systems, magnets, and plasma fueling are paced to a large extent by the technological requirements of the most advanced fusion facilities, the topics treated in plasma technology and engineering also emphasize those development areas and components particularly relevant to tokamaks.

Nonetheless, considered on a worldwide basis, there are also sizeable research efforts on alternate confinement approaches, which may offer potentially more attractive reactor features than the tokamak. All of the alternate approaches treated in Section I.B.2 of this report, which include stellarators, reversed-field pinches, and mirrors, are pursued at a much lower level of effort than tokamaks, and they are correspondingly less advanced. At the present stage of developing fusion as a practical energy source, many of the technical issues treated in the fusion nuclear technology and materials area (such as blankets, neutronics, tritium processing, neutron-interactive materials, and plasma-interactive materials) are generic to the various confinement approaches. However, in view of the major quadripartite effort on the International Thermonuclear Experimental Reactor (ITER) Conceptual Design Activity, many critical development issues in the fusion nuclear technology and materials area are rapidly becoming tokamak-specific.

Finally, in Table I.1, an attempt has been made to provide a comparative ranking of the capabilities of the United States, Western Europe, Japan, and the Soviet Union in several subcategories of the six major assessment areas listed earlier in Section I.A. The reader is cautioned that the information in Table I.1 should be interpreted only in the context of the analysis of the various activities presented in Section I.B, Chapters II-IV, and the Executive Summary of this report. It should also be emphasized that the United States, Western Europe, Japan, and the Soviet Union each have extensive capabilities in fusion research and development, so that the ranking in Table I.1 often reflects relatively small variations in capabilities or differences in program emphasis.

Nonetheless, two conclusions are inescapable from an examination of Table I.1 and a careful reading of this report. First, the Soviet fusion effort is presently the weakest of the four programs in most areas of the assessment. (Electron cyclotron heating, plasma confinement theory, and mirror research are three notable exceptions.) Second, if present trends continue, the West European and Japanese programs will surpass that of the United States, now the world leader in fusion research. Indeed, before the middle 1990s, the upgraded large-tokamak facilities, JT-60U (Japan) and JET (Western Europe), are likely to explore plasma conditions and operating regimes well beyond the capabilities of the TFTR tokamak (United States). In addition, if present trends continue in the area of fusion nuclear technology and materials, and plasma technology development, the capabilities of Japan and Western Europe in these areas (both with regard to test facilities and fusion-specific industrial capabilities) will surpass those of the United States by a substantial margin before the middle 1990s.

Table I.1
RANKING OF WORLD FUSION PROGRAMS
1990 (→ 1995 *)

	United States	Western Europe	Japan	Soviet Union
Tokamak Confinement				
Large Tokamaks	2→3	1	2	4
Medium-Size Tokamaks	1	1	4	3
Diagnostics	1	2→1	3	4→3
Data Analysis and Interpretation	1	1	3	3
ITER Physics	1	2	3	3
ITER Engineering Design	2	1	2	4
Alternate Confinement Approaches				
Stellarators	2→3	2	1	4
Reversed-Field Pinches	1→2	1	3	-
Mirrors	-	-	2	1
Plasma Technology and Engineering				
Neutral Beams	1→2	1→2	1	4
Ion Cyclotron Systems	2	1	2	4
Lower Hybrid Systems	3	2→1	1	4
Electron Cyclotron Systems	1→2	3→2	4	1
Pellet Fueling	1	2→1	3	4
Magnets	3	1	1	4
Industrial Capability	3	1	1	4
Fusion Nuclear Technology and Materials				
Blanket				
Solid Breeder	3	1	2→1	4
Liquid Metals	3→4	1	4→3	2
Tritium Systems	1→2	2→1	3	4
Neutronics	2→3	3→2	1	4
Neutron-Interactive Materials	1→3	3→1	2→1	4
Plasma-Facing Components	1→3	1	1	4
Plasma Confinement Theory				
Major Disruptions	1→2	1	4	3→?
Enhanced Confinement	1	3→2	2→3	4→3
Transport	1	2→1	4	3
Magnetohydrodynamics	2	1	4	3→?
Fusion Computations				
Scientific Computations	1	2	3→4†	3→2†
Data Acquisition Systems	1	2→1	2→3†	4→3†
Engineering Computations	1	3→2	1→2	4

1 = best; 2 = second best; 3 = third best; 4 = weakest.
* Projections assuming continuation of present levels of effort.
† Assumes acquisition by Soviet Union of modern computational hardware, other factors constant.

B. SUMMARY OF COMPARATIVE ASSESSMENTS

1. Tokamak Confinement

a. Overview

The basic idea of the tokamak was conceived in the Soviet Union in the early 1950s and led to experimental studies on a series of small tokamaks at the I. V. Kurchatov Atomic Energy Institute in Moscow. By 1968-1969, the plasma parameters in the T-3 tokamak had been raised to record levels, which led to the initiation of a number of tokamak projects outside the Soviet Union. Soviet scientists constructed a moderate-size tokamak, T-10, but it lacked a capability for neutral-beam injection (NBI), which had proved highly successful in raising the plasma temperature in non-Soviet tokamaks. During the decade of the 1970s, Soviet leadership in experimental tokamak physics declined, and by the early 1980s the Soviet effort was not at the forefront of world tokamak research. Despite hardware limitations, however, the mainline Soviet tokamak program continues to be pursued vigorously by a highly competent experimental staff with superb theoretical support.

The 1970s and early 1980s saw the ascendancy of Western Europe and the United States to positions of dominance in tokamak research. The development of closer ties among the countries of the European Community came at a time of grave concerns regarding future energy supplies, and it coincided also with the realization that tokamak performance appeared to scale favorably with size to the reactor level. Accordingly, Western Europe chose fusion as a vehicle for enhanced cooperation in science and technology and decided, in 1973, to construct jointly a very large tokamak device called the Joint European Torus (JET). By offering an attractive project on a scale larger than any single nation was prepared to undertake, the European Community minimized national competition and made cooperation clearly advantageous. The overall resources available for fusion in Western Europe were sufficient, however, to maintain strong national tokamak programs in all of the main participating countries. By maintaining strong support for the tokamak program throughout the late 1980s, Western

Europe has now taken a slight lead over the United States, both in the scope of its program and in the usual measures of plasma performance in the large devices.

The Japanese tokamak program began in the early and middle 1970s, but the Japanese devices did not make any major or fundamental contributions to world tokamak research during this period. By 1975, the development of fusion had become a major objective of Japan, and the focus of a rapidly expanding program was a large tokamak, JT-60, to be constructed at a new Japanese Atomic Energy Research Institute (JAERI) site. To prepare for JT-60, Japan executed an agreement with the United States for collaborative experimental work on the Doublet III tokamak at General Atomics. The tokamak program in Japan has lacked the breadth of the programs in either Western Europe or the United States: it has been focused quite narrowly on operation of a single large device, the JT-60.

(1) Large Tokamaks

By the middle 1970s, the favorable early results on the Soviet T-3 tokamak had been followed by the successful demonstration of techniques for auxiliary, that is, non-ohmic, plasma heating in a number of tokamak devices in the United States and Western Europe. As a result, projects to construct large tokamaks, whose plasma parameters could approach reactor-like values, were initiated in Western Europe (JET), the United States (TFTR), Japan (JT-60), and the Soviet Union (T-20/T-15). By 1985, three of these large tokamaks, TFTR (1982), JET (1983), and JT-60 (1985) had become operational. The T-15 tokamak, which was a smaller substitute for a more ambitious reactor-prototype device, T-20, achieved an initial plasma in late 1988, but is still not in full experimental operation. In the late 1970s, the Soviet Union also initiated a project to build a deuterium-tritium tokamak, T-14/TSP, that uses adiabatic compression to reach peak plasma parameters. The TSP device is treated here as a "medium-size" tokamak.

The objectives of all four members of the large-tokamak generation are broadly similar: to approach the plasma conditions of a fusion reactor as closely as possible, and to establish a base of knowledge of reactor-like plasmas sufficient for the design and optimization of future tokamaks operating at or near ignition conditions. At the time of initiation of the large tokamak projects, however, there were important differences of emphasis among the four devices within these broadly similar objectives, and this led to significant differences in the design of the machines and their auxiliary systems.

The design of JET, which was influenced by highly favorable confinement projections, sought to maximize the plasma current density, to provide the largest possible ohmic heating input. This was done both by reducing the aspect ratio and by elongating the plasma cross section. To take advantage of long confinement times and to allow time for the still-relatively-weak ohmic heating to produce equilibrium temperatures, the machine pulse length needed to be as long as possible. With the addition of strong auxiliary heating, the large projected density-confinement-time products in JET would allow break-even regimes to be reached in which "thermonuclear" reactions (that is, reactions among thermal ions) would dominate the fusion reactivity. The choice of auxiliary heating technique was thus relatively open, and the influence of the strong radio-frequency (RF) program in Europe led to the adoption of ion cyclotron heating for providing more than half of the auxiliary power.

The design of TFTR, on the other hand, was based on relatively conservative confinement projections and on extreme concern regarding the possible effects of impurities in the plasma. Accordingly, the auxiliary-heating power density was maximized and fusion break-even was to be achieved at relatively modest density-confinement-time products by the use of "two-component" reactions (that is, reactions between beam ions and thermal ions). For these purposes, the machine pulse length could be quite modest. The auxiliary heating needed to be primarily in the form of neutral-beam injection, with the beam energy somewhat above the energy of the peak of the deuterium-tritium reaction cross section. Both JET and TFTR were designed for the eventual use of deuterium-tritium fuel.

The design of JT-60 was probably influenced more by TFTR than by JET, and neutral-beam injection at fairly high power density was chosen for the primary auxiliary heating technique. However, the desire to make JT-60 as reactor-prototypical as possible led to a design with a relatively long machine pulse length, as well as a radio-frequency (lower hybrid) system designed to demonstrate non-inductive current drive. A poloidal divertor was provided for impurity control.

Because of a commitment made to the Japanese authorities, JT-60 was to operate only in hydrogen.

Unique among the four large tokamaks, the T-15 uses superconducting toroidal-field coils—a choice mandated by limitations in power available at the Kurchatov site in Moscow. Since shielding is not provided, the T-15 will operate only with hydrogen. The auxiliary power will be mainly in the form of electron cyclotron heating—a technique in which the Soviet Union has established and maintained a leadership position.

The construction of JET and JT-60 made extensive use of the industrial capabilities of Western Europe and Japan, respectively. In both cases, a large-scale industrial research and development (R&D) program preceded the start of construction. The subsequent manufacturing contracts were competitive fixed-price contracts, but among a limited group of bidders who had become qualified through their research and development activities. This process is more cooperative and less adversarial than are procurement practices in the United States. Both JET and JT-60 were completed essentially on schedule, although the early pace of the JET project was slowed by the administrative complexities of international collaboration. In both cases, the machine operating parameters have slightly exceeded the original design specifications. Ironically, the delays and engineering difficulties with T-15 seem to be due mainly to the role of industry in its construction. Previous Soviet tokamaks, as well as the superconducting toroidal-field coils for T-15, have been built at the D. V. Yefremov Electrophysical Apparatus Research Institute in Leningrad. However, several major components of T-15, including the cryogenic system, have been built by Soviet industry, where quality-control has clearly not been adequate.

The staffing and operation of JET have been an international effort involving essentially all of the countries of Western Europe. In the case of JT-60, a significant industrial involvement has continued throughout its operating phase and has supplemented the relatively limited number of direct JAERI staff. Both machines have operated reliably, as has TFTR. In all three cases, however, significant faults have developed in toroidal-field coils, sometimes requiring extensive down-time for repair; JET is presently out of operation while an octant of the machine (three coils) is replaced. It is too early to assess the quality of operations on T-15, which will be staffed by the Kurchatov experimental team presently working on the T-10 tokamak.

The financial resources available for the operation of JET and JT-60 are roughly comparable, and they are substantially higher than those for TFTR. However, in the case of JET and JT-60, a significant fraction of these resources is presently going into machine and auxiliary-system enhancements and upgrades. When these are subtracted out, the base operating costs of the three machines are found to be quite similar.

The parameters of the four large tokamaks and their auxiliary systems are listed in Table I.2. In the case of TFTR, JET, and JT-60, the parameters are those that had been achieved by the end of 1989. In the case of T-15, these machines and auxiliary heating parameters can not be achieved until 1991. Upgrades and future enhancements are discussed in Section B.1.b; JT-60 has already been shut down to prepare for the upgrade, JT-60U.

Of the three large tokamaks that have operated, JET has been the most adaptable in terms of plasma configuration and mode of operation, and it has explored neutral-beam and ion-cyclotron heating of both limiter and divertor plasmas over a wide range of plasma currents. The JET "divertor" is of the "open" type and is obtained by bringing the X-point of the magnetic separatrix just inside the vacuum vessel. This has been sufficient, however, for JET to have the clearest demonstration, among the large tokamaks, of the favorable "H-mode" of enhanced confinement, in which the energy confinement time can be twice its value in the less favorable "L-mode."

Because of its relatively high heating power density, the TFTR has succeeded in maintaining a slight lead in ion temperature and (deuterium-deuterium) fusion neutron production. In addition, TFTR's energetic—and therefore highly penetrating—neutral beams have led to the discovery of a different regime of enhanced confinement due to strong central peaking of the plasma density profile. By operating at high power and relatively low current, the TFTR was first to confirm the existence of the theoretically predicted "bootstrap" current that arises in high-beta-poloidal, low-collisionality tokamaks. Both JET and TFTR obtain their best results when operated with deuterium.

Table I.2

PARAMETERS OF LARGE TOKAMAKS AND THEIR AUXILIARY SYSTEMS (1989)

	TFTR	JET	JT-60	T-15*
Year Operational	1982	1983	1985	1988
Major Radius of Plasma (m)	2.5	3.0	3.0	2.4
Minor Radius of Plasma (m)	0.85	1.2 x 2.1	0.90	0.7
Toroidal Field on Axis (T)	5.2	3.5	4.8	3.5
Maximum Plasma Current (MA) (with Divertor)	2.5	7.0 (5.0)	3.5 (2.7)	1.4
Plasma Cross Section	Circular	D-shape	Circular	Circular
Limiter/Divertor (Null Location)	Limiter	Limiter Single or double-null	Outer-null Lower-null	Limiter
Working Gases	H/D/T	H/D/T	H	H
Neutral Beam				
Power (MW)	30	20	25	9
Energy (keV)	120 (D)	80 (D)	75 (H)	80 (H)
Ion-Cyclotron				
Frequency (MHz)	47-80	25-55	120	-
Source Power (MW)	5	24	4	-
Absorbed Power (MW)	4	18	2	-
Electron Cyclotron				
Frequency (GHz)	-	-		83
Source Power (MW)	-	-		10
Absorbed Power (MW)	-	-		6
Lower Hybrid				
Frequency (GHz)	-	-	1.7-2.2	-
Source Power (MW)	-	-	20	-
Absorbed Power (MW)	-	-	7	-
Heating Pulse Length (s)	2	20 (RF)	6	1-5 (NB)
Machine Pulse Length (s)	3	30	10	5

* Operation at these parameters scheduled for 1991.

The inability of JT-60 to operate with deuterium has seriously limited its performance, although the impact of this restriction could not have been anticipated at the start of the project. Although JT-60 was configured from the outset with a divertor, the location of the divertor null was chosen poorly from the physics viewpoint, and the H-mode was not achieved. Even when JT-60 was reconfigured, in 1987-1988, to have the more conventional "lower-null" divertor, an H-mode with convincingly improved confinement was still not realized—presumably due to the restriction to hydrogen operation. However, JT-60 has been successful in demonstrating lower-hybrid current drive at high plasma current and has achieved record values of current-drive efficiency.

The "best" plasma parameters that have been achieved in the three large tokamaks that have operated are listed in Table I.3. In each case, the parameters are for the discharge that gives the highest value of the product of central ion density, energy confinement time, and central ion temperature. The JET discharge is from 1989, and had beryllium gettering over much of the vacuum-vessel surface. The values given for Q_{DT} are those projected for a similar experiment conducted in an equal mixture of deuterium and tritium. Overall, the best parameters achieved in JET and TFTR are seen to be very similar, and those of JT-60 are not far behind.

(2) Medium-Size and Small Tokamaks

Table I.4 presents the medium-size tokamaks in operation, or about to be brought into operation, in the United States, Western Europe, Japan, and the Soviet Union, and lists their major areas of programmatic emphases. In the United States, the DIII-D tokamak has a program of relatively broad overall scope, approaching that of the large tokamaks.

The program of medium-size, national tokamak facilities in Western Europe is strong and continuing. It includes a mix of mature and new devices that will ensure continuity of research productivity for at least the next five years. Radio-frequency heating and current drive in all frequency ranges, long-pulse operation, and impurity control are all areas of programmatic emphasis and strength.

Western Europe also has a diverse collection of small tokamaks, including devices in most of the smaller countries.

Table I.3
COMPARATIVE BEST PLASMA PARAMETERS ACHIEVED IN LARGE TOKAMAKS
(Data from the same shot)

	TFTR (1988)	JET (1989)	JT-60 (1987)
Plasma Current (MA)	1.4	4.0	3.2
Heating Power, Injected (MW)	22 (NB)	18 (NB)	21 (NB)
Limiter/Divertor	Limiter	Divertor	Limiter
Ion Temperature (keV)	27	23	3.7
Electron Temperature (keV)	8.5	8.5	3.0
Stored Plasma Energy (MJ)	3.7	8.0	3.1
Confinement Enhancement Factor Over L-Mode	~3	~2	~1
Lawson Parameter: Product of Central Ion Density and Energy Confinement Time ($m^{-3}s$)	1.2×10^{19}	4×10^{19}	1.6×10^{19}
Performance Measure: Product of Lawson Parameter and Central Ion Temperature ($m^{-3}s$ keV)	3×10^{20}	8×10^{20}	6×10^{19}
Projected Q-Value in Deuterium-Tritium Operation	0.5	0.7	-

Table I.4
MEDIUM-SIZE TOKAMAKS
(Presently operating or to be in operation by the early 1990s)

Ip (MA)	United States	Europe	Japan	Soviet Union
> 3.0	DIII-D - Shaping - Divertor - NBI - ECH	-	-	-
2.0 - 3.0	C-MOD - High field - Shaping - Divertor - ICH	ASDEX-U - Shaping - Divertor - NBI - ICH Tore Supra - NbTi - Long Pulse - NBI - ICH - LHCD	-	-
1.0 - 2.0	-	FT-U - High Field - LHH	-	TSP - Adiabatic Comp. - ICH - D-T
0.3 - 1.0	PBX-M - Shaping - Second Stab. - NBI - LHCD TEXT - Transport - ECH MTX - ECH (FEL)	TEXTOR - Plasma-Wall - ICH ASDEX (shuts down 1990) - Divertor - NBI - ICH - LHCD COMPASS - Long Pulse - Shaping - ECH	JFT-2M - Shaping - Divertor - NBI - ICH - LHCD JIPP-T-IIU - ICH TRIAM-1M - Nb_3Sn - Long Pulse - LHCD	T-10 (shuts down 1990) - ECH Tuman-3 - Adiabatic comp.

Medium-size and small tokamaks are relatively poorly represented in the Japanese program. JAERI will continue to operate one medium-size tokamak (with a good record for innovative research) in addition to JT-60, but the redirection of the Ministry of Education fusion program toward the heliotron/torsatron concept will probably result in a sharp curtailment of tokamak research in the universities.

For the purpose of the present assessment, the important Soviet tokamak TSP has been classed as a "medium-size" device. Located at the Troitsk branch of the Kurchatov Institute, the TSP is unique in the world program in that it seeks to use adiabatic compression to achieve a break-even level of plasma performance, eventually in deuterium-tritium. Present-day scaling laws indicate that TSP may fall substantially short of its plasma objective, and practical difficulties may preclude the introduction of tritium. Nonetheless, TSP has unique capabilities that should allow it to explore some interesting plasma regimes. When the medium-size tokamak T-10 shuts down in early 1990, the resources of the tokamak group at the Kurchatov Institute will be focused almost entirely on T-15.

The Ioffe Physical-Technical Institute in Leningrad is expected to maintain a strong and innovative program on small and medium-size tokamaks, but is dependent upon relatively uncertain funding through the Soviet Academy of Sciences.

(3) Diagnostics

The complement of diagnostics on the four large tokamaks is at least sufficient to support the objectives of the experimental programs on these devices. In the case of TFTR, JET, and JT-60, there are multi-channel, high-spatial-resolution instruments for obtaining the profiles of most of the plasma parameters, as well as several cases of multiple measurements of the same plasma parameter. The diagnostic complement for T-15 is much less sophisticated in this regard. Many of the diagnostics for JT-60 were developed as a direct result of bilateral exchanges with TFTR. In the difficult area of ion-temperature-profile measurements, the United States has taken a clear lead, with instruments operational on both TFTR and DIII-D. Among the large tokamaks, only TFTR is installing diagnostics to measure the fine-scale fluctuations that are believed to be the underlying cause of anomalous cross-field transport.

Diagnostics development activities are underway in all of the countries with major fusion programs. The efforts in Japan and the Soviet Union on alpha-particle diagnostics—for use in future deuterium-tritium tokamaks—are particularly noteworthy.

(4) International Thermonuclear Experimental Reactor

The ITER Conceptual Design Activity, which began in 1988 and will extend through 1990, was established, under the auspices of the IAEA, as a quadripartite activity involving the European Community, Japan, the Soviet Union, and the United States. The major roles and responsibilities within the Conceptual Design Activity were apportioned as evenly as possible among the four parties. Thus, the United States supplies the Chairman of the ITER Council, the Soviet Union provides the Chairman of the International Scientific and Technical Advisory Committee (ISTAC), the Managing Director from Japan chairs the Management Committee, and the European Community provides the site for joint design work, that is, Garching, near Munich.

The major scientific and technical roles in the ITER Design Team have also been apportioned evenly. There is a matrix structure of four Project Units and eight Engineering Design Units, and each party provides the leadership of one of the Project Units and two of the Engineering Design Units. Each party spends the equivalent of $16 million to $18 million annually on the ITER Activity—split about equally between design and R&D. The contribution to ITER from the Soviet Union represents a much larger fraction of its national fusion budget than do the contributions from the other three parties.

Since the formal structure of the ITER Activity is so symmetrical, an assessment of the relative contributions of the four parties must be based upon the impressions of Design Team participants or ISTAC members from the United States, and these are necessarily somewhat subjective. Nonetheless, an attempt has been made in Table I.5 to provide a comparative ranking of the four parties' contributions to ITER in various areas of design and R&D.

Table I.5
COMPARATIVE RANKING OF CONTRIBUTIONS TO ITER

	United States	Europe	Japan	Soviet Union
Physics				
Design	1	3	3	2
Experimental R&D	1	1	3	3
Engineering Design and R&D				
Magnets and Structures	2	1	2	4
Neutral-Beam Systems	1	3	2	4
Radio-Frequency Systems	3	1	3	1
Plasma-Facing Components	3	1	2	4
Nuclear Design and R&D				
Fuel Cycle	2	1	2	4
Blanket	2	2	1	4
Maintenance	3	2	1	3
Systems Engineering and Costing	1	3	2	3

1 = best; 2 = second best; 3 = third best; 4 = weakest.

The European Community has established a dominant position in almost all aspects of engineering design of ITER, probably due to the proximity of the highly regarded Next European Torus (NET) team. Both Japan and the Soviet Union have contributed strongly to the joint design activity, and they have also taken steps to ensure that their national programs are readily responsive to ITER's R&D needs. All four parties have contributed about equally to physics aspects of the design activity, although the United States has the formal lead in this area.

(5) Summary Ranking

An attempt has been made in Table I.6 to provide a comparative rank ordering, albeit quite subjective, of the present capabilities of the United States, Western Europe, Japan, and the Soviet Union in various aspects of tokamak research.

It should be emphasized, however, that all four countries (or groups of countries) have broad and comprehensive capabilities in tokamak research, so that some of these rankings reflect relatively minor variations in scientific and technical strengths—or, in some cases, simply differences in program emphasis.

b. Outlook

The relative standing of the United States, Western Europe, Japan, and the Soviet Union in tokamak research of the 1990s will be determined largely by the results obtained on the large tokamaks TFTR, JET, JT-60, and T-15, respectively. In the case of the United States, the results from TFTR will be augmented importantly by those from the medium-size tokamak DIII-D, which has major programs in the confinement and stability of strongly elongated plasmas and in high-power neutral-beam and electron-cyclotron heating, and from the Alcator C-Mod tokamak at MIT (to be operational in late 1990), with major programs in the confinement and heating of dense, shaped plasmas at high magnetic field. In the case of the Soviet Union, the results from hydrogen operation in T-15 may be supplemented by those from adiabatic compression of deuterium-tritium plasmas in the TSP tokamak, although the outlook for tritium operation in TSP is clouded by technical and political uncertainties.

Both JET and JT-60 will benefit from major machine upgrades and enhancements of auxiliary capabilities that are being implemented in the early 1990s. In the case of JT-60, an enlarged vacuum vessel is being constructed to accommodate the largest D-shaped plasma that can be fitted within the existing toroidal-field coils; the upgraded machine is called JT-60U and will operate in 1991. Table I.7 lists the planned upgrades and enhancements of the four large tokamaks that have been approved, or for which approval seems probable.

The outlook for JET is most favorable. Many of the performance-enhancing items listed in Table I.7 are already well into fabrication, such as beryllium divertor plates, a lower-hybrid current-drive system for sawtooth control, increased ion-cyclotron heating power, and an increase in the neutral-beam energy to 140 keV. Just recently, the proposed extension of JET's operating lifetime through 1996 was formally approved, thereby not only providing time for the

Table I.6

COMPARATIVE RANKING OF PRESENT CAPABILITIES IN TOKAMAK RESEARCH

	United States	Europe	Japan	Soviet Union
Program Resources and Scope (Large Tokamaks)	2	1	2	4
Program Resources and Scope (Small- and Medium-Size Tokamaks)	1	1	4	3
Tokamak Design and Construction	3	1	1	4
Machine and Auxiliary Systems Operation	1	1	1	4
Neutral Beam Injection	1	1	1	4
Ion Cyclotron Heating	2	1	3	3
Electron Cyclotron Heating	2	3	4	1
Lower Hybrid Heating and Current Drive	3	2	1	3
Diagnostics (General)	1	2	3	4
Diagnostics for D-T Plasmas	1	2	2	2
Data Acquisition and Analysis	1	2	3	4
Data Interpretation and Theoretical Support	1	1	4	1
Advanced Tokamak Concepts	1	2	4	3
Tokamak ETR Studies	3	1	1	3
Tokamak Commercial-Reactor Studies	1	2	3	4

1 = best; 2 = second best; 3 = third best; 4 = weakest.

orderly completion of JET's existing activities, but also creating an opportunity for further additions to its program. These further additions are likely to exploit JET's long-pulse capabilities, to test modes of plasma operation that are prototypical of ITER, especially in the area of impurity control. A novel single-null divertor concept has been proposed for JET, in which a new internal divertor-coil moves the X-point well inside the vacuum vessel to provide space for extended exhaust channels, thereby allowing for control of plasma recycling. The introduction of tritium will be postponed until the final period of JET's operating lifetime, that is, 1995-1996.

The principal features of JT-60U are a doubling of the plasma current and provision (and approval) for operating with deuterium. Upgraded wave-guide launchers will maintain JT-60's position at the forefront of research in lower-hybrid current drive. It seems likely that negative-ion beams will be selected for "second-stage" heating and current drive in JT-60U, and there is indication that the present negative-ion-beam development program in Japan will be successful in producing a 20-MW system by the middle 1990s. If so, there is a distinct possibility that JT-60U will take a clear lead in world tokamak research, especially in ITER-prototypical heating and current-drive experiments, by 1994-1995.

Empirical scaling laws may be used to make projections of plasma parameters in the upgraded JET and JT-60U—in particular, to assess relative machine capabilities in terms of the usual measure of plasma performance: the product of central density, energy confinement time, and central ion temperature. Using L-mode confinement scalings and assuming the plasma currents available in limiter modes of operation, the JT-60U is projected to perform better than JET, although the differences are not large in relation to the uncertainties in the scaling laws. However, the maximum plasma current may not, in practice, be compatible with good confinement in JT-60U, because it requires a low value of the safety factor q at the plasma edge; the safety factor is in the range where macroscopic instabilities can seriously degrade confinement—or lead to plasma disruption. Even at a reduced current of 5 MA, however, the empirical L-mode scaling laws predict that JT-60U will perform about as well as JET. On the other hand, there could be degradation of confinement due to the toroidal field ripple, which is relatively large in JT-60U.

Table I.7

PLANNED MACHINE UPGRADES AND ENHANCEMENTS OF AUXILIARY CAPABILITIES (1990-1996)

(See Table I.2 for baseline parameters)

	TFTR	JET	JT-60U	T-15
Minor Radius (m)	0.85	1.2 x 2.1	1.0 x 1.5	0.7
Toroidal Field (T)	5.2	3.5	4.2	4.5
Plasma Current (MA)				
Limiter	3.0	7.0	7.0	2.3
Divertor	-	5.0	6.0	-
Edge Safety Factor (q) at Maximum Current	~2.9	~3.2	~2.0	~2.4
Divertor Type	-	Single null Closed Pumped	Single null Open	-
Limiter/Divertor Plate	Carbon-carbon	Beryllium	Carbon-carbon	-
Neutral Beam				
Power (MW)	30	20	40	9
Energy (keV)	120 (D) 120 (T)	140 (D) 160 (T)	120 (D)	80 (H)
Ion-Cyclotron				
Source Power (MW)	16	32	10	-
Electron Cyclotron				
Source Power (MW)	-	-	-	10
Frequency (GHz)	-	-	-	124
Lower Hybrid				
Source Power (MW)	-	12	24	-
Frequency (GHz)	-	3.7	1.7 - 2.2	-
Additional Features	- Fluctuation diagnostics - Tritium	- High-speed pellets - Feedback for m=2 - Tritium	- Deuterium operation - Negative ion beams	- Timing uncertain

Both the upgraded JET and JT-60U should be capable of accessing the more favorable H-mode of confinement in divertor operation, but the improvement in confinement will be partially offset by having to work at slightly lower plasma current. Assuming that confinement in the H-mode is twice that in the L-mode, both JET, with a current of 5 MA, and JT-60U, with a current of 4 MA, should be capable of reaching plasma regimes in which the product of central ion density, energy confinement time, and central ion temperature is in the range 12-15 x $10^{20} m^{-3} s$ keV. In these regimes, the deuterium-tritium-equivalent Q-value would be in the range of 1.0 to 1.5, with more than half of the fusion reactivity coming from reactions among thermal ions. Eventually, JET will be able to explore this regime in actual deuterium-tritium plasmas.

Enhancements of TFTR's capabilities will be limited to an increase in the ion-cyclotron heating power, installation of carbon-carbon composite tiles in high-heat-flux regions, and relatively early introduction of tritium. The near-term program will emphasize confinement studies with upgraded diagnostics. If its favorable confinement regime can be extended to higher plasma currents, the TFTR will have the capability to achieve the first demonstration of fusion break-even ($Q \geq 1.0$) in deuterium-tritium plasmas.

The investigation of plasma confinement on T-15, using a combination of high-power electron-cyclotron heating at 83 GHz and neutral-beam injection, presently planned for the period 1991-1992, should provide significant information that cannot be closely matched in non-Soviet experiments. (The DIII-D program at General Atomics comes closest.) If Soviet researchers are successful in developing higher-frequency (124 GHz) gyrotrons, the T-15 device, operated at higher toroidal field, will provide a truly unique test of the application of electron-cyclotron heating at reactor-like plasma parameters.

The program plans of the four large tokamaks through 1996 are indicated in Table I.8.

Looking beyond the present generation of large tokamaks, the outlook is clouded by ITER funding uncertainties and by the very high cost of "next-step" devices, that is, engineering test reactors. Both Western Europe and Japan have the technical resources—and clearly also the financial means—to construct their respective engineering test reactors, NET and FER (Fusion Experimental Reactor), without external participation. On the other hand, the poor performance of industry on the construction of T-15 casts doubt on the Soviet capability to construct their national next-step device, the OTR. The United States has discontinued design work on a national engineering test reactor. In even the best of circumstances, there will be a long hiatus in mainline experimental tokamak research from the middle 1990s, when the large tokamaks of the present generation are scheduled to complete their programs, to the early 2000s, when an engineering test reactor could become operational.

Table I.8
EXPERIMENTAL PROGRAM PLANS FOR LARGE TOKAMAKS

	1990	1991	1992	1993	1994	1995	1996
TFTR	Carbon-carbon tiles Fluctuation diagnostics	High-power ICH 3 MA		Tritium D-T break-even		Shutdown	
JET	Shut-down	Limiter/divertor expts at 7/5 MA Beryllium tiles and screens LHCD for sawtooth control High-speed pellet		Pumped divertor Long-pulse impurity control		Tritium D-T break-even	
JT-60U	Constr.	Limiter expts at 7 MA Divertor expts at 6 MA High-power heating & current drive Carbon-carbon divertor armor		Negative-ion beam		Uncertain (shutdown?)	
T-15	OH Install NB RF	Auxiliary heating NB, ECH		Higher frequency ECH (timing uncertain)		Long-term plans not discussed	

Only the United States is considering an intermediate-scale device, the Compact Ignition Tokamak (CIT), which could be operational before the end of the century. The CIT would be a high-field, copper-coil tokamak with a toroidal field of 10 to 11 T and a maximum plasma current of 11 to 12 MA, and would explore the ignited-plasma regime at short pulse length. Projected values for the product of central ion density, energy confinement time, and central ion temperature are in the range required for self-ignition in deuterium-tritium, that is, about 10^{22} $m^{-3}s$ keV, or six to nine times larger than the values expected to be achieved in either JET or JT-60U. The pulse length of CIT would be about 5 seconds. A smaller, even-higher-field ignition tokamak, called Ignitor, has been proposed by Italy and is presently undergoing formal review within EURATOM. Its chances of authorization are not thought to be high, unless almost all of the cost is borne by Italy's national program.

Among the four ITER parties, the European Community maintains the strongest design effort on an equivalent national device, the NET. Although cost considerations will require that all reasonable possibilities for an international ITER-like project are pursued first, the European Community can be expected to authorize construction of NET in about 1995 if ITER is not progressing into construction by that time. To reduce costs, the European Community may encourage some level of international participation in NET.

Although the Japanese at first seemed lukewarm toward participation in ITER, perhaps because they still expected early authorization of their national FER project, their enthusiasm for ITER seems to have increased markedly. Japan is now seen as likely to join a future phase of the ITER Activity, even to the extent of joining a multinational construction project if this were to materialize. Should ITER not go forward, it is probable that successful results on JT-60U will lead to authorization of the Japanese engineering test reactor, FER; but this device will be somewhat less ambitious—and less costly—than the present ITER design.

The main thrust of Soviet strategy for future fusion development has, for many years, been the internationalization of the design and construction of a tokamak engineering test reactor. Thus, ITER represents the major element in long-range fusion planning in the Soviet Union. Failing a continuation of the present quadripartite agreement, it seems likely that the Soviet Union will seek a bilateral or trilateral arrangement under which an ITER-like device could be built.

2. Alternate Confinement Approaches

a. Overview

In this section, we summarize the status of world fusion research on the following alternate confinement approaches:

- stellarators;
- reversed-field pinches; and
- mirrors.

Here, "alternate" means alternative to the tokamak approach. On an international basis, all of the alternate approaches are pursued at a much lower level than tokamaks. Among the alternate approaches, stellarators are pursued most vigorously. While stellarators and reversed-field pinches use toroidal magnetic field geometry, mirrors use a linear (open-ended) confinement geometry.

(1) Stellarators

While the US stellarator experimental program was terminated (at the national laboratory level) in favor of tokamak development in 1970 and remained dormant until initial operation of the Advanced Toroidal Facility (ATF) at Oak Ridge in 1988, the Soviet, West European, and Japanese programs continued research in this area. The Japanese and West European programs produced experimental results in the period 1979-1982 that led to a revival of international interest in the stellarator as a possible fusion reactor. Despite continued Soviet interest in stellarators, the Soviet experimental program did not participate in this renaissance, although its theoretical contributions were strong and relevant.

The Japanese stellarator program in the period 1980-1989 centered around the Heliotron-E device at the Kyoto Plasma Physics Laboratory. This machine has been the leading stellarator experiment in the world program. It has produced world-record stellarator parameters for ion temperature, plasma pressure relative to magnetic pressure, and the Lawson confinement parameter. The Heliotron concept was developed by Professor K. Uo (now retired), and is based on large aspect ratio, and high rotational transform and shear.

The West European program had only slightly less impact in the 1979-1989 time period. The Wendelstein VII-A device (IPP-Garching, West Germany), holds the remaining stellarator records (for electron temperature and plasma pressure). The Wendelstein approach is theoretically the most self-consistent stellarator configuration found in the world fusion program, and a series of devices dedicated to moderate transform and zero magnetic shear has been built at IPP-Garching since the middle 1960s (W-II, W-VII-A, W-VII-AS).

The Soviet stellarator program has been carried out by noninteracting (and even noncompeting) groups at the General Physics Institute in Moscow and at the Khar'kov Physical-Technical Institute in the Ukraine. Historically, both groups have been relatively unproductive in the experimental area. However, the emergence of new experimental management at Khar'kov in the middle 1980s has resulted in some recent improvement there.

Each of the fusion programs has brought new stellarator experiments into operation during the past two years: W-VII-AS in West Germany (IPP-Garching), the Compact Helical System (CHS) in Japan (Ministry of Education), ATF in the United States (Oak Ridge), and U-3/U-3M at Khar'kov in the Soviet Union. In addition to these newly operating machines, Japan continues to run the successful Heliotron-E experiment, albeit with a reduced budget and staff. Also, the Soviet L-2 experiment at the General Physics Institute in Moscow has carried out electron cyclotron heating experiments at a modest level. The machine parameters of the presently operating stellarator devices are summarized in Table I.9.

For comparison, we have chosen the "magnetic size" of the device (proportional to the stored magnetic field energy, $\sim B^2 R a^2$) as the figure-of-merit for confinement capability. This is shown in the last column of Table I.9, and is normalized to the largest value (that for W-VII-AS). The existing machines vary by a factor of 25 in this parameter.

Table I.9
MAJOR OPERATING STELLARATORS

Device	Institution	Minor Radius a (m)	Major Radius R (m)	Magnetic Field B (T)	Size (~ $B^2 R a^2$) (Ratio to W-VII-AS)
W-VII-AS	IPP-Garching (West Germany)	0.2	2.0	3.0	1.00
ATF	Oak Ridge (United States)	0.27	2.1	2.0	0.85
Heliotron-E*	Kyoto University (Japan)	0.2	2.2	2.0	0.49
U3-M	Khar'kov Physical-Technical Institute (Soviet Union)	0.15	1.0	3.0	0.28
CHS	National Institute for Fusion Studies (Japan)	0.2	1.0	1.5	0.13
L-2*	General Physics Institute (Soviet Union)	0.11	1.0	1.5	0.04

* Near maximum expected performance.

The magnetic size parameter is only a rough guide to the *maximum* possible stored magnetic energy available for confinement in a given device. None of the newly operating machines has yet surpassed the parameters of Heliotron-E or W-VII-A. The ATF and U-3M facilities encountered field errors during initial operation; in the presence of field errors, the effective minor radius is reduced and the figure of merit decreases as a^2. Also, W-VII-AS had initial difficulties in reaching its design magnetic field, and this reduced its "size" proportionately.

These machines have since overcome the initial difficulties, and the operating parameters are improving. Heliotron-E and L-2 have attained performance near the expected optimum and are reaching the end of their most productive periods.

New devices are under design or construction in Japan, West Germany, and the Soviet Union (Khar'kov). The United States has no approved follow-on stellarator facility to the ATF experiment. The relative parameters and status of these next-step projects are shown in Table I.10.

Table I.10
NEXT-STEP STELLARATOR PROJECTS

Device	Institution	Minor Radius a (m)	Major Radius R (m)	Magnetic Field B (T)	Size (~ $B^2 R a^2$) (Ratio to W-VII-X)	Status
W-VII-X*	IPP-Garching	0.65	6.5	3.0	1.0	Pre-design
LHD	National Institute for Fusion Studies (Japan)	0.55	4.0	4.0	0.8	R&D
U2-M	Khar'kov Physical-Technical Institute	0.22	1.7	2.4	0.02	Construct

* As described at the IAEA Technical Committee meeting on stellarators, Oak Ridge, 1989. A new and slightly smaller design (a - 0.53 m, R = 5.5 m) has recently been presented.

The most ambitious project is the Large Helical Device (LHD) at the National Institute for Fusion Studies, a new laboratory operated by the Ministry of Education in Toki, Japan. New facilities are being constructed, and R&D activities are underway for the LHD project. The LHD is very similar, conceptually, to the ATF torsatron in the United States, with moderate transform and shear, though the "magnetic size" of LHD is about 30 times that of ATF.

Plans for the largest device come from the W-VII-X design study at IPP-Garching. The W-VII-X design optimizes the modular stellarator configuration to reduce pressure-driven currents and to reduce diffusion losses due to field inhomogeneity. The Khar'kov group in the Soviet Union is completing a medium-scale stellarator device, U-2M, to be operational in 1991. It is apparent from Table I.10 that U-2M is at least one generation behind. Even though it is the next step for the Soviet program, U-2M is not equivalent in capability to LHD or W-VII-X.

In addition to the "home resources" of each stellarator program, there are also varying degrees of participation in international exchanges with the experimental programs of the other groups. The Japanese program in stellarator/torsatron research is carrying out an active program of experimental participation in the ATF and W-VII-AS programs, while the US/Soviet bilateral exchange continues in the stellarator area.

(2) Reversed-Field Pinches

Research on reversed-field pinches (RFPs) began with the Zeta device at Culham Laboratory in the 1960s. Research on this alternate confinement approach, notably the work of British physicist J. B. Taylor, led to the important concept of helicity conservation and minimum energy states in a plasma. In the RFP, the minimum energy state is one in which the toroidal field is reversed on the outside of the plasma.

Two new RFP devices, which are medium-scale and comparable in size and current, are being built. These are the RFX at Padova (Padua) University in Italy, and the ZT-H facility at Los Alamos National Laboratory. These two programs have very competent staffs, and both RFX and ZT-H will play an important role in further advancement of the reversed-field pinch confinement approach. There is also a small RFP facility, called TPE-1RM-15, at the Electrotechnical Laboratory in Japan. The TPE-1RM-15 facility has made important contributions to the basic understanding of confinement scaling at high current densities and electron temperature.

(3) Mirrors

Mirror-based fusion research suffered a major international setback when the United States decided to end this line, mothballing the MFTF-B experiment at Lawrence Livermore National Laboratory and terminating the TARA experiment at the Massachusetts Institute of Technology. At the time of this decision, the United States had the leading mirror program, the only other competitors being the GAMMA-10 tandem mirror at Tsukuba University in Japan, and Soviet experiments at the Kurchatov Atomic Energy Institute and the Nuclear Physics Institute in Novosibirsk.

Despite the US decision, Soviet mirror research continues, with perhaps some setbacks to morale. New results have been reported from AMBAL, the multiple-mirror GOL device, and the Gas Dynamic Trap at Novosibirsk, and from the OGRA-4 and PR-8 machines at Kurchatov. The results from the Gas Dynamic Trap are cited as providing support for a possible compact fusion neutron source (see Section II.C.2). Theoretical work also continues at a low level on optimizing the combined mirror-stellarator approach (DRAKON), at the Kurchatov Institute.

The Japanese GAMMA-10 group is pursuing optimization of tandem mirrors, and the work is of high quality. However, significant new results have not been reported for several years.

b. Outlook

The Japanese stellarator program, taken as a whole, must be regarded as the world leader. This view is based both on the success of present confinement devices (Heliotron-E and CHS), as well as on the ambitious nature of the LHD project. In terms of the "magnetic size" figure-of-merit alone, the projected West European W-VII-X device is about 20 percent "larger" than the LHD, but the Japanese Ministry of Education has instituted a new laboratory for the LHD project and has already started R&D work. Meanwhile, the W-VII-X project remains a paper study and its future is linked to the decisions to be made about the West European NET project and ITER. These tokamak decisions might also threaten the JAERI tokamak program, but the independent, Ministry of Education LHD program should be relatively unaffected. The US program has no approved follow-on to ATF, and the Soviet Union's next step stellarator device is really comparable to the present generation of devices elsewhere in the world.

The ATF is the largest operating stellarator, and is likely to be the near-term focus for much of the supporting confinement physics for LHD. The configuration of LHD is very similar to ATF (LHD is scaled up from ATF by a factor of 2 both in radio and magnetic field), and a strong program of Japanese participation in ATF experiments is planned. Operation of Heliotron-E is being reduced, and CHS is a relatively small device. Thus, the near-term output from the Japanese program may be reduced. The degree to which the Japanese program will be competitive in the stellarator confinement physics area in the near term (one to five years) will depend upon the mix of resources given to continued operation of the Heliotron-E and CHS facilities, compared with LHD construction.

The Wendelstein program is pursuing an independent line, and doing very high quality work. The direct configurational connection with LHD is missing, so the prospects for direct international collaboration are less promising. However, the W-VII-X project can be carried out independently by IPP-Garching, and will be competitive with LHD if approved in a timely manner.

The Soviet stellarator program appears likely to continue, although it may be more appropriate to think of the Khar'kov activity as a Ukrainian national program rather than as part of the Soviet Union's fusion activity. It is more comparable in scale with the CASTOR tokamak in Prague than with the United States, West European, or Japanese devices. The official extended title for the Khar'kov machines is "Uragan" (hurricane); the original proposal named the devices "Ukraine" but this was vetoed by Moscow; thus, the ambiguous "U-3M" nomenclature.

In the reversed-field-pinch area, as indicated earlier, two new RFP devices, comparable in size and current, are being built. These are the RFX at Padova (Padua) University in Italy, and the ZT-H at Los Alamos. Because the RFX is scheduled to begin operation in 1990, several years before ZT-H, its commissioning could move the West European program well ahead of the United States. Collaboration between the United States and Western Europe will be especially important to further progress in developing the reversed-field-pinch approach. Scientifically, the RFX and ZT-H are complementary facilities: the former is subject to slow loss of equilibrium, and the latter may be subject to instabilities. Their differences will make collaboration beneficial. While the TPE-1RM-15 facility at the Electrotechnical Laboratory in Japan will remain competitive in the short term, it will be overshadowed by the larger RFX and ZT-H facilities in the middle 1990s.

The outlook for mirror research is for reduced activity, barring an unexpected breakthrough. The Soviet Union has the largest program in this area at the Nuclear Physics Institute in Novosibirsk, and continuation of this effort appears to be assured. However, there appear to be no plans for a major increase in experimental activity. The Japanese GAMMA-10 group at Tsukuba University is pursuing concept optimization of tandem mirrors with a high-quality effort, but the long-term outlook is unclear because of the large capital costs of the LHD stellarator project.

3. Plasma Technology and Engineering

a. Overview

Experimental advances in fusion plasma physics are often only possible after advances in the technologies for components that heat, fuel the plasma, and produce the confining magnetic fields. Capability is determined by specific laboratory and/or industry expertise, and by the infrastructure that is needed to design and manufacture high-performance, reliable components and systems. For example, a successful ion cyclotron heating (ICH) effort requires specific knowledge and experience on how to design, fabricate, and operate the fusion-specific RF launching structures, as well as the existence of laboratories and industries that can provide the required RF power sources and coaxial-line components.

Plasma technology development efforts are closely tied to experimental facilities. Thus, the technology employed on present magnetic fusion research facilities and that which will be used in the future form the basis for these discussions.

In this section, specific technological capabilities are evaluated in the following areas:

- neutral beam technology;
- radio frequency heating technology;
- fueling; and
- magnets.

This is followed by a brief assessment of industrial strengths.

(1) Neutral Beam Technology

Neutral beams have been used for plasma heating on nearly every major tokamak facility in the past 15 years. Only recently, radio frequency techniques have begun to play a major role.

Relative to other techniques, the physics of beam heating is well understood and excellent predictive capability exists. It is the only technique which can drive current in a plasma with reactor parameters and for which a physics database exists. On the other hand, the technology is difficult and the extrapolation to reactor applications has been widely questioned. Beam energies in the range of 1 to 2 MeV are required for central current drive, and negative-ion sources will have to be developed with reasonable efficiency in this energy range. Advances in accelerator technology are needed to produce the needed 50 to 100 amperes of total beam current with a reasonable number of components.

Present capability is reflected by the achieved operating parameters of neutral beam systems. These data are summarized in Table I.11. The parameters shown in parentheses are those of upgrades of the JET and JT-60 beam systems planned over the next two years. While a neutral beam system (9 MW at 70 keV) is planned for T-15, it is not of the same scale as the systems in the table and will not reach full operation for several more years.

These data indicate comparable capability in positive-ion-based neutral beam technology in Japan, the United States, and Western Europe. The Soviet effort has not reached the same level of achievement, at least in part because there has not been an experimental facility to provide the need for such technology. What is not presented, and what is more difficult to quantify, is the observation that the JT-60 beams came into operation more readily and are more reliable than competing systems. This is probably due to extensive off-line testing of the components and the capability of Japanese industry to deliver quality components.

Table I.11
NEUTRAL BEAM PARAMETERS FOR THE LARGE TOKAMAKS

Device	Beam Energy	Power	Species	Pulse Length (Design)
JT-60	75 keV (120 keV)	25 MW (40 MW)	H (D)	10 s
TFTR	110 keV	30.5 MW	D	2 s
JET	80 keV (140 keV)	21 MW	D	10 s

Negative-ion source development is underway by all groups, and incremental progress is being reported. Concepts for high-current accelerators are being evaluated, but only small-scale tests have been conducted.

(2) Radio Frequency Heating Technology

Neutral beams were the earliest and, even with the recent progress on JET using ion cyclotron heating, remain the most successful and broadly used auxiliary heating method for tokamaks. Despite this success, there has been a longstanding (and increasingly successful) effort to develop various types of RF heating technologies, because of limitations in the technology of neutral beam systems and because of the added flexibility that RF can provide. The technology issue is motivated by the need for higher-energy, longer-pulse systems which have sufficient reliability and ease of maintenance to be compatible with the fusion reactor environment.

While all of the major tokamaks have one or more significant RF heating programs, different choices have been made based on device characteristics, available technology, and program objectives. Three classes of modes have received the most attention: ion cyclotron (IC), lower hybrid (LH), and electron cyclotron (EC). (The letters H or CD are often used as a suffix to these acronyms to indicate "heating" or "current drive" respectively.) The extent of this diversity is evident in Table I.12.

Table I.12
RADIO FREQUENCY HEATING SUMMARY

	Frequency	Pulse Length (Source)	Power (Design)	Power/ Source	Coupled	Date
Ion Cyclotron						
TFTR	40-60, 47 MHz	2 s (+)	4 MW, 6 MW		3.4 MW	1989
LHD	60 MHz	10 s	10 MW (in plasma)			1996
CIT	95 MHz	5s	10 (+) MW (in plasma)	1.5 MW		1997
JET	25-55 MHz	20 s	32 MW (in plasma)	2	18 MW	1988
JT-60	110 -130 MHz	10 s	6 MW	0.75 MW	3.1 MW	1987
Tore Supra	35-80 MHz	30 s (+)	12 MW	2		1990
Lower Hybrid						
JET	3.7 GHz	10 s	10 MW (in plasma)	0.5 MW		1990
JT-60	1.7-2.23 GHz	10 s	15 MW	1 MW	11 MW	1988
Tore Supra	3.7 GHz	30 s (+)	8 MW (in plasma)	0.5 MW		1990
FT-U	8 GHz	3s	8 MW	0.5-1.0 MW		1990
Electron Cyclotron						
T-10	75, 81 GHz	0.2 s	2.8, 1.6 MW	0.4 MW	2-2.5 MW	1988
T-15	83 GHz	1.3 s	10 MW	0.4 MW		1991
DIII-D	60 GHz	0.5 s (+)	2 MW	0.2 MW	1.6	1989
	110 GHz		2 MW	0.5 MW		1991
LHD	56, 112 GHz	10 s (+)	5 MW	0.5-1 MW		1997
MTX	140, 280 GHz	seconds	2 MW	2 MW		1990
Tore Supra	110 GHz	30 s	2 MW	0.35 MW		1992

The launcher is usually the limiting element in the amount of ion cyclotron power that can be effectively coupled to the plasma, and power density is a useful figure of merit. The launching structures on the highest power experiment, JET, are mounted inside the vacuum vessel. The power density is in the 200 W/cm^2 range. In contrast, the TFTR and JT-60 antennas are much smaller and are limited to port dimensions. As a result, the design power densities are much higher—about 2.5 kW/cm^2 for JT-60 and 1 kW/cm^2 for TFTR. While the power has been limited to 3.1 MW on JT-60, this corresponds to a quite respectable 1.6 kW/cm^2 power density. High-power experiments were attempted on T-10 with a novel "Christmas tree" launcher but were not successful.

For lower hybrid, as is the case for ion cyclotron technology, launcher performance limits the amount of power that can be coupled to a plasma. Present source technology is adequate for systems in the 2 to 4 GHz range; development is underway in Western Europe and the United States for sources in the 6 to 10 GHz range, needed for future facilities (including the FT-U tokamak at Frascati). The penalty (as is also the case with the present level of development for sources in the ion cyclotron frequency range) for using smaller and/or less efficient tubes is one of cost and system complexity.

As shown in Table I.12, of the large tokamaks, JT-60 has the only major lower hybrid capability, at least until the JET system begins operating. Similar experiments are not planned in either the United States or the Soviet Union.

Progress in electron cyclotron heating has been limited by the availability of high-power millimeter wavelength microwave tubes. Launchers are relatively simple and have not been a significant limitation. Virtually all electron cyclotron systems in the West and Japan have used gyrotrons built by Varian Associates in the United States. This position was established by long-term development which began in the late 1970s. During the past several years, a significant effort has begun in Western Europe with laboratory research programs and industrial efforts at Thomson CSF and Valvo.

The gyrotron concept was developed in the Soviet Union and the experiments on T-10 have, by at least a factor of two, the highest power to date. These experiments are relatively short pulse (50 to 200 ms). High-power long-range development of the type now underway in the United States and Western Europe has not been reported in the Soviet Union, even though the 10-MW T-15 system is stated to have a nominal pulse length of 1 to 3 seconds.

Increases in gyrotron power and frequency capabilities are becoming progressively more difficult. Thus, within the United States, free electron lasers (FELs), based on SDI development, are viewed as a potential alternative to the gyrotron, especially for frequencies over 150 to 200 GHz. FEL technology is being developed in Japan for a broad range of industrial and research applications, although present systems are not at the level of average power required for fusion heating.

(3) Fueling

Control of where fuel is deposited within a fusion plasma is an important tool for optimizing plasma confinement and may help minimize impurity level and helium ash buildup. The injection of high-velocity (presently 1 to 2 km/s) frozen pellets of hydrogen is widely used in present experiments for this purpose. The United States began work in this area in the middle 1970s and established a dominant position. Pellet injectors based on US technology have been used by all fusion programs. In the past five years, substantial work was started in Western Europe and has contributed to advancing the technology. Concepts for producing pellets in the 5 km/s range are now under development by both blocs. Soviet and Japanese systems are apparently based on technology developed in the United States, and to a lesser extent, Western Europe; and there is no significant development of advanced concepts for pellet injectors.

The physics and technology for fueling with high-density "plasmoids" is now being explored in the United States.

(4) Magnets

All fusion programs have substantial capability in magnet technology, as indicated by the performance of magnets in the Large Coil Task. Soviet capability is limited by lack of priority within industry and the overall scarcity of high-quality manufacturing resources. Superconductivity is viewed by all participants in magnetic fusion as an important area for the development of applications and industrial capability. The United States is alone in not having built and operated a superconducting tokamak. In general, the Japanese and West European positions in magnet technology (which are determined as much or more by issues of quality control and experience than by fundamental understanding of superconductivity) are enhanced by their approach to the use of fusion as a mechanism to foster industrial development, in general.

(5) Industry

As evidenced by the fabrication of the TFTR, JET, and JT-60 tokamaks (including their heating systems), and the magnets for the Large Coil Task, strong domestic industrial capability exists for fusion in the United States, Japan, and Western Europe. With this statement, it is also apparent that each party has sufficient depth that even an expanded fusion effort would not require a redirection of the "high-tech" segment of industry. As a whole, Soviet capability is neither as deep nor as broad as its Western counterparts, and a strong national commitment would be required to apply the high-tech manufacturing resources that do exist to fusion. Despite the high political visibility of fusion within the Soviet Union, recurring problems with industry are still slowing the TSP and T-15 tokamaks; and a change in industrial priorities is not apparent.

Having grouped the Western efforts and Japan, it should be noted that there are significant differences. The development of high-tech industry is an objective of Japan and Western Europe, and the policies and institutions of these blocs allow easy and effective collaboration between industry and laboratories. In the United States, relations between laboratories tend to be awkward because of the lack of an established framework for effective interactions. In addition, the appropriate role of industry is unclear at the present time.

b. Outlook

Future progress in neutral beams is likely to depend upon the commitment to a national or international project with an established need for high-energy beams. ITER will advance beam technology if construction is approved and if beams remain the choice for current drive. Apart from ITER, negative-ion beams with energy up to 500 keV are being discussed for all the large tokamaks as well as for the Large Helical Device in Japan. With the expected commitment to the latter device, the possibility of a 40-MW system on JT-60U, and the lack of definitive plans elsewhere, the Japanese could take a lead in negative-ion-based neutral beams. The JT-60U beam energy will be 120 keV, so that development of MeV-range accelerators is unlikely to occur until a major facility commitment is made.

High-power ion cyclotron experiments for plasma heating (and often for current drive) play a major role in the Western and Japanese fusion programs, and there is in each case a strong industrial base. Continued progress is allowed by physics development and program support is expected. Ion cyclotron experiments do not play a major role in Soviet plans. Soviet industry, while not up to Western standards, is less limited in ion cyclotron source technology than in other heating technologies.

The outlook for lower hybrid technology parallels that for ion cyclotron technology except that, while a reasonable industrial base exists, there are no large fusion experiments planned in the United States. The experience gained in developing and operating launchers in Western Europe and Japan (a second-generation 24-element waveguide array has already been used on JT-60) is an important step towards the more demanding requirements of ITER.

In the near term, the United States (Varian Associates) will likely remain the principal supplier of gyrotrons for electron cyclotron heating experiments in the West and Japan. Competitive suppliers with sustained funding for the recently-initiated programs in Europe and Japan, including ~100 GHz long-pulse gyrotrons for Tore Supra and the Large Helical Device, are possible. The Soviet Union will continue making progress on short-pulse technology (less than 0.5 sec), but the Soviet long-pulse capability remains to be demonstrated.

With continued support, the United States is likely to retain its present leading position in fueling technology, but with significant contributions coming from the West European program.

Progress in superconducting magnets will be determined in part by the need for that technology in future facilities. Present magnet programs in the West and Japan have all proposed major magnet test facilities. Decisions on these facilities are likely to require a decision on ITER construction and on the respective national roles in that project. The lack of industrial capability in the Soviet Union is a substantial handicap in its ability to make further advances.

4. Fusion Nuclear Technology and Materials

a. Overview

Fusion nuclear technology (FNT) includes those components and technical disciplines related to fusion energy conversion and recovery, tritium fuel breeding and processing, and radiation protection. Fusion nuclear technology and materials research can be conveniently divided into five areas: (i) blanket, (ii) neutronics, (iii) tritium processing systems, (iv) neutron-interactive materials, and (v) plasma-interactive materials (plasma-facing components). The blanket is a key component in which fusion energy conversion and breeding of the tritium fuel take place. Blanket types of the greatest interest in the world program can be classified into solid breeders and liquid metals.

An attempt at assigning a relative ranking to the strength of the fusion nuclear technology and materials research in the four programs is shown in Table I.13. Key points of the comparative assessment in the various categories of fusion nuclear technology and materials research are provided below.

(1) Liquid Metals

The various world programs on liquid-metal blankets are very different in character, size, and capabilities. Different strengths and weaknesses exist in all programs. Table I.14 shows a relative ranking of program size, skills, and capabilities for the four world liquid-metal blanket programs.

In general, Western Europe has the strongest, most focused program. Most of the important issues related to component development are being adequately covered. The overall manpower is not large, but is well-focused. Funding is strong and reliable. Existing experimental capabilities are strong and construction of upgraded facilities is planned.

Table I.13
COMPARATIVE RANKING BY AREA IN
FUSION NUCLEAR TECHNOLOGY AND MATERIALS RESEARCH

	Western Europe	Japan	Soviet Union	United States
Blanket				
Solid Breeder	1	2	4	3
Liquid Metals	1	4	2	3
Tritium Systems	2	3	4	1
Neutronics	3	1	4	2
Materials (Neutron-Interactive)	3	2	4	1
Plasma-Facing Components	1	1	4	1

Programs in the remaining countries are less focused; but, in some cases more innovative. The Soviet Union has recently become more organized; its various organizations are working together toward the goal of component development for ITER/OTR. The Soviet Union has a substantial pool of manpower and good theoretical background; however, poor modeling and construction capabilities limit the program's effectiveness and credibility. The large effort on free-surface applications for the plasma-interactive components makes the program unique.

The US program is relatively small, consisting primarily of a single MHD facility and several small corrosion loops. Credible, validated designs for components are lacking; however, a number of design studies over the past 10 years have identified potentially attractive configurations. Low manpower, absence of design focus, and no near-term goal of component construction and operation make the US program relatively weak.

Table I.14
COMPARATIVE RANKING OF LIQUID-METAL-BLANKET PROGRAMS

	United States	Soviet Union	Western Europe	Japan
1. Program Size				
a. Manpower				
Design, Theory, and Modeling	3	1	2	4
Experimental	4	1	3	2
b. Experimental Facilities	4	2	1	4
2. Skills and Capabilities				
a. Theory	2	1	4	3
b. Modeling	1	3	2	4
c. Facility Operation	2	3	1	4
d. Fabrication of Components	3	4	1	2
3. Overall Ranking	3	2	1	4

1 = best; 2 = second best; 3 = third best; 4 = weakest.

JAERI has no significant activities on liquid-metal blankets, and the Japanese fusion program relies on contributions from the universities, which independently pursue their own interests. This leads to mostly academic research. The program is not well focused and is relatively broad, but is, in many respects, innovative. Perhaps the most notable aspect of the Japanese program is the potential to expand rapidly by drawing on extensive expertise and fabrication capabilities from universities, national laboratories, and industry.

(2) Solid Breeders

Solid blanket R&D presently includes tritium recovery experiments in fission reactors, property measurements, and compatibility studies and modeling. The US program had the lead on solid breeder blanket development from the late 1970s to the early 1980s. However, the European and Japanese programs started new aggressive programs in the middle to late 1980s, while the US program activities declined. The Soviet program has not made significant contribution in this area for the past several years.

The West European program has now emerged as the strongest R&D program on solid breeders. It is comprehensive, including the most important aspects of blanket design, ceramic preparation and fabrication, property measurements, and tritium release experiments. The program utilizes many powerful facilities, primarily fission reactors, existing in Western Europe, in addition to the participation of the European Community in an IAEA agreement for collaborating with the United States, Japan, and Canada. The West European effort is currently about three times that of the US effort and is comparable to that of Japan.

While the West European and Japanese programs are comparable in funding, there are many important differences between the two programs in approach and capabilities. The Japanese program is focused primarily on the development of one breeding material, Li_2O, while the West European program is considering several breeding materials. Japan does not have adequate fission reactor testing capabilities and relies on international collaborative agreements for the use of fission reactors in Western Europe and the United States. Western Europe has tritium production capabilities and a broad industrial base. The Japanese program has designated the development of a tritium production capability as a national priority and is completing a design for an integrated breeder blanket unit test in the Japan Material Test Reactor. This is an example of targeting a sensitive technology for which no capabilities presently exist in Japan. Also, a plan is being finalized for construction at JAERI of a blanket manufacturing technology facility with a special laboratory for handling beryllium.

(3) Tritium Systems

The US program on tritium systems is in a world leadership position. The Tritium Systems Test Assembly (TSTA) at Los Alamos National Laboratory is a unique facility, being the only integrated facility operating or planned. The West European program is also very strong. France has tritium handling capabilities in its weapons program. However, French experts have not yet fully shared their experience with the rest of Europe. Two large-scale tritium handling facilities are being constructed in Europe, one at KfK and the other (called ETHEL) at the JRC Laboratory in Ispra, with estimated operating dates in 1991. The present program at KfK is aggressive, with a strong research staff, and is now producing some of the best world results on tritium R&D. The goal of the ETHEL facility is to perform tritium experiments related to safety and blanket tritium extraction. It now appears that JET will be the first operating tokamak to be integrated with a tritium processing loop. The present plan is to complete the construction of the tritium processing and isotope separation system at the JET site and to have the system commissioned and ready to be installed on JET by 1991. The tritium activity at JET is outstanding in terms of the quality of staff and the quality and pace of the tritium R&D program.

Tritium handling technology has been targeted for an extensive R&D effort in Japan since the early 1980s. The Tritium Processing Laboratory (TPL) was constructed at JAERI with the first tritium operation (3-gram level) occurring in March 1988. However, the experimental program which is actually being conducted at TPL is limited. Japan appears to be several years behind the United States and Western Europe. Japan is participating in the operation of TSTA in the United States to gain direct experience with tritium handling technology.

(4) Neutronics

Neutronics includes methods, codes, nuclear data measurements and evaluation, and internal experiments for tritium breeding, nuclear heating, radioactivity, afterheat, and radiation shielding. Japan now has the largest fusion neutronics program in the world. This remarkable progress from a modest program in the 1970s to the lead program in the 1980s has been achieved, in part, by constructing simultaneously, in the early 1980s, the two largest neutronic facilities in the world: the Fusion Neutron Source (FNS) at JAERI, and OCTAVIAN at Osaka University. Both have a yield of $\sim 3 \times 10^{12}$ n/s, with pulsed and steady operation and other important experimental capabilities. These facilities adapted many technologies developed in the United States and Western Europe and are operated by scientists, many of whom were trained in the United States and West Germany. Japan also has a very active measurement and evaluation program on nuclear data.

The US program presently has no fusion neutronics facility in operation and relies heavily on a joint collaborative program with Japan for conducting integral neutronics experiments. The United States has strong analysis and computational capabilities and a broad base of data and experience developed in the fission and weapons programs. Such capabilities and experience allow the United States to be in a strong position.

At present, the West European fusion neutronics effort is somewhat larger than that in the United States, but smaller than that in Japan. However, the West European program remains somewhat behind the US program. Most of the transport codes being employed in Western Europe were developed in the United States. The nuclear data efforts in the United States and Western Europe are comparable. The West European program on fusion neutronics integral experiments is very limited in scope and is far behind that of Japan.

(5) Materials (Neutron-Interactive)

The first wall and blanket must be constructed of durable structural materials that can withstand mechanical and thermal loads and neutron radiation effects. Structural material development is a major element of fusion nuclear technology. In addition, plasma facing components (PFCs) require structural materials as well as plasma-facing materials that can withstand a high heat load and erosion by plasma particles.

The effort on structural materials in both the West European and Japanese programs is about twice as large as that of the United States. The funding for the US fusion materials program has declined sharply over the past several years. However, the United States still appears to have a technological edge in this area, deriving from more effective use of resources, better neutron-irradiation facilities, and more attention to long-term materials needs. The Soviet fusion materials program seriously lags behind the other three programs. Table I.15 provides a comparative assessment and relative ranking of fusion materials R&D in the four programs.

Table I.15
COMPARISON OF WESTERN EUROPE, JAPAN, THE SOVIET UNION, AND THE UNITED STATES IN FUSION MATERIALS DEVELOPMENT

Comparison Area	Western Europe	Japan	Soviet Union	United States
Metallic Structural Materials	- Ferritic and austenitic steels - Vanadium alloys (Very Good)	- Ferritic and austenitic steels - Vanadium alloys - Molybdenum alloys - Titanium alloys (Excellent)	- Austenitic steels (Good)	- Ferritic and austenitic steels - Vanadium alloys (Very Good)
Innovative Materials	- Low activation - Recycle (Good)	- Low activation (Good)	- None (Poor)	- Low activation (Excellent)
Ceramic Structural Materials	- None (Poor)	- SiC/SiC composites - Al/SiC composites (Excellent)	- None (Poor)	- None (Poor)
PFC Materials	- Graphite - TiC coatings (Good)	- Graphites - TiC coatings - W-Re coatings (Excellent)	- Graphites (Good)	- W-Re coatings - TiC coatings - Graphites (Excellent)
Emphasis	Near-term	Balanced, near-, and long-term	Near-term	Balanced, near-, and long-term
Overall Ranking	3	2	4	1

The past decade has witnessed tremendous growth in the Japanese fusion materials program. Starting from very elementary initial conditions, the Japanese fusion materials R&D program is maturing to one of the world leaders. It has the largest number of personnel of the four major world programs, and outstanding strength in non-neutron testing capabilities. Testing of materials properties in a neutron environment is accomplished by bilateral collaboration with the United States and Western Europe, because of the lack of appropriate neutron irradiation test facilities in Japan. Materials development concepts in the United States and Western Europe find immediate applications in Japan. The Japanese program, compared to those in the United States and Western Europe, is generally weak in developing innovative ideas, and is also weak in theory and modeling of radiation effects.

The fusion materials development program in Western Europe maintains strength and balance between theory and experiments for both near-term and long-term applications. The program is placing emphasis on the R&D needs for NET. There are a number of excellent irradiation facilities in Western Europe.

The fusion materials program in the Soviet Union has been fragmented and uncoordinated, unlike the other three major world programs. The Soviet approach is to make use of materials that have been developed in the fission program and to design around the limitations on the operating conditions imposed by the use of existing materials.

The West European, Japanese, and US efforts on plasma-facing components are comparable in size, scope, and focus. The Soviet program in this area is not substantial, and the level of effort is much smaller than that in the West. The US program is the strongest in terms of test-stand capabilities, special materials development, and a balanced modeling and experimental R&D program. The major strength in the West European program is the testing capabilities in existing tokamaks. The Japanese effort emphasizes fundamental studies.

b. Outlook

At present, the level of effort on fusion nuclear technology and materials research is the largest in the West European program and second largest in the Japanese program. The level of effort in each of these two programs is two to four times larger than that of the United States. Manpower in the Soviet program is comparable to that of the Japanese and West European programs, but the funding is lower than that in the United States. The investment in R&D made in the late 1970s to the early 1980s, the broad technological base, and the efficient use of resources in the United States helps the United States to maintain relatively competitive programs in certain areas. However, in the past several years, there has been a significant decline in funding and no new facilities planned in the US program, while the West European and Japanese programs have increased their funding in this area several fold and have embarked on new R&D initiatives, including the commissioning of new facilities. If the trend of the past several years continues, the world leadership in fusion nuclear technology and materials R&D will be a competition between Japan and Western Europe, with the United States as a distant third. The ability of the United States to remain strong enough to be viewed as a viable partner in international collaborative efforts may also suffer. The Soviet effort, despite its breadth and large manpower pool, has been fragmented and relatively weak in many critical areas. Commitment of new resources of funding and facilities, access to fast computers, as well as sharpening of focus and improvement in management, are necessary for the Soviet program to be effective. It is unlikely, however, that the Soviet program will rise to a leadership position in this area in the near future.

5. Plasma Confinement Theory

a. Overview

The strongest theory program in the international controlled fusion effort is that of the United States. The theory effort of Western Europe is in second place; it is close to the United States and rapidly moving closer. Confinement theory in the Soviet Union, once the world leader, has lost five or more years to the West, although the skill of individual Soviet theorists remains striking. Japan's theory effort is clearly the smallest and weakest, despite pockets of strength; one suspects a high-level Japanese decision to import most confinement theory. The small size of the Japanese theory effort in fusion is not unlike the level of Japanese theoretical activity in other areas of scientific research, such as astrophysics, fluid dynamics, and so forth.

This ranking, broadly consistent with previous FASAC reports, essentially reflects productivity—the quality and importance of theoretical research as revealed in the published literature. Not surprisingly, it agrees with a previous estimated ranking based on numbers of personnel; by this measure, the West European theory effort is comparable in size to that in the United States, while the Soviet effort is about 65 percent, and that of Japan is 20 percent, the size of the US program.[4]

We begin with two general comments concerning the comparison of foreign programs with that of the United States. First, while each of the three theory programs under consideration shows areas of impressive strength, none of the three has theoretical *breadth* matching that of the United States. It is true that the West European program shows broad strength, contributing useful theory to most of the areas of central concern to plasma confinement. But the list of the areas in which US theorists share (at least) a leadership role—including such critically important topics as transport simulation, "second-stability" tokamak operation, "fishbone" and sawtooth oscillations, magnetic island evolution, and suprathermal particle stabilization—is unique.

Second, none of the programs under consideration seems to have achieved as successful an integration of theory into the overall fusion effort as characterizes US fusion research. While all fusion programs use theory in the design of experiments and devices, none does so more systematically and effectively, it seems, than the United States. The relatively scant heed paid to theory in Japanese experimental design is well known, and exemplified by the initial location of the divertor coils in JT-60. Soviet theorists are especially well respected, yet the practical utility of Soviet theory advances has been, in several cases, first exploited in the West. Western Europe is strongly sensitive to certain theorists and certain theoretical currents; yet, the West European program is marked by a number of isolated and disconnected theory groups—especially, but not only, in the universities.

We next attempt more detailed consideration. To concentrate the argument, it is convenient to consider just four physics issues, chosen on the basis of their importance to the overall fusion goals as well as their vulnerability to specifically theoretical research. These are: (i) the major disruption; (ii) enhanced confine-

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4 D. E. Baldwin et al., "The Role of Plasma Theory in the Development of Magnetic Fusion," *Panel XIX Report to the Magnetic Fusion Advisory Committee*, 1988.

ment regimes in tokamaks (the H-mode); (iii) plasma transport, especially turbulent transport; and (iv) plasma MHD activity. (We note that the amount of proposed theoretical work for ITER is largest in these four areas.) Below, we assess the theoretical contributions of Western Europe, the Soviet Union, and Japan in each area, noting relative US strength as a baseline.

Research in major disruptions has historically been a province of US and Soviet theorists. The Kadomtsev disruption model (Soviet Union) is probably the single most influential construct in this area, although Rutherford's nonlinear island theory (United States), less disruption-scientific, has been similarly persuasive. Soviet research on disruptions has lagged, however, while West European theorists, with their historical expertise in linear fluid stability, have introduced several stimulating concepts. Japan, despite manifest interest in fundamental nonlinear plasma phenomena, has not made central contributions to the topic.

Disruption physics is one of several fields in which progress depends especially upon close interaction between analytical and numerical research. Partly for this reason, the strongest theoretical programs in tokamak disruption are presently those of Western Europe and the United States, whose efforts are roughly comparable.

The existence of enhanced confinement regimes is a West European experimental discovery: the "H-mode"—the tokamak operating regime of peculiar plasma quiescence and improved confinement—was first observed on ASDEX. Yet the most successful theoretical investigations have been undertaken in the United States. Japanese theorists have competed in this area, with imaginative and stimulating suggestions. However, the corresponding US research is more polished, more thorough, and has agreed far better with experiment. West European H-mode research has been tardy and strongly influenced by US work; the Soviet Union, hobbled by experimental inadequacies—and despite a tradition of edge-physics theory that would seem to be pertinent—has yet to compete seriously.

Confined plasma transport is another area benefiting from close analytical-numerical ties. Western Europe has shown strong growth in this area, providing compelling anomalous transport models as well as several interesting analytical ideas. Soviet theorists, despite an illustrious history in plasma transport, seem inadequately coupled to both experimental data and computational backup. Furthermore, many talented Soviet theorists are drawn to more basic, less tokamak-oriented transport issues—the fundamental physics of turbulence. Japanese contributions to modern, practical plasma transport issues are few, although Japan too has a distinguished tradition of excellent fundamental work in plasma statistical mechanics.

US transport research, with regard to the practical issues of modeling and predicting tokamak energy confinement, is outstanding. The United States is a clear world leader in turbulence phenomenology; it is rivaled only (and only recently) by Western Europe in its effective use of transport simulation; and it enjoys generally unexcelled experimental contact. The recent "transport initiative" both epitomizes and reinforces US excellence in this area.

By MHD activity, we refer to the numerous, manageably low-level perturbations observed in tokamak plasmas: sawtooth oscillations, fishbones, Mirnov oscillations, and so on. The earliest concerns of theoretical plasma physics, including equilibrium and linear stability theory, are relevant here, with the result that all the world fusion programs have made important contributions. For example, the early Japanese work of Hamada and Taniuti continue to bring useful insight. Soviet contributions have been enormous—not surprising in view of the relation between disruption and sawtooth activity (sometimes called "mini-disruptions"). The United States, developing and exploiting outstanding tools for numerical simulation, has made leading contributions during the past decade, especially with regard to fishbone excitations. In particular, the development of reduced fluid models in the United States (an innovation for which the Soviet Union correctly claims shared credit) has significantly accelerated progress in all aspects of MHD research.

However, it appears that, at the present time, Western Europe leads the world with regard to the theoretical understanding of MHD activity. Its imaginative work on sawtooth oscillation is comparable to that of the United States and perhaps slightly more influential; its fundamental investigations of MHD stability show unmatched sophistication and depth, especially with regard to finitebeta effects; it has a superb record in identifying key stability limits; and its exploitation of numerical methods has improved to the point of rivaling the United States.

We conclude that, in four critical areas of theoretical confinement research, US theorists are either leading the international effort or in close competition with Western Europe for leadership status. A similar conclusion would probably pertain even if a broader range of physics issues were considered. On the other hand, we cannot conclude that the United States leads, or nearly leads, in all theory areas of interest. Japan, for example, appears to have an exceptional group of young, talented theorists in its alternative concepts program. In several fundamental plasma physics areas—fields that might eventually bring major benefit to the understanding of confinement—Soviet, Japanese, and West European efforts lead those in the United States. The most important example is the nonlinear fluid dynamics research of the Soviet Union, which clearly leads the world, and which may ultimately provide a deep and predictive theory of plasma turbulent transport.

b. Outlook

The quality of West European theoretical research, and especially its unequalled rate of growth, suggest that Western Europe will become the world leader in plasma confinement theory during the next five years.

Japanese confinement theory will make important gains in certain areas—computer simulation is an example—but the Japanese program will remain small and far from world leadership for the foreseeable future.

The Soviet theory outlook is problematic. Strong underlying capabilities and improved computational hardware, together with the exciting general changes in Soviet mobility and communication, could portend a dramatic intellectual flowering—as is now apparent with regard to Soviet nonlinear dynamics. On the other hand, a balky experimental program would surely inhibit Soviet theory in coming years as much as it has in the past.

6. Fusion Computations

a. Overview

In this section, fusion computations in the various programs surveyed are divided into the following three categories:

- scientific computations;
- data acquisitions; and
- engineering computations.

(1) Scientific Computations

Fusion scientific computations are carried out along similar lines in all of the programs compared. Capabilities and accomplishments are described below in the areas of fundamental computational studies and in selected applied areas.

The United States has, by far, the strongest fundamental computational studies program; no other group is comparable. Research in this area is expected to lead in the long term to the development of first-principles models for plasma performance, which should be superior to the semi-empirical models presently employed.

The US contributions in the fields of nonlinear, multidimensional simulation and particle simulations are unequalled. This level of excellence is shared among many groups: Princeton, UCLA, Oak Ridge National Laboratory, General Atomics, Los Alamos National Laboratory, Lawrence Livermore National Laboratory, SAIC, the Institute for Fusion Studies (University of Texas), and New York University. While there are isolated examples of this kind of work in Western Europe (JET and IPP-Garching), Japan (Hiroshima University), and the Soviet Union (the Kurchatov Atomic Energy Institute and the Keldysh Applied Mathematics Institute), the United States has had the most active and the most productive program.

Fusion-related computational activity in Western Europe, the Soviet Union, and Japan is directed more toward device-relevant questions. The areas which can give an indication of relative ranking include configurational optimization, experimental interpretation (predictive and data analysis codes), and divertor modeling.

The configurational optimization of next-step devices is pursued in a similar manner and at a comparable level by all of the groups. The goal is to find the configuration which will generate the toroidal current required for confinement, and provide the most margin against large-scale instabilities in a compact design to minimize the cost.

All of the groups made significant contributions to the definition of the ITER configuration in the 1988-1989 Joint Work: the Princeton PEST code (United States), the Keldysh Institute finite-element stability code (Soviet Union), and the ERATO code, both by the Lausanne originators of the code (Western Europe), and by the JAERI group (Japan), who developed a high-resolution variant. The JAERI group has adapted and significantly improved the West European ERATO code by adding the capability to analyze magnetic separatrices.

As noted above, the United States has the lead in the development of large-scale multidimensional, nonlinear dissipative codes. These provide a more realistic treatment of limits to the tokamak operational space than the linear MHD codes used for ITER design. However, the nonlinear codes are so computationally demanding (5 to 30 hours of CRAY-II CPU per configuration) that it is not feasible at present to use them to survey the operational boundaries, which is the desired information for an ITER-level design. (The ideal, linear codes surveyed about 20,000 ITER profile and configuration variants, which would have required in the range of 13 to 65 CRAY-II *years* with the nonlinear codes.)

The situation in this area is typical. If an activity is required for success of the program, each of the participating groups has the resources to ensure that it is done. Activities which are not universally recognized as necessary will elicit a more varied response.

In the area of experimental interpretation, the United States is in a leading position, with the TFTR and DIII-D groups. The Princeton TRANSP data analysis code has been imported by the JET group to analyze JET data. Both DIII-D and

JET have studied configurational effects, but the DIII-D group has been more active in detailed data analysis, based upon the EFITD code at General Atomics. The JET group has both the tools (Blum IDENTC code) and the expertise to lead in the configurational studies area, but has apparently chosen not to emphasize this topic.

The Soviet program (Kurchatov Institute) is intellectually very strong in this area, but has been unable to fully exploit even the existing computational resources. While these resources are not at the level of other groups, they are adequate for T-10 and T-15 analysis. The group, however, has not adapted to routine use of automated data analysis. (There are individual exceptions, for example, the Yushmanov-Pereversev analysis code.)

The Japanese program is the weakest in the experimental interpretation area. It is not unusual for extraordinary experimental claims to be represented in one viewgraph presented at a meeting, with no other documentation provided. Examples from ITER include: (i) the assertion that volt-seconds consumption in JT-60 was 50 percent lower than in DIII-D or JET, based on the evidence of the one transient event in a single discharge; and (ii) the claim that 80 percent of the current has been driven in JT-60 by the "bootstrap current," again, based on crude steady-state modeling of the expected loop voltage.

In the increasingly important area of divertor modeling, the West European program (IPP-Garching) has made the leading contributions, although the strongest US group, at Princeton, has collaborated so closely that it is perhaps impossible to separate the respective contributions. The Garching group has developed one- and two-dimensional simulations of scrape-off layer performance. The most widely used two-dimensional code (B2, written by B. Braams) was developed both at IPP-Garching and at Princeton. The Garching group has had the decided advantage of a continuously operating divertor experiment (ASDEX), while Princeton converted its divertor experiment, PDX, to a beta test experiment, and General Atomics has not emphasized divertor studies on DIII-D. This area has recently received more emphasis by the JAERI group, because of its importance for ITER (and FER) design. The two-dimensional code developed by Ueda is equivalent to the B2 code developed by Braams, and benchmark studies are underway as part of the ITER Joint Work. The FER group has recently been successful in obtaining approval for a multiple-processor parallel computer devoted to divertor simulation.

(2) Data Acquisition

The topic is addressed because questions of possible illicit technology diversion to the Soviet Union have been raised, and because the capabilities for mutual access to data by other parties vary widely. This is an important topic for joint projects.

The experimental data acquisition systems of the US, West European, and Japanese groups are comparable, and superior to those of the Soviet Union. The Soviet data acquisition systems appear to be adequate for present and next-step experiments. The majority of fusion data systems (both Eastern and Western Bloc) are based on DEC hardware.

Data from experiments in the United States and Western Europe are easily accessible and heavily used by participants in joint experiments, Tore Supra pump limiter experiments, and ASDEX confinement experiments. The hardware exists for such collaboration with the JT-60 group at the JAERI Naka site, but it is not used as heavily. (ITER participants have been provided accounts on the Naka VAX.) Electronic communications with the Soviet Union have recently been installed, but are at a rudimentary level (short messages only).

The US and West European experimental data acquisition systems are mostly VAX-based. The major exceptions are JET and Tore Supra, which use Norsk systems. The JAERI Naka group has acquired a VAX for communications and data transfer among ITER participants. The Soviet fusion program has developed a link with the Central Research Institute for Physics (KFKI), in Budapest, for "reverse-engineered" DEC clones, below the VAX level (PDP 11/780). The system developed for T-15 has been used as a pilot project for a Local Area Network by the KFKI group. A part of the T-15 system is now in use by the T-10 group and by the Kurchatov Institute theorists. The system appears to be adequate for T-15 experimental needs, although its first real test will come with integrated operation of all T-15 subsystems (see Section II.C.6).

The T-15 data acquisition system has been developed as part of the civilian research activity, and no connection with military or illicit technology transfer has been found. There is a report that several CONVEX mini-supercomputers have been installed at the Troitsk site, which is affiliated with the Kurchatov Institute. These computers would have been obtained in contravention of the COCOM guidelines, but no direct confirmation of this report has been made (see Section II.C.6).

(3) Engineering Computations

The comparison here is made on the basis of contributions to the ITER joint design work. Overall, the United States and Japan have the highest capabilities in this area, because many neutronics, mechanical, thermal analysis, and CAD codes are available from non-fusion laboratory and commercial sources, and the computational resources available to US and Japanese participants are the best of the ITER parties. The West European (NET) group has made comparable contributions in these areas, whereas the Soviet Union clearly lags in engineering computations. Soviet researchers have made considerable progress (see Section II.C.6), however, and are believed to contribute their share in this area because of their dedication of a higher level of "home-team" effort to the ITER project than those of the other parties.

In fusion-specific engineering calculations, the differences between the groups are much smaller. The topic of stabilization of axisymmetric instabilities is a good indicator, since this capability determines the maximum elongation of the configuration. This, in turn, has a strong impact on the size required to produce the desired plasma current, and, hence, the cost of the device.

The United States has the leading plasma simulation code in this area, the TSC code, developed by Princeton with contributions from the CRPP group at Lausanne. The JAERI group uses a simpler description of the plasma, but a more detailed (three-dimensional) vacuum vessel model (developed by Yamane at Mitsubishi). The NET group uses the Coccorese code, which is less detailed than either the US or JAERI codes. These three codes are computationally demanding, and this limits the degree to which they can be used to survey the relevant design space. The key variables are the number of blanket segments, plasma elongation and triangularity, and variants for control algorithms.

The Soviet Union has contributed optimized codes (developed by Gribov and Vabishchevich) which greatly reduce the computational time requirements, and, as a result, the Soviet group now has the responsibility for assessing axisymmetric stability requirements for the proposed single-null divertor ITER variant (Section II.C.6).

Similarly, the Soviet group has made strong contributions to poloidal field design in ITER, through use of two-dimensional equilibrium computations strongly backed with analytical modeling by L. Zakharov.

b. Outlook

While the availability of computational hardware has an important effect on fusion-related performance, the most important determinant appears to be the dedication to solving fusion-relevant problems. Thus, the JAERI group, which arguably has (or soon will have) access to the most advanced computers, does not perform as well as might be expected when compared with the other fusion participants. The United States has the lead in this area and should continue, with Western Europe, the Soviet Union, and Japan all contributing effectively. The Soviet contribution has been improving steadily for the past five years, and this is expected to continue.

CHAPTER II

ASSESSMENT OF SOVIET MAGNETIC FUSION RESEARCH

A. INTRODUCTION

An earlier FASAC report, *Soviet Magnetic Confinement Fusion Research,*[1] presents a detailed assessment of the status and outlook for magnetic confinement fusion research and development in the Soviet Union, covering the period prior to June 1987. This chapter provides an updated summary of the principal findings and the outlook for future Soviet contributions.

Research in magnetic fusion is one highly visible measure of a nation's capabilities in advanced technology and the physical sciences. During the 1960s and early 1970s, Soviet fusion research was marked by seminal contributions of historical proportion. Indeed, the Soviet invention of the tokamak confinement approach and the very encouraging experimental results obtained on the T-3 tokamak in the late 1960s resulted in the vigorous pursuit of tokamaks on a worldwide basis, thereby providing the seeds for subsequent internationalization of fusion research and development.

The worldwide fusion effort has continued to benefit during the 1970s and 1980s from the substantial Soviet contributions in fusion theory, alternate confinement approaches, and selected technology areas (such as microwave source development). While Soviet preeminence in experimental tokamak physics declined during the 1970s and 1980s, the Soviet fusion program has the human and technological resources to design and construct, without external participation, tokamak devices which could demonstrate the scientific and engineering feasibility of fusion. Soviet technical contributions to the International Thermonuclear Experimental Reactor (ITER) design effort have been of particularly high quality. Successful technical results on the superconducting T-15 tokamak and

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1 R. C. Davidson, L. A. Berry, R. A. Ellis, Jr., R. D. Hazeltine, J. T. Hogan, R. S. Post, and W. M. Stacey, *Soviet Magnetic Confinement Fusion Research,* Foreign Applied Sciences Assessment Center, Science Applications International Corporation, McLean, Virginia, October 1987.

the high-field TSP tokamak would restore the Soviet experimental program to forefront status.

Following a brief description of the organization and scope of fusion research in the Soviet Union in Section II.B, the status and outlook for Soviet fusion research and development is summarized, in Section II.C, in the following six areas:

- tokamak confinement;
- alternate confinement approaches;
- plasma technology and engineering;
- fusion nuclear technology and materials;
- plasma confinement theory; and
- fusion computations.

The reader is referred to the FASAC report *Soviet Magnetic Confinement Fusion Research* for more detailed assessments and the associated bibliography covering the period prior to June 1987.

B. ORGANIZATION AND PLANNING OF FUSION RESEARCH IN THE SOVIET UNION

As illustrated in Tables II.1-II.3 (Rutherford, 1989), the Soviet Union has a large national effort on magnetic confinement fusion, with 1,225 professional staff and 3,880 total staff involved in fusion research activities. The main Soviet fusion effort is on tokamaks, with large programs at the Kurchatov Atomic Energy Institute in Moscow (the T-15 and T-10 tokamaks) and in Troitsk (the TSP tokamak). The Yefremov Electrophysical Apparatus Institute in Leningrad plays a major engineering role in the design and construction of fusion hardware components and power supplies. The majority of Soviet fusion research, including the programs at the Kurchatov (Moscow and Troitsk) and Yefremov Institutes, is administered by the State Committee for the Utilization of Atomic Energy, which is funded by the Ministry of Nuclear Power and Industry. In addition, the Academy of Sciences administers key fusion activities at several other institutes: most notably, the General Physics Institute (Moscow), which emphasizes stellarator research; the Khar'kov Physical-Technical Institute (Khar'kov), which also emphasizes stellarator research; the Ioffe Physical-Technical Institute (Leningrad), which emphasizes diagnostic development and small tokamak research; and the Nuclear Physics Institute (Novosibirsk), which emphasizes research on mirrors.

Table II.1

SOVIET FUSION MANPOWER LEVELS (1989)

Institute	Total Staff[1]	Professionals[2]
Kurchatov Atomic Energy Institute (Moscow and Troitsk)	1,700	490
Khar'kov Physical-Technical Institute, AS UkSSR (Khar'kov)	550	180
Yefremov Electrophysical Apparatus Institute (Leningrad)	500	150
Nuclear Physics Institute, AS USSR (Novosibirsk)	250	80
General Physics Institute, AS USSR (Moscow)	120	40
Vekua Institute of Physics and Technology, AS GeSSR (Sukhumi)	110	60
Ioffe Physical-Technical Institute, AS USSR (Leningrad)	100	30
Others[3]	550	195
Total Personnel	3,880	1,225

1 Total staff includes only "direct" staff and excludes a much smaller number of "indirect" staff at each institute engaged in activities such as security, accounting, and purchasing.

2 Professional staff includes those with university degrees.

3 Other institutions include: Inorganic Materials Institute im. Bochvar (Moscow); Power Engineering Research and Development Institute (Moscow); Physics Institute im. P. N. Lebedev, AS USSR (Moscow); Nuclear Research Institute, AS UkSSR (Kiev); Applied Mathematics Institute im. M. V. Keldysh, AS USSR (Moscow); and others.

Table II.2
SOVIET FUSION FUNDING LEVELS*

	1985	1986	1987	1988	1989
Operating expenditures	82	82	106	114	148
Capital expenditures	42	42	64	36	22
Total	124	124	170	150	170

* All figures are in millions of rubles. The tentative budget for 1990 is 170 million rubles.

Table II.3
BREAKDOWN OF SOVIET FUSION EXPENDITURES (1989)

1. Magnetic/Inertial	
• Magnetic confinement	77%
• Inertial confinement	18%
• Other	5%
2. Ministry/Academy	
• Ministry of Nuclear Power and Industry (State Committee for the Utilization of Atomic Energy)	90%
• Academy of Sciences	10%
3. Major Contracts	
• Ministry of Nuclear Power and Industry	
• Main Department for Fundamental Issues of Nuclear Physics and Controlled Thermonuclear Fusion (35 contracts total)	
- Kurchatov Institute	71%
- Yefremov Institute	13%
- Others	16%
4. Internal/External Expenditures (Typical)	
• Internal expenditures within a fusion laboratory	70%
• External contracts with other laboratories and industries	30%

In contrast with the US fusion program, which is administered by the US Department of Energy, the Soviet program lacks strong central planning and coordination. Indeed, the program directors at the various institutes appear to have considerable autonomy in planning and executing local programs. In this regard, Ye. P. Velikhov is the single most important scientific figure in forging a "national" fusion program in the Soviet Union. Indeed, as Vice President of the Soviet Academy of Sciences and Director of the Kurchatov Atomic Energy Institute, he exerts considerable technical and political influence on Soviet fusion research and development, and is a powerful advocate of Soviet international collaboration in fusion.

In the absence of a developed civilian high-tech industrial base, the fabrication of hardware components for the Soviet fusion program is carried out in-house or under contract with other institutes that have special capabilities (Hokin, 1988). Examples include the Yefremov Institute (superconducting magnets for T-15), the Gor'kiy Physical-Technical Institute (gyrotrons for T-10 and T-15), and the Central Research Institute for Physics in Hungary (DEC-clone data acquisition system for T-15). Through a combination of tight budgets for hardware expenditures (176 million rubles for T-15, and 156 million rubles for TSP), bureaucratic inefficiencies, engineering difficulties, and questionable quality control, the Soviet fusion program has experienced significant delays in bringing the large-scale tokamak facilities, T-15 and TSP, into operation (see Sections II.C.1 and II.C.3). Comparable delays and problems with component reliability are difficult even to contemplate in Japan, Western Europe, and the United States, where there are so many capable high-tech industries.

Nonetheless, it would be a serious error to underestimate Soviet capability to develop fusion as a practical energy source, particularly in view of the significant human and intellectual resources committed to fusion research, and the possibility that *perestroyka* may eventually lead to a strengthened technological capability. Nowhere is this more evident than in the Soviet Union's vigorous and effective participation in the multinational ITER design effort (see Section II.C.1). The national experimental thermonuclear reactor (OTR) project has been restructured to support Soviet participation in the ITER activity (Roberts, 1989). The Directorate of OTR/ITER projects is headed by Ye. P. Velikhov, with the involvement of B. B. Kadomtsev, V. A. Chuyanov, V. V. Orlov, V. A. Krylov, Yu. A. Sokolov, and V. S. Strelkov in key technical and administrative roles. The Soviet effort focuses on all areas of ITER, with more than 30 full-time specialists and 100 part-time specialists involved in related technical activities. The major ITER activities are concentrated at five research institutes, with overall coordination provided by the Kurchatov Atomic Energy Institute. The five institutes and their areas of responsibility are indicated in Table II.4. To summarize, the Soviet effort on ITER is high quality and substantial in size. For example, 1989 funding at the Kurchatov Institute was 26 million rubles for ITER/OTR and ITER-related work on T-10 and T-15.

Table II.4
MAJOR ITER ACTIVITY AREAS AT SOVIET RESEARCH INSTITUTES

Institute	ITER Activity Area
Kurchatov Atomic Energy Institute (Moscow)	ITER project coordination; plasma theory; plasma heating; supporting experiments on T-10 and T-15.
Yefremov Electrophysical Apparatus Institute (Leningrad)	Engineering systems; superconducting magnets; pellet injectors.
Power Engineering Research and Design Institute (Moscow)	Nuclear technology systems; blanket; first-wall and divertor structural materials.
All-Union Materials Institute (Moscow)	Tritium systems and materials.
All-Union Power Engineering Research and Design Institute (Leningrad)	Reactor engineering systems; reactor facility layout; site selection and construction.

C. SUMMARY OF ASSESSMENTS

1. Tokamak Confinement

a. Overview

The basic idea of the tokamak was conceived in the Soviet Union in the early 1950s and led to the initiation of experimental studies in the middle 1950s on a series of small tokamaks in L. A. Artsimovich's division at the Kurchatov Institute in Moscow. Initial results from the T-3 tokamak, reported by Artsimovich in 1965, provided the first indication of improvement in confinement in the tokamak relative to other toroidal devices. By 1968-1969, the T-3A plasma parameters had been raised to the record values T_e = 1,000 eV, T_i = 400 eV, n_e = 4 X 10^{13} cm^{-3}, for pulse durations of about 50 milliseconds and with energy confinement times of about 7 milliseconds. As a result of the spectacular successes on T-3, a number of tokamak devices were put into operation outside the Soviet Union during the early 1970s. By far the most important area of progress during this period was the successful demonstration of techniques for auxiliary, that is, non-ohmic, plasma heating. The technique of neutral beam injection (NBI) was particularly effective, but it was developed largely outside the Soviet Union.

After 1975, a number of larger tokamaks, designed to extend the achievable plasma parameters, were brought into operation, including the T-10 device at the Kurchatov Institute. The T-10 was constructed at the Yefremov Institute in Leningrad. Unlike similar-sized tokamaks in the United States and Europe (for example, PLT at Princeton, Doublet III at General Atomics, and TFR-600 at Fontenay-aux-Roses), the T-10 device was designed with relatively small ports and without provision for neutral beam injection. However, a medium-size tokamak, the T-11, was also put into operation at the Kurchatov Institute to explore very intense neutral beam heating, resulting in then-record values of the plasma beta. During this period, also, a number of small tokamaks were built at the Ioffe Institute in Leningrad for the purpose of testing plasma heating both by adiabatic compression and by radio-frequency techniques.

During the decade of the 1970s, Soviet leadership in experimental tokamak physics declined, and, by the early 1980s, the Soviet tokamak effort was not at the forefront of the world program. By 1985, all three members of the present generation of large tokamaks, TFTR (1982), JET (1983), and JT-60 (1985), had become operational outside the Soviet Union, whereas completion of the Soviet T-15 device, which uses superconducting toroidal-field coils, continued to be delayed by engineering difficulties. Operation of the T-10 device was extended well beyond its planned shutdown date, in order to provide an operating facility for the Kurchatov experimental group.

The early history of the Soviet tokamak program, and its status as of late 1986, were described in the 1987 FASAC report, which also contains tables of the principal parameters of Soviet tokamaks and their auxiliary systems.

In the remainder of this subsection, the assessment of Soviet capability in the tokamak confinement area is organized according to the following topics:

- large tokamaks (T-10, T-15, and TSP);
- small tokamaks (Tuman-3, T-11, T-7, etc.);
- diagnostics; and
- ITER participation.

(1) Large Tokamaks

In recent years, the experimental tokamak effort at the Kurchatov Institute has focused almost entirely on the T-10 device. The original objective of the T-10, like that of comparable tokamaks in the West, was to extend the results of smaller tokamaks to higher plasma temperature, by increases in plasma current, toroidal field, and plasma size. The development of Soviet gyrotrons in the frequency range 80 to 90 GHz at 100 to 200 kW per tube provided the opportunity for a unique experimental program on electron cyclotron heating (ECH) with powers in the megawatt range. Fortunately, even multimegawatt ECH power could be launched through the small experimental ports on T-10.

The ECH source power on T-10 has been increased steadily from 1 MW in 1984, to 2 MW in 1986, and then to its present level of 4 MW, which first became operational in 1987. The present system encompasses 11 gyrotrons, seven at 81 GHz and four at 75 GHz, each rated at 400-kW power with a 100-ms pulse length. The power absorbed by the plasma is typically 60 to 70 percent of the source power. The principal result of the ECH experiments on T-10 has been that extremely high central electron temperatures are obtainable at maximum power, specifically $T_e(0)$ = 8 to 10 keV at $n_e = 1.5 \times 10^{13}$ cm^{-3} with P_{abs} = 2.0 to 2.2 MW (Alikayev et al., 1987b). However, the electron energy confinement time deteriorates with increasing ECH power, following the same relationship $\tau_{Ee} \propto P_{tot}^{-0.5}$ found with other auxiliary heating techniques (Alikayev et al., 1987a). The ECH results have been interpreted by the T-10 group as implying a strongly nonlinear relationship between cross-field transport and the electron pressure gradient, leading to a surprising insensitivity of the pressure profile to the profile of heat deposition (Esipchuk and Kadomtsev, 1986). The results of experiments on T-10 in which the ECH resonance is moved off axis are in agreement with this idea of "pressure profile consistency" (Alikayev et al., 1987a). A theory has been advanced to explain these observations (Kadomtsev, 1987), although the results of neutral beam heating experiments on other tokamaks (for example, TFTR and DIII-D) do not support the idea of invariance of the pressure profile. The scaling of energy confinement time in ECH plasmas also seems to be different from that found in neutral-beam-heated tokamaks, exhibiting only weak dependences on the plasma current but increasing strongly with plasma density; the density limit can be increased markedly by high-power ECH (Alikayev et al., 1989).

Since T-10 shares power supplies with T-15, it could be run only intermittently during 1989, when the emphasis shifted to bringing T-15 into operation. During a brief late-1989 run of T-10, low-voltage ECH-assisted startup was demonstrated, with a maximum toroidal electric field of only 0.3 V/m. One final run period is scheduled for March-June, 1990, to be devoted to electron cyclotron current drive (ECCD) experiments in support of ITER; new windows, mirrors, and waveguides are in preparation to launch the electron cyclotron waves in the direction of the plasma current.

The T-15 tokamak, a smaller substitute for the more ambitious reactor-prototype device called T-20, was approved in 1978, the world's first large tokamak to use technologically advanced Nb_3Sn superconducting toroidal-field coils. The related engineering problems have caused considerable slippage in the scheduled completion date of T-15, which was initially to be operational in 1983. By the middle 1980s, the completion date had slipped to 1988. Although "first plasma" was indeed achieved in December 1988, the T-15 device is not yet in useful experimental operation: an experimental run-period called "ohmic startup" is presently scheduled for early 1990.

The T-15 is a circular-cross-section tokamak, somewhat smaller than TFTR, with a toroidal field on axis of up to 3.5 T (to match the 83-GHz gyrotrons for ECH) and plasma currents up to 1.4 MA. The device itself is designed to be capable of higher fields (up to 4.5 T) and currents (up to 2.3 MA), and this enhanced capability may be implemented at some later stage, depending upon the availability of higher-frequency (124 GHz) gyrotrons. The ohmic-heating and poloidal-field coils are copper, limiting the pulse length to about 5 seconds. The T-15 device will be equipped with two auxiliary-heating systems: (i) an ECH system with twenty-four 83-GHz 400-kW gyrotrons of the same type as are used on T-10 (but new units) for a total ECH source power of about 10 MW; and (ii) an NBI system with three 80-keV (hydrogen), 3-MW beamlines, each with two ion sources, for a total injected power of about 9 MW. The power absorbed into the plasma from the ECH and NBI systems is projected to be about 6 MW and 5 MW, respectively.

The Nb_3Sn toroidal-field coils were built by the Yefremov Electrophysical Apparatus Institute and were successfully tested individually at the currents necessary to produce a 3.5-T field on axis in T-15. However, during the "first-plasma" experiments on T-15 in December 1988, it was found that the cryogenic system would not cool the coils below about 11 K (inlet) and 14 K (outlet)—well above the design value (4.5 K) and too high for superconducting behavior. Continued failure of the two-stage cryogenic system (first stage, liquid nitrogen; second stage, liquid helium), which is blamed on faulty design of the industry-built compressors, prevented any experimental operation in 1989. The downtime was used to install the full poloidal-field system, one neutral beam injector (without sources) and several diagnostics; also, the vacuum vessel was successfully baked to 250°C, with a base pressure of 10^{-7} torr.

The Yefremov Institute has been called in to rebuild the compressors, and cool-down of the cryostat resumed in December 1989, preparatory to a period of "commissioning and OH experimental startup" to extend through February, 1990. The objective during this period is to achieve a toroidal field of 3.0 T and a plasma current of 0.4 MA.

A further shutdown will begin in March 1990, and will extend through spring 1991. During this period, the full ECH and NBI auxiliary-heating systems will be installed. There is a possibility of a second brief period of ohmic experimental operation in late 1990, in parallel with installation activities. Operation with the full auxiliary-heating systems will begin in mid-1991.

The TSP (tokamak with high field, formerly called T-14) is a tokamak under construction at the Troitsk branch of the Kurchatov Institute, which seeks to use adiabatic compression to achieve very high values of plasma density, as well as reactor-like plasma temperatures. The eventual objective is to introduce deuterium-tritium plasmas and to approach fusion breakeven conditions. The TSP device was approved in 1979 and, like T-15, its completion has been delayed considerably.

The basic idea of adiabatic compression is to pre-heat a medium-density plasma to kilovolt-level temperatures and then to compress the plasma, in a time short compared with particle and energy confinement times, either in minor radius (by pulsing up the toroidal field) or in major radius (by pulsing up the vertical field, thereby pushing the plasma inward in major radius). In TSP, a combination of the two types of adiabatic compression is used—specifically compression in minor radius ($a = 0.32 \rightarrow 0.20$ m), followed by compression in major radius ($R = 1.6 \rightarrow 0.41$ m). Adiabatic compression in major radius was demonstrated first on the ATC tokamak at Princeton in the middle 1970s; combinations of minor and major radius compression have been tested on the Tuman-3 tokamak at the Ioffe Institute. Assuming that the plasma does behave adiabatically during compression, the density will rise by a factor equal to the ratio of the volume of the precompression plasma to that of the postcompression plasma, and the temperature will rise as the two-thirds power of the density. In TSP, the toroidal field on the axis of the precompression plasma is 2 T, and the field on the axis of the plasma in its final, postcompression position is 13 T. The plasma current increases by a smaller factor: from up to 500 kA precompression to up to 1.3 MA postcompression. The plasma density is to rise from about 5×10^{13} cm^{-3} to about 10^{15} cm^{-3}, and the plasma temperatures from about 2 keV to 10 keV. Compression in minor radius is to be carried out in about 10 ms; the subsequent major-radius compression must also be accomplished in a maximum of 10 ms.

Performance projections for TSP depend sensitively on the assumptions regarding the scaling of energy confinement with compression. Scalings of the "Alcator" and "neo-Alcator" type, which fitted the data from ohmically-heated tokamaks of the late 1970s and early 1980s, give highly favorable projections for the very-high-density compressed plasmas obtainable in TSP, roughly corresponding to Q-values (ratio of fusion power to input power) approaching unity if deuterium-tritium plasmas are used. However, present-day scalings, derived from data on auxiliary-heated tokamaks of the 1980s, are much less favorable to high plasma density and depend mainly on the value of plasma current; these scalings indicate much lower levels of performance for TSP, corresponding to $Q \leq 0.1$. If these scalings apply, then the energy confinement time in the TSP plasmas would become comparable to the compression time, implying that compression would not, in practice, be adiabatic.

Adiabatic compression requires large inductive energy storage, especially if the toroidal field is to be pulsed-up rapidly. For TSP, four motor-generator units are to be used to energize various inductive storage devices, including a large 1-GJ toroidal storage inductor (looking like the TF(toroidal field)-coil set on TFTR), which is to be used for all TF power, and two smaller cylindrical storage inductors to be used for ohmic heating and poloidal field power. A new electrical substation is under construction at Troitsk to provide the primary power.

At present, only one of the four motor-generator units is operational; the second unit has been installed but lacks an external power supply, while the third and fourth units have not yet been delivered. In any event, operation of more than one motor generator will not be possible until completion of the new substation, which has been delayed considerably. Because of these power-supply problems, the large 1-GJ toroidal inductor is not presently in use; instead, the smaller cylindrical inductors are being used for the TF in initial ohmic and auxiliary-heating experiments without compression. Initial ohmic discharges with plasma currents up to 150 kA at toroidal fields of about 1 T have been achieved. However, although the stray fields in the vacuum-field configuration were found to be very small, conventional OH operation produces large stray fields and high impurity levels—suggesting that the poloidal-field and plasma control systems have been poorly designed. Impurity problems are being addressed by a variety of graphite, carbon-carbon composite, and boron nitride limiter and tile techniques. Mechanical analysis of the vacuum vessel, especially the welds on the inner side of the torus, has shown that the present vessel will be inadequate to withstand the forces involved in full-compression operation.

During 1990-1991, the TSP device will be operated intermittently, with considerable downtime for installation of auxiliary heating systems (NBI, 2 MW; ICRH, 4 MW). Since the vacuum vessel will accommodate plasmas with various minor and major radii, the TSP will be particularly suitable for studies of the size-scaling of confinement in ohmically-heated plasmas with currents up to about 500 kA. With auxiliary heating, the objective will be to obtain precompression plasma temperatures of about 2 keV. During this period, work will also continue on the third and fourth motor-generator units.

With favorable assumptions on the completion of the needed power supplies, experiments on adiabatic compression of high-temperature plasmas could be carried out in 1992-1993. Prospects for tritium operation in TSP, tentatively scheduled to begin in 1994, have become quite uncertain and are discussed below in subsection II.C.1.b.

(2) Small Tokamaks

Small tokamaks in the Soviet Union include the Tuman and FT series of devices at the Ioffe Institute, the T-11 device, formerly at the Kurchatov Institute and now moved to Troitsk, the small superconducting device T-7 at the Kurchatov Institute, the very small TO-1 and TO-2 devices at the Kurchatov Institute, the T-3M device at the High Temperatures Institute in Moscow, and the TMR device at the Vekua Institute in Sukhumi.

The Tuman-3 tokamak has had a successful program of innovative experiments on RF heating, adiabatic compression, and control of MHD-like instabilities. It has been the testbed for the particular adiabatic compression techniques to be employed on TSP. It has strong diagnostics capabilities. The Tuman-3 program will apparently be continued through mid-1993, although the present vacuum vessel will be replaced in late-1990 to allow higher-field operation. It is proposed to replace the FT-2 tokamak at the Ioffe Institute with a new, very-small-aspect-ratio ($R/a \sim 1.7$-1.8) tokamak, called "Globus," which would use power supplies and diagnostics from Tuman-3. If funded, the new device could become operational at the end of 1993, about six months after the shutdown of Tuman-3. However, the prospects for the project, which would need capital funding through the Academy of Sciences, are regarded as uncertain.

The T-11 tokamak is now devoted to tests of high-power-density (~10 kW/cm^2) ICRH antennas. The very small tokamaks TO-1 and TO-2 (the latter with a toroidal divertor) are devoted to disruption-control and ICRH experiments, respectively. The NbTi superconducting tokamak T-7 is no longer operated. The T-3M tokamak is used for materials studies, especially novel limiter and divertor-plate concepts. The TMR is devoted to Alfvén-wave heating.

(3) Diagnostics

The plasma diagnostics available in the Soviet Union lack some of the sophistication of equipment available in the United States, Western Europe, or Japan. However, the diagnostics installed on the mainline Soviet tokamaks, for example, T-10, are generally sufficient to support the objectives of the experimental programs on these devices. Compared with the United States, there is less tendency to make multiple measurements of the same plasma parameters, and apparently less urgency to develop multichannel, high-spatial-resolution instruments. In regard to "standard" diagnostics for measuring plasma parameters and their profiles, the Soviet tokamaks are adequately equipped, but the Soviet Union has lagged behind the West in spatially-resolved spectroscopic measurements of ion temperature, preferring to rely on charge-exchange diagnostics, which become ineffective in larger tokamak plasmas. Diagnostic techniques developed outside the Soviet Union have often been successfully adapted to Soviet experiments, and the Soviet side has actively encouraged, under the bilateral agreement, long-term visits by diagnosticians from the United States.

In general, the conceptual design of diagnostics in the Soviet Union is superior to the fabrication of the actual instruments. The most advanced and innovative diagnostics development activity is at Leningrad (Ioffe Institute and Leningrad Physical-Technical Institute), and the small tokamaks at the Ioffe Institute are equipped with some relatively sophisticated instruments, for example, in the areas of Thomson scattering, laser fluorescence, and microwave scattering. The atomic physics group at the Ioffe Institute conducts state-of-the-art work in charge-exchange and H-alpha measurements and has now become interested in alpha-particle measurements using a diagnostic neutral beam. The diagnostics group at Troitsk is also fairly strong, with particular interest in neutron and alpha-particle diagnostics for TSP: the Troitsk group has been especially active in bilateral collaborations.

(4) ITER Participation

As a prelude to the Geneva Summit Meeting in November 1985, the Soviet Union proposed that the United States and the Soviet Union lead a collaborative effort to build a next-generation tokamak experiment. In October 1986, the United States, in consultation with Japan and the European Community, responded with a proposal on how to implement such an activity. The ensuing discussions led to the establishment, under the auspices of the International Atomic Energy Agency (IAEA), of the ITER Conceptual Design Activity, which began in 1988 and will extend through 1990. The ITER Activity is under the overall guidance of the ITER Council, composed of governmental representatives, and the Council is advised by an International Scientific and Technical Advisory Committee (ISTAC). The technical work is directed by the ITER Management Committee, composed of a managing director from each of the participants.

The Soviet Union has played a leading role in ITER from the beginning. Academician B. B. Kadomtsev, one of three deputy directors of the Kurchatov Institute and head of its Plasma Physics Department, chairs the ISTAC and has been a forceful advocate of ITER from its inception. Within the ITER structure, the Soviet Union supplies the head of one of the four Project Units (G. Shatalov, Nuclear Engineering), and the heads of two of the eight Design Units (V. Muratov, Containment Structure; V. Parail, Current Drive and Heating). The Soviet Union has also provided several key members of the "permanent" physics group on ITER, most notably V. S. Mukhovatov, previously head of T-11 at the Kurchatov Institute. Recently, V. A. Chuyanov was brought back from Troitsk to the main Kurchatov Institute to head the Technology Division of the Plasma Physics Department—a position that gives him responsibility for essentially all the Soviet work on and in support of ITER. Design activity on the comparable national device, namely, OTR, has apparently been almost entirely subsumed by ITER.

The Soviet program has also been particularly responsible in addressing ITER's R&D needs. Major technology R&D tasks are underway on 140-GHz, 1-MW gyrotrons, ion sources and accelerators for negative-ion beams, TF-coil conductors, properties of structural materials at cryogenic temperatures, liquefier and other cryosystem components, testing of high-Z materials for divertor plates, lithium-lead breeders, and blanket structural materials. The operating lifetime of T-10 was extended for the purpose of carrying out an electron cyclotron current drive experiment for ITER. The Soviet Union has also launched a major effort on the conceptual design of ITER diagnostics (Young et al., 1989)—an area in which it seems determined to have a strong input. The Khar'kov Physical-Technical Institute is nominally responsible for organizing the work on ITER diagnostics, but much of the conceptual work is done at the Ioffe Institute and at Troitsk, with Khar'kov and the Yefremov Institute providing about 15 engineers to support the effort.

Overall, the Soviet Union claims to have spent 26 million rubles for ITER/OTR activity and ITER-related work on T-10 and T-15 in 1989—approximately 18 percent of the total operating budget for fusion of 148 million rubles. (This would compare with about 5 percent in the United States.)

b. Outlook

Successful results on the T-15 superconducting tokamak and on the TSP tokamak in deuterium-tritium would restore the Soviet experimental tokamak program to forefront status. However, the delay in construction of T-15 has created a significant gap in the research capability of mainline tokamak devices in the Soviet Union relative to those in the United States, Western Europe, and Japan. Even now, the successful operation of T-15 cannot be assured, because the full superconducting toroidal magnet system has not yet been tested at design field.

The investigation of plasma confinement on T-15, using a combination of high-power electron cyclotron heating at 83 GHz and neutral beam injection, assuming that it occurs in the period 1991-1992 as presently planned, will provide significant information that cannot be closely matched in non-Soviet experiments. (The DIII-D device at General Atomics uses gyrotrons with a slightly lower frequency, 60 GHz, thereby limiting it to lower field and lower plasma density.) If the Soviet Union is successful in developing the higher-frequency (124 GHz) gyrotrons, the T-15 device, operated at a field of 4.5 T, would provide a truly unique test of the application of ECH at reactor-like plasma parameters. Although the Nb_3Sn superconducting toroidal-field coils have been the source of most of the delays on the T-15, their successful fabrication represents a significant engineering accomplishment in itself. However, because the pulse length in T-15 will be limited by the normal (that is, copper) ohmic-heating and poloidal-field coils, the use of superconducting toroidal-field coils will be of only marginal benefit in increasing the physics capabilities of the machine.

After one final experiment on electron cyclotron current drive, which seems likely to be successful in producing about 200 kA of noninductive current, the T-10 tokamak—operational since 1975—will be shut down in July 1990. A conceptual design has been carried out of a possible upgrade, called T-10S, which would have a new vacuum vessel to accommodate an elongated plasma and a double-null divertor. The implementation of this upgrade, not yet approved, will depend upon future budgets; its chances are not thought to be very high.

Despite problems with hardware, the mainline Soviet tokamak program at the Kurchatov Institute continues to be pursued vigorously, by a highly competent experimental staff with superb theoretical support. The research plans are well-conceived and take proper account of the results of tokamak research outside the Soviet Union.

The problems remaining to be solved before the TSP tokamak at Troitsk can be brought to full performance appear to be quite severe. Even if the power-supply problems can be solved, the machine itself may suffer from serious design flaws, both in mechanical strength and in plasma control. Although there is little doubt that a useful experimental program can and will be carried out on TSP, it is questionable whether the full compression capability will ever be exercised. If not, it seems unlikely that the minimum level of plasma performance said to be necessary to justify the introduction of tritium (specifically, $Q \geq 0.1$) will be reached. In the near future (1990-1991), the experimental program will be limited to ohmically and auxiliary heated plasmas without compression. It would be possible to correct the design faults and rebuild the flawed components in TSP, so that the originally intended level of performance, with compression, can be approached, but such a course of action would necessarily delay tritium well beyond the presently planned start date of 1994. A further serious difficulty has arisen in regard to tritium, in that an anti-nuclear group, called the "Greens," has become very active near Troitsk and has focused its attention on activities at the Institute. An attempt is underway to develop a deuterium-tritium operational scenario on TSP that will reduce the required on-site tritium originally planned level of 100 kCi to as little as 1 kCi. (Analyses of TFTR deuterium-tritium scenarios, taking into account the tritium hold-up on in-vessel components, indicates that it would be extremely difficult, if not impossible, to operate with so low an on-site inventory.)

Seemingly undismayed by these difficulties, the Troitsk group is working on a successor-device, called TSP-2, which would be an ignition-level deuterium-tritium burning device with 5- to 10-s pulses. However, no funds have yet been made available for engineering studies of such a device. The Troitsk group does have an impressive program on neutron and alpha-particle diagnostics, which should provide for an effective deuterium-tritium physics program whenever tritium operation becomes possible.

The prospects for the Soviet Union's smaller and more innovative tokamaks, which are now to be found mainly at the Ioffe Institute, depend on a sufficient flow of capital and operating funds through the Academy of Sciences. The Ioffe group has some good ideas for new machines, but expectations are not high that the needed capital funds will be approved.

At the present time, the Soviet experimental program is being adversely affected by distortions and instabilities in the Soviet economic system. It is openly acknowledged that these problems are complicating the production and distribution of materials needed in the fusion program, making it increasingly difficult for the program to generate meaningful schedules for its projects. As tokamak devices grow larger, it is increasingly necessary to have major components fabricated by industry, where quality control is not at satisfactory levels. At the same time, the productivity of the work force at laboratories such as the Kurchatov Institute is being reduced by a rapid rise in political activity and involvement, by shortages of required materials, by deprivations in the necessities of everyday life, and by the higher wages available in market-driven sectors of the economy.

Although the Soviet Union has continued to maintain a design effort on a very large reactor-class tokamak that would be built purely nationally, presently represented by the OTR study, the main thrust of the Soviet strategy for future fusion development has, for many years, been the internationalization of the design and construction of such a device. ITER now represents the major element in long-range fusion planning in the Soviet Union. Substantial technical resources are being devoted to ITER design and to ITER-related R&D activities, and it seems likely that political initiatives at the highest levels will be taken, aimed at producing an international commitment to proceed with ITER. The issue will arise first in 1990, when the ITER parties must decide whether to extend the activity into an "engineering design phase" beginning in 1991. Failing a further quadripartite agreement, it seems likely that the Soviet Union will seek a bilateral or trilateral agreement to build an ITER-like device.

The Soviet technical capability for constructing larger and more ambitious tokamaks is weaker than that in Western Europe, Japan, or the United States. Therefore, in the absence of international cooperation, the pace of Soviet progress towards a thermonuclear reactor would probably be slowed. However, it must be emphasized that the Soviet program does have the human and technological resources required to design and construct, without external participation, tokamak devices that could demonstrate the scientific and engineering feasibility of fusion, and could even begin to produce a small amount of useful fusion power. It follows that the Soviet Union would be a productive and valuable partner in an international program of fusion development and, in particular, in the design and construction of an ITER-like device.

2. Alternate Confinement Approaches

a. Overview

The status and outlook for Soviet research on stellarators and mirrors at the time of the 1987 FASAC report can be summarized as follows.

Stellarator research was reviving at the Khar'kov Physical-Technical Institute, and static at the General Physics Institute. Both groups were planning next-step devices. Serious field errors had been discovered in the Uragan-3 device at the Khar'kov Physical-Technical Institute. A reconstruction of the machine was planned, and a new medium-scale device, Uragan-2M, was to be constructed by the end of 1989. The stellarator group at the General Physics Institute was concerned that the successor to L2 (L2-M) might be cancelled as a result of reorganization of the institute.

At the time of the 1987 FASAC report, the prospects for mirror research were improving at the Nuclear Physics Institute in Novosibirsk. In particular, support was increasing for tandem mirror research (AMBAL devices), the multiple mirror approach (GOL series) and the Gas Dynamic Trap (GDT). In contrast, mirror research at the Kurchatov Institute was stagnant for lack of institutional support.

More recently, the Khar'kov stellarator group has continued at an increased level of activity. Uragan-3 has been reconstructed as Uragan-3M, and initial neutral beam heating experiments have been carried out. The schedule for Uragan-2M has slipped about one year, due to the late arrival of power supplies. The present completion date of Uragan-2M is December 1990. The L2-M project has been cancelled at the General Physics Institute, and the major activity of the group is focused on replacement of the L-2 vacuum vessel. This is required because the present vessel is 13 years old and the base pressure has reached unacceptable levels. This will require about one year of downtime. The time scale for a larger next-step device (2.5 m major radius) at the General Physics Institute is estimated to be four to five years in the future.

At present, the mirror research program at Novosibirsk appears to have progressed with new results reported from AMBAL, GOL, and the Gas Dynamic Trap. The Kurchatov mirror group appears to have revived, with increased activity on the PR-8 tandem mirror and the OGRA-4K superconducting cusp device. An earlier problem with the lack of liquid helium restricting the run-time of the Kurchatov mirror group has been resolved.

We now present a more detailed assessment of Soviet capabilities in the stellarator and mirror areas. Table II.5 lists the pertinent experimental facilities and institutes involved in research on alternate confinement approaches.

Table II.5

ALTERNATE CONFINEMENT RESEARCH IN THE SOVIET UNION

Institute	Confinement Approach and Facility
Khar'kov Physical-Technical Institute (Khar'kov)	Stellarators Uragan-3 and -3M Uragan-2M
General Physics Institute (Moscow)	Stellarators L-2 L2-M (cancelled)
Nuclear Physics Institute (Novosibirsk)	Mirrors AMBAL-10 (tandem mirror) GOL-3 (multiple mirror) GDT (gas dynamic trap)
Kurchatov Atomic Energy Institute (Moscow)	Mirrors PR-8 (tandem mirror) OGRA-4K (magnetic cusp) Mirror/Stellarator DRAKON (theory)

The L-2 device at the General Physics Institute is a small-scale torsatron with average mirror radius = 0.11 m, major radius = 1 m, and toroidal field ~1.5 T. The research group has continued electron cyclotron heating (ECH) studies since the time of the 1987 assessment. The machine operates routinely with 300 kW of second harmonic ECH at 75 GHz at a magnetic field of 1.33 T. However, the plasma pulse length is very short (10 ms) and is limited by the gyrotron power supply. A US-Soviet collaboration in ECH deposition calculations using ray-tracing codes from Oak Ridge (United States) and the General Physics Institute (Soviet Union) was carried out in 1989, and agreement was reported, despite the inferior computer hardware available to the L-2 group (Wilgen and Goldfinger, 1989). Plans for neutral beam heating on L-2 have been abandoned, but the T-11 beams (once destined for L-2) have apparently moved with S. V. Mirnov from intended application at the T-3M site at Shatura to the TSP tokamak at Troitsk.

At the time of the 1987 FASAC report, the L2-M device was the planned next step in the stellarator program at the General Physics Institute. L2-M has been cancelled, and the group's major project at present is the construction of a new vacuum vessel for L-2. This is required because the base pressure in the present vessel (installed 13 years ago) has increased to intolerable levels. The new vessel is ready for installation, which is thought to require about one year. The group is reportedly confident that a larger device (major radius ~ 2.5 m) will be constructed in a four- to five-year time frame, but no budget has been approved.

At the Khar'kov Physical-Technical Institute, Uragan-3 is a small-scale $\ell = 3$ torsatron (minor radius = 0.15 m, major radius = 1 m). As reported in the 1987 FASAC report, a joint US-Soviet exchange had disclosed serious field errors caused by improper construction. This flaw was utilized in a study of impurity screening by the ergodic magnetic layer (EML) produced by the field errors. The EML was found to screen light impurities with energies in the range 0.1-1 eV (State Committee on the Utilization of Atomic Energy, 1988). The surface physics group, headed by V. Voytsenya, employed a novel coating method for RF antennas (TiN) in the Uragan-3 device.

In addition to the field error problems cited earlier, it was reported in the 1987 FASAC report that neutral beam heating experiments on Uragan-3 were lagging. Since then, a new coil set has been constructed, the device has returned to operation, and the first (low-level) neutral beam experiments have been conducted (Harris, 1989). The heating power and pulse length were both very low: $P_{NB} < 30$ kW and $t_{pulse} = 10$-20 ms. The beam experiments are viewed as preparation for the next-step Uragan-2M device.

The Uragan-2M device is the next-step facility planned in the Khar'kov program. It is a small-scale torsatron (average minor radius = 0.22 m, major radius = 1.7 m, and toroidal magnetic field = 2.4 T). The device has relatively small helical ripple (edge ripple = 7 percent) and moderate rotational transform (i [0] = 0.2-0.57, i [a] = 0.75). The projected completion date has slipped from the original

1988-1989 schedule, and is now predicted to be December 1990. The 200-MW, 0.8-GJ flywheel generator for the Uragan-2M power supply was assembled in December 1988; and one of eight vertical field coils, and seven of 16 toroidal field coils were received in April 1989, with helical winding delivery scheduled for June 1990 (Bykov et al., 1990).

At the time of the 1987 FASAC report, the long equilibrium mirror/stellarator configuration, called the DRAKON, was under investigation at the Kurchatov Institute. However, activity in this area appears to have slowed. Theoretical work on the optimization of the straight sections by variable ellipticity has been carried out (Dobryakov, 1989), but there appear to be no plans for experimental work.

The major effort on magnetic mirrors in the Soviet Union is at the Nuclear Physics Institute in Novosibirsk, with smaller activities at the Kurchatov Institute in Moscow (Table II.5).

During the past few years, the mirror program at the Nuclear Physics Institute has reported new results on tandem mirrors (AMBAL series), multiple mirrors (GOL series) and the Gas Dynamic Trap. Single-cell experiments have continued in the AMBAL. A target plasma in AMBAL-10 with a uniform density distribution and electron temperatures up to 25 eV has been produced, with fast ion density up to $10^{12} cm^{-3}$ (State Committee on the Utilization of Atomic Energy, 1988). The Novosibirsk group has also continued multiple mirror research. The first stage of the GOL-3 device has been constructed, but no plasma results have been reported (State Committee on the Utilization of Atomic Energy, 1988).

The mirror group at the Nuclear Physics Institute has also reported experimental results from the Gas Dynamic Trap, which produces "sloshing" ions with 0.15 μs fast-ion lifetime (State Committee on the Utilization of Atomic Energy, 1988). The group claims good prospects for a future compact neutron generator based upon the GDT approach due to the absence of destructive modes associated with the sloshing ions.

At the Kurchatov Institute, results have been reported from the new PR-8 device and the superconducting magnetic cusp device, OGRA-4K. The PR-8 device is a tandem mirror with a 4 m central cell and a 2 T mirror field. PR-8 has started operation, with the goal of attaining a plasma density of $10^{12}cm^{-3}$ and electron and ion temperatures of 100 eV (State Committee on the Utilization of Atomic Energy, 1988). Ion cyclotron heating studies have also begun (Casey, 1988).

The OGRA-4 cusp device has attained a plasma density of $6 \times 10^{12}cm^{-3}$ with a 4-5 fold reduction in density in the null region. Earlier problems concerning the scarce supply of liquid helium at the Kurchatov Institute, which severely curtailed running time, appear to have been resolved (Casey, 1988).

b. Outlook

The stellarator program in the Soviet Union has steadily improved at the Khar'kov Physical-Technical Institute and remained static at the General Physics Institute. At the Khar'kov Institute, neutral beam experiments on the rebuilt Uragan-3 torsatron are expected to continue. These are viewed as preparation for the next-step Uragan-2M device, which is expected to be operational in December 1990. While Uragan-3 and Uragan-2M are likely to provide useful physics results, these devices are relatively small and are not expected to contribute in a major way to the evolution of the stellarator/torsatron approach in the international fusion program, as compared with the Advanced Toroidal Facility (ATF) in the United States, the Wendelstein devices (W-VII-AS and W-VII-X) in Western Europe, and the Heliotron-E and Large Helical Device facilities in Japan. The Khar'kov stellarator effort is perhaps more properly viewed as a Ukrainian national program, since there is little evidence of collaboration or coordination with the activities at the General Physics Institute. The L-2 device at the General Physics Institute is undergoing a much-needed renovation, but the prospects are uncertain for a next-step device, which has been sought by this group for the past 10 years. A larger facility is apparently at least four to five years from approval.

The mirror program in the Soviet Union has remained relatively stable, even in light of the reduced emphasis on mirrors in the international program. Mirror research at the Kurchatov Institute has been reinvigorated since the 1987

FASAC report, although recent changes in the management at the Kurchatov Institute may lead to a reassessment of the mirror activity there. The Nuclear Physics Institute in Novosibirsk has an active experimental and theoretical program, and this is expected to continue with the operation of the new GOL-3 device, and emphasis on the Gas Dynamic Trap (GDT) as a possible configuration for a fusion neutron source.

3. Plasma Technology and Engineering

a. Overview

Experimental advances in fusion plasma physics are often only possible after advances in the technologies for components which heat and fuel the plasma, and produce the confining magnetic fields. Capability is determined by specific laboratory and/or industry expertise and by the infrastructure which is needed to design and manufacture high-performance, reliable components and systems. For example, a successful ion cyclotron heating (ICH) effort requires specific knowledge and expertise on how to design, fabricate, and operate the fusion-specific RF launching structures, as well as the existence of laboratories and industries that can provide the required RF power sources and coaxial-line components.

The Soviet effort in plasma technology has made substantial and significant advances in nearly every area. A strong and continuing gyrotron development effort combined with an electron cyclotron heating effort on the T-10 tokamak and operation of a superconducting tokamak (T-7) seven years before any other nation are two examples. At the same time, these advances are qualified. T-7 has not received major emphasis within the ongoing Soviet program, as evidenced by its infrequent operation. In addition, there have been repeated delays in the completion of the superconducting T-15 tokamak due to both the quality of fabrication by industry and the difficulty in accessing that component of industry that can produce reliable components. Similarly, the short pulse length of the T-15 gyrotron systems will likely limit what can be accomplished on that facility relative to what will be done with the long-pulse sources on DIII-D at General Atomics in the United States, and the planned 2-MW, 110-GHz system on Tore Supra in France.

The present Soviet capability in heating, fueling, and magnet technology is assessed below.

Electron cyclotron heating has been the most visible and most successful element of the T-10 experimental program over the past several years. The T-10 ECH program utilizes a gyrotron system with higher frequency and greater total power, both installed and coupled, than that on the DIII-D tokamak. Experiments with over 2 MW of power in the 80-GHz range have been conducted on T-10. Both the power sources and the launchers have performed with sufficient reliability and efficiency to produce significant physics results. However, even though ECH is the focus of the T-15 program, no results have been reported on development of the gyrotrons with 1- to 3-second pulse lengths needed for the 10-MW T-15 system (Temkin, 1988), and the Soviet Union is reported also to be lagging behind the United States in high-power, long-pulse window development (Granatstein et al., 1988).

Soviet neutral beam experiments on the T-11 tokamak contributed to the early development of beam heating physics and technology. However, beams have not been used on T-10, and, as a result, recent contributions have lagged. Significant neutral beam heating is planned for T-15, and good progress on the ion source has been reported (Hogan, 1986). This system, while not competitive with TFTR, JET, or JT-60 in total power or energy, will still allow significant experiments.

The installed ion cyclotron heating (ICH) power on the T-10 and the U-3 stellarator indicates at least reasonable Soviet capability in producing megawatts of power in the tens of megahertz range. The power coupled to the plasma is, in each case, significantly less than the source power. This was also true for early experiments in the United States. In this case, utilization of the full source power required several years of committed development to improve the high-voltage standoff capability of the RF launchers and to minimize impurity generation. No ICH is planned for T-15. Low-power lower hybrid experiments (0.6 MW at 900 MHz) have been reported on T-7, but, as with ICH, there are no plans for T-15.

Pellet fueling experiments on T-10, using a copy of an early Oak Ridge pellet injector, were reported in 1985. There has been no follow-up to this work. Now, however, there are plans for a pellet injector on T-15, and, while no parameters have been given, development is reported to be underway (Casey, 1988).

The importance of superconducting magnet technology for tokamaks has long been recognized by the Soviet Union, as witnessed by the early commitment to and subsequent operation of T-7, and the commitment to build T-15 in the late 1970s. To be successful, the magnets in a facility like T-15 must be based upon an understanding of basic superconducting technology and be designed and fabricated with attention to detail and excellent quality (the need for high-quality manufacturing is also true for normal conducting magnet systems as well). An assessment of overall Soviet capability in superconductivity is outside the scope of this task, but it certainly seems adequate to support facilities the scale of T-7 and T-15 even though it is not likely to be competitive with the West and Japan. The difficulties with T-15 component fabrication are well documented; it is clear that the resources presently available to the Soviet fusion program are barely able to cope with a facility the scale of T-15, let alone a larger device.

b. Outlook

While the limitations of Soviet plasma technology and engineering are real, their implications with regard to future progress in the Soviet fusion program are less certain. The basis for this uncertainty lies in the substantial accomplishments of the Soviet space sciences program in the face of comparable, if not equally difficult, technology needs and the likely existence of better manufacturing resources that are currently not available to the Soviet fusion effort. With such support, it is reasonable to expect that the expertise that exists at the individual scientist and laboratory level that allowed the Soviet Union to be a leading fusion contributor in the late 1960s and early 1970s could be applied to present and planned large facilities. There was some hope that the high visibility of fusion under Gorbachev might have increased the priority of fusion within the Soviet Union and therefore improved the quality of industrial support. Apparently this has not happened, as T-15 schedules have continued to slip. Despite this disappointment, a change in the ability of the Soviet fusion program to "get things done" remains a possibility and would signal greater contributions in the future.

Even within the present constraints, Soviet advances are expected. This is particularly clear in the gyrotron area, where the combination of existing Soviet source technology (although long-pulse sources would be more desirable) and the stated program emphasis on T-15 will enable significant, if not leading, contributions to the development of electron cyclotron heating.

There are, at present, no plans for an ion cyclotron heating program on T-15. This would suggest that progress in Soviet ICH technology for large tokamaks is likely to be slow. However, there is no reason to believe that such an effort could not be mounted successfully over several years if it were allocated sufficient resources and given programmatic emphasis on T-15. A 10- to 20-MW system based on Soviet technology would likely have a larger number of low-power sources, but this should only affect the system's overall cost and complexity to a relatively small degree. The outlook for lower hybrid sources is similar to that for ion cyclotron sources except that a relatively larger number of sources might be required due to the greater difficulty of producing sources in the few gigahertz range versus the tens of megahertz range needed for ion cyclotron heating.

4. Fusion Nuclear Technology and Materials

a. Overview

Fusion nuclear technology (FNT) and materials research includes the reactor blanket, neutronics, tritium, plasma-interactive materials, and neutron-interactive materials. Until recently, the primary goal of the Soviet fusion program has been the development of hybrid (fission-fusion) reactors. Although most of the major fusion programs have some activities on hybrids, only the Soviet program has emphasized hybrids as the primary goal for fusion development (Orlov et al., 1989; Velikhov and Kartashev, 1989; Glukhikh, 1989), and the Soviet Union is the world leader in hybrid research. This has substantially influenced the activities of the FNT and materials research in the Soviet Union in several important ways: (i) the selection of technology, materials and design options, and the emphasis of R&D experiments and analysis has been focused on low-power-density blankets with neutron wall loadings in the range of ~1 MW/m^2; (ii) the fusion activities have been closely tied to the fission program; and (iii) the Soviet participation in international design activities for the next experimental fusion reactor, INTOR, in the early 1980s, and now ITER, has been very strong as Soviet scientists consider such a device to be a sufficient "demonstration reactor" for the hybrid system (Velikhov and Kartashev, 1989). It should be noted that Soviet fusion program policy has recently changed to more serious consideration of "pure" fusion reactors. This change is likely to impact the emphasis of future R&D programs in the Soviet Union.

The blanket options most favored worldwide are solid breeders and liquid metals. The Soviet program led the world in the solid breeder area in the late 1970s by performing sophisticated tritium release experiments in fission reactors. However, no Soviet experimental work in this area was reported in the 1980s. For the past 10 years, the contribution of the Soviet program to the development of solid breeder blankets has been limited to a modest design activity and some material property measurements.

The strongest area of FNT research in the Soviet Union is in the liquid metal blanket area, where the Soviet program is now in a world leadership position. About 10 organizations in the Soviet Union are involved in liquid metal research. The Yefremov Electrophysical Apparatus Institute is the scientific manager, and the Kurchatov Atomic Energy Institute administers the program. The Soviet liquid metal program involves the following elements: (i) liquid metal blanket concept development; (ii) MHD and heat transfer experiments and models; (iii) technology of electrical insulators and corrosion coatings; and (iv) applications of droplet jet and film flows (Karasev et al., 1986, 1988; Dem'yanenko et al., 1988). Powerful MHD facilities exist, most of which are located at the Leningrad Polytechnic Institute and in Riga (Dem'yanenko et al., 1988; Proc. US/Soviet Exchange I.4, 1988; Proc. US/Soviet Exchange II.5, 1989). The two largest facilities are located in Riga: (i) the MAGDA facility - a 5 T superconducting solenoid magnet, 80 cm bore, 310 cm long; and (ii) a 2 T normal-conducting dipole magnet, 600 cm long, 140 cm pole separation, 140 cm wide. Smaller facilities at Riga include sodium loops, a flow coupler loop, flow meter test stand, and the mercury laboratory. Similar small loops exist at the Leningrad Polytechnic Institute for supporting tests and instrumentation development.

Soviet research in liquid metal MHD includes theoretical analysis and confirmation experiments. Little computational modeling is possible due to the lack of computational hardware. Some computers exist, but they are slow and very limited in capability. Therefore, the computational modeling is based on many simplifying assumptions. The theoretical capabilities in the Soviet Union are outstanding. A large, permanent pool of capable experts allows this to occur. Experiments tend to be limited by several factors: relatively low quality of construction; lack of important equipment and accurate instrumentation; and limited data processing systems. Most experiments provide initial insights or gross comparison with theory. It is rare to see data of high enough quality to provide theory validation or an accurate database.

In the fusion neutronics area, the Soviet program has large manpower resources, but most of the technology now used is imported from the West. Fusion neutronics analysis requires basic nuclear data and calculational methods. Up to the early 1970s, the Soviet program was able to employ its own domestic experience, data, and tools from the weapons and fission programs. However, the very rapid development of computers and advances in technologies related to experimental techniques and instrumentation that occurred in the West have forced the Soviet scientists to import codes and data libraries from the United States and Western Europe.

The computer codes now used most often in the Soviet Union are US codes (Zagryadskiy et al., 1989; Orlov et al., 1984); for example, the Discrete Ordinate and Monte Carlo transport codes ANISN, DOT, MORSE, and MCNP. One transport code developed in the Soviet Union is BLANK, which is based on the Monte Carlo method. However, the use of these sophisticated codes in the Soviet Union is still seriously limited due to the lack of fast computers with large storage capacity, which are generally required for a comprehensive neutronics and shielding analysis of fusion systems.

The evaluated nuclear data files presently in use in the Soviet Union for fusion applications are primarily those from the United States (ENDF/B and ENDL) and Western Europe (for example, UKNDL). A local library (BROND) also exists (Zagryadskiy et al., 1989; IAEA Nuclear Data Report, 1988). The integral experiments for fusion neutronics and shielding in the Soviet Union are focused mostly on materials such as ^{238}U, ^{232}Th, and beryllium for hybrid applications. They are generally carried out in collaboration with other Eastern Bloc countries such as East Germany, Bulgaria, and Czechoslovakia. The experiments are generally limited to simple systems.

In the area of tritium processing for fusion systems, there is almost no contribution to the literature from the Soviet program. Soviet representatives to international design activities such as ITER appear not to have direct first-hand experience with tritium.

Compared to other world programs, the Soviet fusion materials program appears to be very limited in scope. The Soviet approach is to make use of materials that have been developed in other programs, primarily fission. In contrast to the large emphasis on developing an advanced structural material superior to austenitic stainless steel in the US fusion program, the Soviet approach is to accept the limitations on the operating conditions that are imposed by the use of existing materials.

The Soviet program in the plasma-facing components area is not substantial, and the level of effort is much lower than that in the West. However, one of the unique aspects of the Soviet program in this area is its emphasis on free surface devices for limiters and divertors (Murav'yev, 1988; Vodyanyuk et al., 1988). Soviet researchers have taken this innovative concept as far as actually installing and testing a droplet limiter device on the T-3M tokamak.

b. Outlook

The assessment of the Soviet fusion program in fusion nuclear technology and materials research reveals a number of important points that will affect its future progress. One major strength is the availability of a large pool of manpower currently working on FNT and materials research. However, plans for initiating new research activities and for construction of new facilities normally proceed at a very slow pace; and in many cases the plans are not implemented. The Soviet experimental work generally suffers from relatively low quality of construction and poor instrumentation capabilities. Theoretical analysis and analytical modeling efforts are intensive, but the Soviet computational modeling capabilities are weak. There is evidence of some effort to improve the quality of the experimental work and to develop better computational capabilities. However, the pace of future progress will depend upon the priority given the fusion program within the system towards having access to more advanced construction and instrumentation technologies and acquiring fast and large computers.

To date, the primary goal of the Soviet fusion program has been the development of hybrid (fission-fusion) reactors. This has substantially influenced the Soviet FNT and materials research program in several ways. The fusion program has relied on the fission program for providing much of the needed database, and the use of existing structural materials, for example, austenitic stainless steel, rather than the development of new materials, was planned. Recent changes in the attitude of the Soviet public toward nuclear fission, in the post-Chernobyl period, is having an impact on the fusion program. Many Soviet fusion scientists are now arguing for the need to consider "pure" fusion reactors. This will require substantial changes in the Soviet R&D program for FNT and fusion materials. The Soviet program will have to consider the issues of high power density, development of new materials, and safety and environmental impact. The reliance on the fission program to supply the database will not be adequate, and new programs capable of providing the required fusion-relevant data will have to be initiated.

FNT and materials research can generally be divided into five areas: (i) blanket, (ii) neutronics, (iii) tritium, (iv) neutron-interactive materials, and (v) plasma-interactive materials. Blankets include liquid metal and solid breeders. The Soviet program has contributed very little to the published literature on solid breeder blankets and on tritium systems. It is unlikely that this situation will change in the near future. The Soviet neutron-interactive materials program is limited and relies on existing materials. Without a new major initiative and substantial commitment of resources and facilities, the ability of the Soviet program to develop independently new materials is limited. The strongest area in the Soviet FNT R&D program is in the liquid metals area, in which the Soviet program has excellent capabilities in facilities and manpower. The Soviet program is making substantial progress and will most likely continue to excel in liquid metal technology. The neutronics activities will likely continue to be strong, but the dependence on the West to provide advanced computer codes and nuclear data will continue.

5. Plasma Confinement Theory

a. Overview

Soviet theorists have been, and remain, among the most talented, most mathematically sophisticated, and best trained in the international fusion program. During most of the 1960s and 1970s, Soviet theoretical leadership was evident across a broad front of crucial confinement issues. Beginning sometime in the middle 1970s, however, the Soviet theory program—like other parts of the Soviet fusion effort—suffered a loss of momentum. Part of the problem stemmed from delays in Soviet experimental projects, the essential impetus to frontline theory. Weaknesses in computational hardware, during a period when numerical simulation was occupying an increasingly larger scientific domain in the West, also detracted from Soviet theoretical achievement. Furthermore, Soviet confinement theory suffered the loss of several of its leading talents, either to other programs (as in the cases of Galeyev and Sagdeyev) or to administration (as in the case of Kadomtsev). Finally, Soviet science has been handicapped for decades by inadequate communications hardware: the paucity of duplicating equipment is perhaps the most notorious example. Awkward communication, which affects not only paper exchange but also telephone and electronic media, has pervasive effects on scientific momentum with far more than nuisance significance.

Thus, Soviet confinement theory entered what appears to have been a 10-year plateau in growth. While continuing to produce work of impressive quality, it lost its position of leadership to the West. The 1987 FASAC report, noting the program's basic intellectual strengths, suggested that Soviet fusion theory was capable of rapid revitalization. Here we find, beginning in the late 1980s, increasingly convincing evidence that recovery is in progress.

One impetus to theoretical resurgence is enhanced computational power. Even by 1987, Soviet simulation of MHD equilibrium and stability was competitive with, if less extensive than, that in the United States. The accelerated progress since then is discussed in the following section; here we note simply that improved computational capabilities are manifest in virtually all current Soviet theory literature. Following a now familiar pattern, the enhanced computing power has affected which problems are attacked, the methods of solution employed, and the manner in which results are displayed. Indeed, the literature now displays a nonchalance—new since the previous report—in using computer graphics and related tools that suggests the ready availability of such implements (see, for example Zaytsev et al., 1989). Although Soviet scientists continue to complain about computational deficiency (Bulanov et al., 1989), the theory literature, at least, would suggest capabilities generally approximating those used by US theorists.

A second encouraging sign is the apparently burgeoning population of younger theorists in the program. The infusion of new talent is especially evident in Soviet nonlinear dynamics research, somewhat peripheral to plasma physics, but it is visible in other areas, such as mirror confinement theory, as well. The Space Research Institute, under Galeyev, seems to have had particular recent success in attracting young Soviet scientific talent. Whether the skill and enthusiasm of such interdisciplinary groups will benefit controlled fusion remains to be seen.

Soviet nonlinear dynamics research appears to have become the largest, and probably the strongest theory program in this area anywhere. Thus, the 1989 Kiev conference, "Nonlinear World," attracted hundreds of participants and produced over 200 papers, the great majority by Soviet authors: clear evidence of a nonlinear effort several times larger than that in the United States. Historic Soviet scientific preoccupations make such strength unsurprising, but it is nonetheless impressive. Soviet nonlinear physics has shown dramatic growth and widening influence in the past few years.

While its bearing on plasma confinement is not established, nonlinear dynamics offers the possibility of casting fundamental light on plasma turbulence and anomalous plasma transport—a possibility that Soviet theorists take very seriously (plasma physics played a central role in about a third of the papers in the Nonlinear World conference). Indeed, Soviet theorists evidently believe that a fundamental understanding of plasma turbulence can follow only from an understanding of the nonlinear coherent structures—solitons, cavitons, and related objects—that are believed to underlie it. Thus, one studies, for example, the turbulent "soliton gas," typically making essential use (as in corresponding US studies) of computer simulation (D'yachenko et al., 1989). Applications of such notions to plasma confinement physics remain relatively primitive, yet often interesting (Isichenko, 1989). In comparison, the US turbulence program is much more advanced with regard to tokamak phenomenology and modeling, while less committed to any prior understanding of coherent phenomena.

A key advantage of Soviet theoretical traditions is especially, but by no means exclusively, visible in the nonlinear dynamics area: the very healthy integration of plasma confinement with other areas of physics. Thus, plasma cavitons, for example, are considered in the context of quantum field theory, while plasma turbulence is viewed in its relation to ordinary fluid turbulence. This remains a striking feature of the Soviet theory literature, and its benefit to plasma confinement science—in terms of new ideas, of sophisticated methodology, of "perspective"—has never been more evident.

The weaknesses of present Soviet theory lie in what US theorists would consider the confinement mainstream: tokamak experimental interpretation, applied turbulence theory, and anomalous transport. Although hardware deficiencies are likely to have affected Soviet research in these areas, the main problem stems, as noted above, from the Soviet experimental hiatus. More than ever before, tokamak theoretical research is driven by experimental discovery, and the most instructive data tend to be local data. The obsolescence of T-10 and delays of T-15 have handicapped Soviet theory.

Thus, with regard to one of the most exciting experimental developments of recent years, the tokamak H-mode, Soviet theorists have been effectively silent—a surprising circumstance, in view of recent Soviet contributions to the related area of tokamak edge physics (Nedospasov et al., 1985; Nedospasov and Fidel'man, 1988). The study and control of tokamak sawtooth oscillation and disruption, areas in which Soviet leadership was once undisputed, now advance primarily due to US and West European research. Soviet numerical simulation of such fluid phenomena is especially laggard—despite the critical role of simulation in understanding fluid evolution. Finally, the relatively weak Soviet theoretical program in anomalous transport has not gained ground in recent years. Soviet theorists have themselves drawn attention to weaknesses in their applied turbulence effort (Bulanov et al., 1989).

Of course there are also areas, close to the mainstream, in which Soviet theory is more impressive. With regard to RF heating and wave propagation, for example, Soviet theory seems not far from the Western standard. In the linear analysis of resistive instabilities, including resistive ballooning modes, "kinetic" tearing modes, and the like, Soviet research is similarly state-of-the-art (Mikhaylovskiy et al., 1989). Soviet stellarator research remains excellent, although somewhat hampered by computational weaknesses. Finally, Soviet theoretical research in magnetic mirror confinement—an area largely abandoned in the United States and Western Europe—is active and of very high quality (Stupakov, 1988). This field has also benefited from ties to other, more basic physics areas; but it has experienced morale problems with the termination of the US mirror effort.

b. Outlook

The driving force and direction of the Soviet controlled fusion effort, like that of all the major fusion programs, is provided by experimental physics, not theory. So long as Soviet confinement devices remain in the second rank, it is unlikely that Soviet confinement theory will overtake research in Western Europe and the United States. On the other hand, novel and exciting results from T-15 or TSP will surely stimulate correspondingly exciting and influential advances by Soviet theorists.

The talent is there. It is impossible to come away from a reading of recent Soviet theory literature without immense respect for the imagination and skill it displays. The special place of theory in Soviet science continues to yield work of unusual quality, even if the quantity has been diminished in recent years.

Aside from this reserve of scientific strength, there are other reasons to be optimistic regarding Soviet confinement theory. The expanding computational limits have already brought visible benefit; we anticipate accelerating gains in this area. Better communication, inevitable for both technological and political reasons, is certain to induce healthy theoretical ferment—perhaps especially in the theory community, with its history of fragmentation and detachment. Already signs of improved integration are visible; for example, the theorists at the Keldysh Applied Mathematics Institute, experts in MHD simulation, appear to be contributing to the main lines of Soviet confinement research much more effectively than in the past (Reiman, 1988). Finally, the ITER Conceptual Design Activity, taken very seriously in the Soviet Union, may well serve to organize and inspire important theoretical advances, even if that program stops at something less than device construction. However, the impact of the Soviet fusion experimental program on Soviet theory can hardly be overstated. Soviet confinement experiments need to catch up with those in Japan and the West.

6. Fusion Computations

a. Overview

The overall status and outlook for Soviet fusion computations at the time of the 1987 FASAC report can be summarized as follows.

Soviet computational capability, while restricted to a small number of practitioners, was of high quality and adequate to support existing experiments and to design more advanced devices. The more advanced data acquisition systems were acquired from the Central Research Institute for Physics in Budapest. These systems were judged to be adequate for the Soviet Union's most advanced operating tokamak, T-10, and a more sophisticated system was being installed for the T-15 device. Finally, engineering calculations did not rely very heavily on computational methods, thereby necessitating a conservative design approach.

At the time of the 1987 FASAC report, a small number of Soviet computational groups produced high-quality work, typically oriented toward the problems associated with experimental devices and next-step activities. This has not changed in the present assessment, but there has been a noticeable acceleration of the Soviet computational effort, partly as a result of participation in the ITER design activity. Computations related to device engineering have improved the most.

In general, the present assessment finds that Soviet computational capability has grown in strength. The research group at the Keldysh Applied Mathematics Institute remains the most productive and innovative, and this group is well-connected both to the mainline Soviet fusion effort and to the international research effort. The T-15 data acquisition system has been completed, and a sub-system is used for T-10 data acquisition activities. However, the adequacy of the overall design will be proven only when integrated operation of T-15 begins. (Restricted, first-plasma operation was reported in early 1989.) The initiation of the ITER design activity has led to new developments in engineering calculations; the most noteworthy is the Soviet contribution to configurational stabilization.

In the remainder of this subsection, the assessment of Soviet capabilities in fusion computations is organized according to the following topics:

- scientific computing (configurational optimization, experimental interpretation, preparations for T-15 and TSP, and ITER divertor modeling);

- data acquisition; and

- engineering computations.

(1) Scientific Computing

The computational group at the Keldysh Institute continues its high-quality work in the area of configurational optimization. Significant new results have been presented and new codes developed. The finite-element two-dimensional stability code has been applied to ITER optimization problems (Tsunematsu et al., 1989). The results contributed to the choice of the ITER plasma elongation. The three-dimensional stellarator equilibrium code has been completed and the results demonstrated. It has the unique capability to model non-star-like (multiply-connected) regions, which are of interest in stellarator/torsatron optimization studies (Medvedev, 1987). Degtyarev and Medvedev spent several months comparing results from their code with the Terpsichore code being developed by the Lausanne group.

A two-dimensional plasma transport code has been developed by the Keldysh group, with the first application to the study of compact torus configurations (Galkin et al., 1989). Such codes are widely used in the analysis of confinement in shaped tokamaks (such as ITER), and this code could be applied to tokamaks. The Keldysh group has also developed an anisotropic pressure equilibrium code, with application to mirrors (Drozdov and Martynov, 1989).

In the area of experimental interpretation, interpretation of the T-10 electron cyclotron heating experiments has been pursued since 1987, including a study of "profile consistency" using two-frequency electron cyclotron heating (ECH). Application of two-frequency ECH allowed the heating zone to be moved and transport models tested (Dnestrovskiy and Pereversev, 1988). The researchers found that a diagonal transport matrix was inadequate to explain the experiment. This result typifies why the Kurchatov group's intellectual level in the interpretation of experimental results remains the best in the world: the Kurchatov group characteristically takes an active approach to the validation of theoretical or semi-empirical models. Western and Japanese researchers typically have a more passive approach, and attempt to extract scaling relationships from amassed databases.

A US-Soviet exchange on the search for high-energy tails produced by electron cyclotron heating reported a null result (Hokin, 1988), but illustrated the capability of the T-10 group to work productively with Western researchers. This is the first significant demonstration of this capability in recent years. (A Culham team made Thomson scattering measurements on the T-3 tokamak in the 1960s, and other exchanges with the United States have involved relatively short visits.)

In the experimental design area, computational work in preparation for T-15 plasma control systems was seen as likely at the time of the 1987 FASAC report. More details have become known about the status of the TSP tokamak at Troitsk, and the control problems appear to be more challenging. Also, the ITER design activity has begun, and the Soviet group has participated actively in that effort. Thus, plasma control activities appear to have shifted from T-15 (although work continues in this area) to TSP and to the ITER design effort.

The development of fast axisymmetric stability codes, based on Fourier methods, has been a major Soviet contribution. Activity in preparing for T-15 operation using these codes has continued with emphasis on real-time control using magnetic-surface reconstruction from magnetic probe signals (Vabishchevich and Zotov, 1987).

As described in Section II.C.1, the TSP device has a severe plasma control problem. Yu. V. Gribov has developed a simplified axisymmetric stability code. Since the 1987 assessment, Gribov has carried out preparatory work for its application to TSP (Gribov et al., 1988).

Significantly, it is Gribov who has assumed a lead role in ITER configurational stability. The Soviet home team was able to respond in a one-week time scale to assess the vertical stability of a proposed single-null divertor design for ITER, receiving the CAD output of the configuration on 5 January 1990, and completing the analysis by 12 January 1990 (Wesley, 1989).

In the ITER divertor modeling area, the Kurchatov divertor code has been used to model ITER plasmas, and A. Kukushkin and Yu. Igitkhanov have played a leading role in ITER divertor design activities. One of the strengths of the Soviet computational effort is the strong analytical capability to understand the code results. Therefore, self-oscillations predicted by the divertor modeling code (and potentially important in understanding the L-mode to H-mode transition in divertor plasmas) have been investigated analytically.

(2) Data Acquisition

The T-10 data acquisition system was described in the 1987 FASAC report, and several visitors have used the system recently (Hokin, 1988). The T-10 system is actually a T-15 subsystem being used for T-10. While it is apparently widely used and adequate for T-10 needs, Hokin's IBM PC/XT accounted for approximately 40 percent of the archived T-10 data.

The complete T-15 data acquisition system was described in the 1987 FASAC report. The quality of the system will receive its first real test with the integrated operation of all the major subsystems of T-15, which has not yet occurred.

More details on the activities surrounding the TSP tokamak have been reported recently, and the first visits by US scientists to the Troitsk site have been made. The computational support for the TSP facility has been reported by US visitors to be superior to that at the Kurchatov Institute's main site, although doubts have been expressed that the system will be able to handle the predicted rate of 26 MB per shot (Overskei, 1988). The interest of the Troitsk director (V. Pis'mennyy) in computational capability is believed to be responsible. This interest includes the establishment of a well-equipped computer learning center for children at the Troitsk site (Brooks, 1989). A Soviet scientist, V. Kalmykov, from the Ioffe Institute, reported that Pis'mennyy had obtained two CONVEX mini-supercomputers for the Troitsk computational center (Hogan, 1988). Computational physicists from the main Kurchatov Institute and the Keldysh Institute appear, however, to provide the primary computational support for TSP.

(3) Engineering Computations

The Gribov code has been applied to the ITER plasma control problem, where the dependence of axisymmetric mode growth rate on blanket segmentation is a challenging issue (Gribov et al., 1989a-c).

The Soviet participants in the ITER activity have reported the use of CAD systems at the Yefremov Institute. However, they are eager to use the MEDUSA software favored by the West European NET team, for compatibility.

The ITER activity was the first customer for an electronic mail bulletin board established as part of the US-Soviet "telebridge" project. The system hardware has proven to be reliable, but the system is apparently too expensive. ITER participants favor use of a newly-installed FAX machine at the Kurchatov Institute for communications. The number of users on the Moscow electronic mail bulletin board has now increased from about five to 50, with participation by high-energy laboratories and various West European industries.

b. Outlook

The Soviet program in fusion computations is expanding in terms of the number of people involved, the degree of difficulty of the problems undertaken, and its impact on the international program through the ITER design activity.

In the area of scientific computing, increased access to PC-level computing resources has supplemented the traditional analytical capability of fusion physicists in the confinement and poloidal field design areas. There is no evidence of access to improved mainframe capability. (The 20-year-old BESM-6 is most frequently cited.) Nonetheless, through heavy emphasis on optimization of algorithms, challenging problems such as those of three-dimensional plasma equilibria have been undertaken and solved. This trend should continue, and would receive a major enhancement if modern mainframe hardware were to be made available to Soviet researchers.

Data acquisition activities continue, for the most part, to rely on Eastern Bloc hardware, although there is great interest in acquiring up-to-date systems. The most elaborate system, for the T-15 complex, is about to receive its first integrated test. This system should prove to be adequate for control and data acquisition activities.

In the engineering area, participation in the ITER design activity has stimulated improvement in the Soviet capabilities in this area. Application of efficient axisymmetric stability codes is an example of the improved impact of the Soviet engineering effort on the ITER design process.

Native CAD software is said to be available, but the Soviet Union would prefer to acquire West European systems, for compatibility with other ITER parties and with the West European NET team.

The increased impact of engineering computations is also a consequence of more widespread access to PC-level computing resources, and this progress is expected to continue.

CHAPTER II: ASSESSMENT OF SOVIET MAGNETIC FUSION RESEARCH REFERENCES

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CHAPTER III
ASSESSMENT OF WEST EUROPEAN MAGNETIC FUSION RESEARCH

A. INTRODUCTION

A detailed assessment of the status and outlook for magnetic confinement fusion research and development in Western Europe is presented in the recent FASAC report *West European Magnetic Confinement Fusion Research.*[1] This chapter summarizes the principal findings of that report.

The West European fusion program combines the scientific resources of some 10 nations, within and outside of the European Economic Community (EC), in the pursuit of controlled thermonuclear fusion energy. Organized in 1959, the program has a history of pivotal contributions to the international fusion effort. Its paramount role in experimental magnetic fusion research has become especially clear in the past decade (see, for example, White et al., 1989)—mainly, but not exclusively, because of accomplishments associated with the Joint European Torus, JET.

The international quest for fusion power is focused within four large programs of comparable size: those of the United States, the Soviet Union, Japan, and Western Europe. The West European effort is distinct in involving several nations. While it is a genuinely unified program, with a considerable degree of centralized planning and budgeting, its international character has encouraged a certain creative breadth. At the same time, the program has benefited from long-standing European national traditions of scientific excellence.

The program employs some 1,200 physicists and engineers, mainly at 16 facilities throughout Western Europe. It is notable for the mobility enjoyed by its sci-

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1 R. D. Hazeltine, K. W. Gentle, J. T. Hogan, M. Porkolab, D. J. Sigmar, D. Steiner, and K. I. Thomassen, *West European Magnetic Confinement Fusion Research,* Foreign Applied Sciences Assessment Center, Science Applications International Corporation, McLean, Virginia, January 1990.

entists, nearly a quarter of whom are working at laboratories outside their home countries during a typical year. Its budget during the first half of the 1980s (including EC funds as well as funds allocated directly by member states) was approximately two-thirds the US magnetic fusion research budget for the same time period. Recent budgets have exceeded those of the United States. Present West European manpower devoted to magnetic fusion has been estimated to exceed the US manpower commitment by some 60 percent (Willis et al., 1989).

Of course the inevitably looser central control of a multinational program has occasioned some inefficiencies: instances of redundancy, delay, and vaguely motivated research can be identified. Furthermore, areas in which the West European program lags can be discerned in both science and technology. But the overriding impression of the panel is that the West European fusion program has well earned its reputation for scientific and technological excellence. Indeed, the panel finds the present West European competence in magnetic fusion science and engineering to be unexcelled in the international effort.

Following a brief description of the organization and planning of fusion research in Western Europe in Section III.B, the status and outlook for West European fusion research and development is summarized, in Section III.C, in the following six areas:

- tokamak confinement;
- alternate confinement approaches;
- fusion technology and engineering;
- fusion nuclear technology and materials;
- plasma confinement theory; and
- fusion computations.

The reader is referred to the FASAC report *West European Magnetic Confinement Fusion Research* for more detailed assessments and the associated bibliography.

B. ORGANIZATION AND PLANNING OF FUSION RESEARCH IN WESTERN EUROPE

As a coordinated international effort, the West European controlled fusion program has had to address unique challenges in management and organization. Its success in orchestrating the research of 10 nations—not all of which have the same scientific goals or fusion ambitions—has been striking. The program is, in fact, a widely acknowledged exemplar of international scientific collaboration.

Despite the fact that two participants are not member states of the European Community (EC), the West European fusion program is part of the European Atomic Energy Agency (EURATOM) and thus formally subsumed by the EC (Maisonnier, 1989; Palumbo and Harries, 1987). In fact, the program originates from agreements entered in 1959, close to the time of the Treaty of Rome, and is formally administered by the Commission of the European Communities (CEC) in Brussels, Belgium.

Because of its international character the program serves, somewhat more than other fusion efforts, political as well as energy-research goals. In particular, it has been enlisted in the general cause of European unity—a role it has performed well. At the same time, the program displays a special diversity, with easily distinguishable and surprisingly independent national programs. It is, in this sense, a peculiar hybrid of national-international effort.

With specific regard to program management, two features most distinguish West European fusion research: (i) relatively loose program reins, allowing for considerable local autonomy; and (ii) relatively long-term budgeting, providing continuity at some expense in flexibility. The first feature, an unsurprising consequence of competing national interests, has occasioned some impatience on both sides of the Atlantic. It may not survive the modern era of larger fusion experiments and stronger international collaboration. The second feature is easily exaggerated, as shall be shown, yet it seems to have benefited the West European research environment.

A third general comment refers more to program direction rather than organization. At least during the period under review, West European fusion planning has been distinctive in its relative emphasis on plasma confinement science, rather than eventual reactor design. Experiments have been commonly proposed more on the basis of what is known and what needs to be understood, with less emphasis on ultimate reactor application. Thus, along with the greater emphasis on science, one can say that West European planning tends to "roll-forward" from what is known, rather than to "roll-back" from some criteria for reactor performance.

JET, the largest tokamak in the world, is also the only one built and operated by a thoroughly international team. Its widely recognized position as "the most outstanding example in fusion of a collaborative project . . . ." (Stacey and Roberts, 1985) reflects not only scientific energy and skill but also outstanding sensitivity in management. Yet, the JET leadership continues to face significant challenges with regard to retaining the highest quality personnel.

With regard to program size and scope, ten nations officially belong to what is sometimes called the "European Fusion Program": eight member states of the European Community (Belgium, Denmark, France, West Germany, Italy, Spain, The Netherlands, and the United Kingdom), plus two non-EC members (Sweden and Switzerland) (Maisonnier, 1989; Palumbo and Harries, 1987). The program employs some 1,200 physicists and engineers at roughly 16 institutions throughout Western Europe. It is acclaimed for the mobility enjoyed by its scientists, nearly a quarter of whom are working at laboratories outside their home countries during a typical year (Maisonnier, 1989).

Its budget during the first half of the 1980s (including EC funds as well as those allocated directly by member states) was roughly two-thirds the US fusion research budget for the same time period. More recent budgets exceed those of the United States; expenditures for 1986, for example, were approximately $455 million.

The experimental program comprises some 30 confinement devices of significant size, including tokamaks, stellarators, pinch devices, and compact tori. West European research in tokamak confinement is especially strong, including an operating tokamak with superconducting coils, Tore Supra; a clearly leading divertor experiment, ASDEX; and what is now widely acknowledged as the most successful tokamak device of the international fusion effort, JET.

The construction and operation of JET, the largest operating tokamak in the world and an obvious jewel of the West European program, has been managed with particular skill. As part of a distinct "Joint European Undertaking" within the EC, it has been described as ". . . certainly the most outstanding example in fusion of a collaborative project . . . a very successful international collaboration" (Stacey and Roberts, 1985).

With regard to organizational structure, EURATOM research on fusion is conducted by 16 institutions in the 10 nations. Thirteen of these institutions are the so-called National Associations, or simply "Associations," each of which typically includes several laboratories. Thus, for example, the Swedish Research Commission, one of the Associations, operates laboratories at Stockholm, Göteborg, and Studsvik. Similarly, the *Commissariat à l'Energie Atomique* (CEA) operates four laboratories in France. The remaining three institutions are non-national organizations: the JET Joint Undertaking, discussed above; the Joint Research Center, Italy, which, although primarily devoted to engineering aspects of fission energy, contributes to fusion technology; and the NET (Next European Torus) design team, formed in 1983 to plan a successor to JET. We note here that three nations—Greece, Ireland, and Luxembourg—participate in the JET project without Contracts of Association with EURATOM.

The Associations are obviously responsible to corresponding national bodies, as well as to EURATOM. In a manner to be described, they are managed by both. Similarly, JET has, along with its ties to the EURATOM offices, separate channels of responsibility to national institutions. At a higher management level, EURATOM, as part of the CEC, reports to the EC Council of Ministers, which must formally approve all major fusion program spending. Key features of this organizational structure are depicted in Figure III.1.

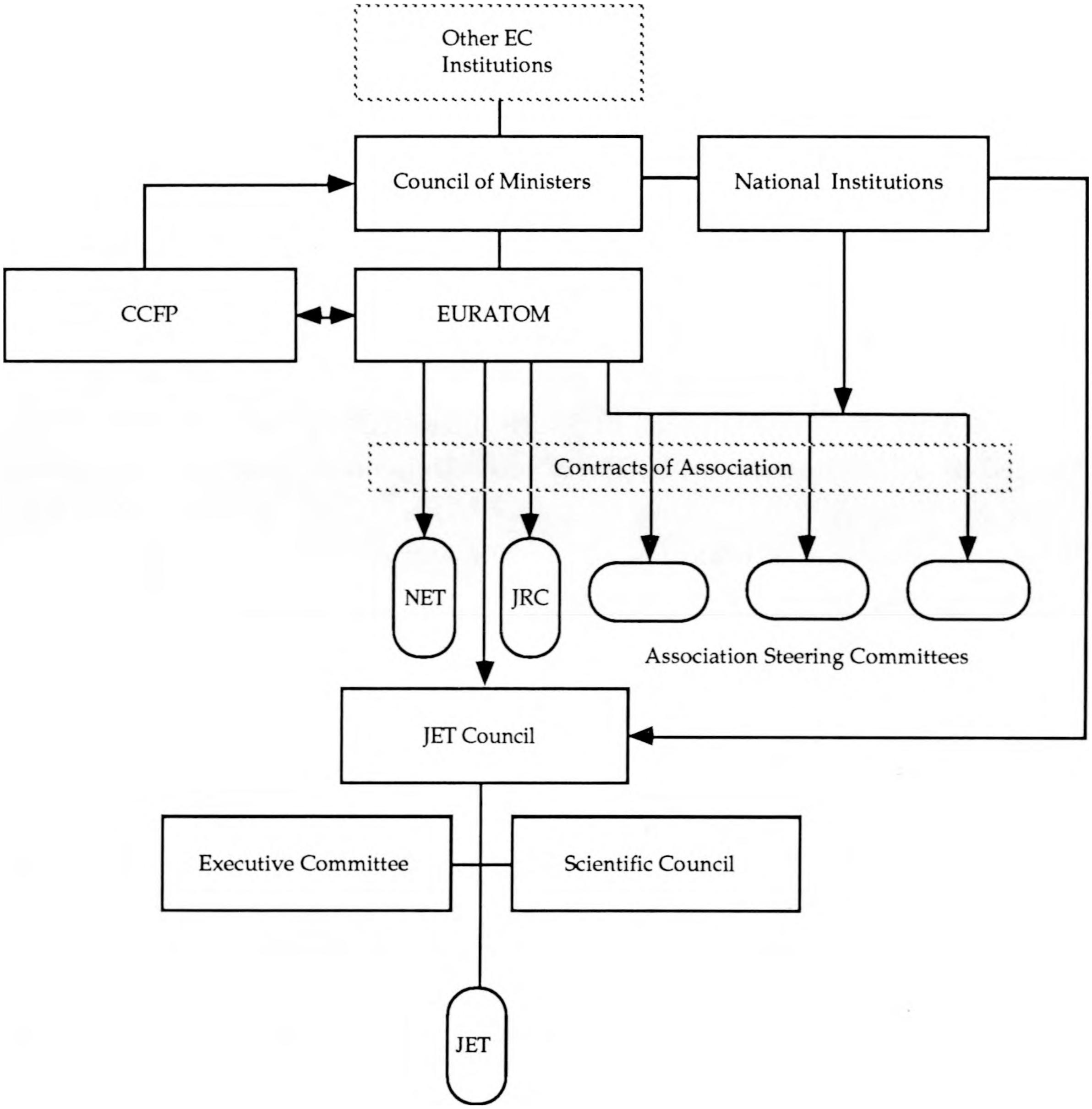

Figure III.1
Organization of the West European Fusion Program

A detailed description of the organizational structure, funding mechanisms and schedule, program staffing, and JET management is presented in Chapter VIII of the FASAC report *West European Magnetic Confinement Fusion*

Research. For present purposes, we conclude this section with the following summary of major points.

- Two features most distinguish West European fusion research: relatively loose program reins, allowing for considerable local autonomy; and relatively long-term budgeting, providing continuity at some expense in flexibility.

- West European fusion planning has been distinctive in its relative emphasis on plasma confinement science, rather than eventual reactor design. One can say that West European planning tends to "roll-forward" from what is known, rather than to "roll-back" from some criteria for reactor performance.

- The construction and operation of JET, the largest operating tokamak in the world and an obvious jewel of the West European program, has been managed with particular skill. It reflects not only scientific energy and skill but also outstanding sensitivity in management. Yet the JET leadership continues to face significant challenges with regard to retaining the highest quality personnel.

C. SUMMARY OF ASSESSMENTS

1. Tokamak Confinement

a. Overview

The ascendency of tokamaks to dominance in fusion research was precipitated by Europeans. In the decade following declassification of fusion research in 1958, a wide variety of magnetic field configurations were explored to confine plasma at the high temperatures required for fusion, but none seemed particularly effective. When development of the tokamak configuration in the Soviet Union eventually produced temperatures superior to those obtained in other devices, the results were not universally accepted until a team from the Culham Laboratory in the United Kingdom visited Moscow with their own apparatus and confirmed the high electron temperatures using laser scattering, the technique which remains the touchstone for temperature measurements.

The 1970s were the dawning of the era of tokamaks. In Western Europe at that time, fusion research was conducted by each country quite independently. As a consequence, each country built at least one tokamak, sometimes more, and considered alternative devices only insofar as resources permitted. Tokamaks thus came to dominate the West European fusion program to an even greater extent than elsewhere, even in the Soviet Union.

The development of the West European confederation as embodied in the European Community and EURATOM has evolved through cooperation, encouragement, and consensus rather than through centralized organization, planning, and prescription. This approach is reflected in the fusion program.

As soon as it became clear that tokamak performance increased with size, Western Europe decided, in 1973, to embark on a large, cooperative tokamak. By offering an attractive project on a scale larger than any single nation was prepared to undertake, the Community minimized national competition and made cooperation advantageous. The complexities of the international negotiations slowed the pace of the project, but the scale was sufficiently grand that JET, although 15 years from inception to first plasma, was not overtaken by events.

By scale and arrangement, JET is the focus of the West European fusion program. Institutional arrangements both encourage and require international staffing. JET is both scientifically and financially attractive to scientists outside the United Kingdom. Furthermore, each of the contributing nations is required to provide staff. The result has been a truly international staff of high quality, not just at the management level, but throughout the ranks of physicists. JET represents and includes the work of its (West European) program participants to a far greater degree than does any single US project.

The West European fusion program has always had strong ties to the United States. For many years Europe looked to the United States for intellectual leadership. With the success of JET and the numerous medium-size national facilities, parity in experiments has been achieved. Fortunately, close working relations remain.

West European capabilities in the area of tokamak confinement can be summarized as follows:

- Tokamaks are the core of the West European fusion program, and this role has occasioned a superior program of tokamak research. The program's breadth includes all scientific and technical issues ultimately needed for reactor design.

- JET, the flagship of European fusion, is now the largest and arguably the best of the present generation of tokamaks. It is a success both in plasma performance and as a showpiece of international cooperation. The engineering performance exceeds the original design specifications, and plasma performance equals or exceeds that of other large machines. Energy confinement times exceed those of any other device by a substantial margin, and the available range of operating parameters is excellent.

- JET has the largest total heating capability of any presently operating machine in the world. This includes neutral beam injection, ion cyclotron heating, and lower hybrid power for noninductive current drive.

- The breadth of the West European radio frequency (RF) heating program is impressive, encompassing all frequency regimes of interest, including the ion cyclotron range of frequencies, Alfvén wave heating, lower hybrid heating and current drive, and electron cyclotron heating (ECH).

- The complementary West European program of medium-size, national tokamak facilities is strong and continuing. It includes a mix of mature and new devices phased to ensure continuity of research. Each of its most prominent machines is currently productive and can be expected to continue for at least five years without interruption.

- With the design of NET, Western Europe is placing itself in a position to build the most ambitious device presently contemplated by any country. As a device with a steady-state ignited plasma, NET would accomplish the stated EURATOM objective of preparing Western Europe to build a fusion power plant, based on either a tokamak or another concept.

- Western Europe possesses the capability to design and build NET. Whether the European community decides to build NET or prefers a joint project such as ITER (International Thermonuclear Experimental Reactor) will depend not on technical exigencies, but on political and economic policy considerations.

b. Outlook

- Tokamak research will remain the centerpiece of the West European fusion program.

- The outlook for JET is favorable: it is virtually assured funding through 1996. JET will play a leading role during the early 1990s in the world fusion program. In particular, it is highly likely that breakeven will be achieved in JET during its operating life.

- The prospects for large tokamaks after JET are less certain. The experience of JET clearly establishes that Western Europe has the capacity and resources necessary to build and operate NET successfully. However, the outlook for the planned devices NET and ITER is difficult to forecast. The prospect of ITER is especially complicated because of its multinational, quadripartite character.

- The West European tokamak program is unlikely to be continuous. Even with the extension of JET until 1996, there will be a considerable hiatus in experiments on large tokamaks in Western Europe because neither NET nor ITER could be near operation by then, even if construction were approved immediately. Prompt construction of NET coupled with a further five-year extension of JET operation are the only foreseeable circumstances allowing program continuity.

- Western Europe will be well positioned in the next five years to take a leading role in the development of tokamak RF heating physics and technology. West European RF experiments have produced the technical know-how to build antennas and RF transmitters. The Europeans also have the trained personnel who allowed Western Europe to pull ahead of the United States in the late 1980s, and who will ensure European leadership in RF heating physics and technology in the early 1990s.

- The outlook for medium-size tokamaks is favorable. A strong program of research on medium-size tokamaks is assured well into the 1990s.

- The program of smaller tokamaks will continue, for the purposes it serves remain important, but the number of tokamaks is likely to decrease. Details are difficult to forecast. Since the budget for smaller tokamaks is comparatively modest and lead times are short, they do not appear in long-range summary plans.

2. Alternate Confinement Approaches

a. Overview

The West European fusion program includes two major experimental programs studying alternatives to the tokamak: the stellarator and the reversed-field pinch (RFP).

The stellarator, the first intensively developed toroidal confinement approach, is now the most developed alternative to the tokamak. Originally proposed in the United States, it offers the potential of inherently steady-state operation, which could alleviate perceived engineering problems with pulsed approaches like the tokamak. The West European program is centered around the activities of the Wendelstein group at the *Institut für Plasmaphysik* (IPP)-Garching.

Disappointment with the apparently poor stellarator confinement, and the encouraging results of the tokamak experiments in the Soviet Union, led to the virtual abandonment of stellarators by the United States in the early 1970s. Stellarator research continued in Western Europe, Japan, and the Soviet Union, however, and it was results from the Wendelstein VII-A experiment at Garching, along with those of the Japanese Heliotron-E device, which led to a reappraisal of stellarators in the early 1980s.

The eventual reactor potential of stellarators is uncertain because of possible deterioration of confinement properties with an increase in temperature. This is an issue being addressed in the ITER design, for example, where preferential loss of alpha particle fusion products due to nonaxisymmetric field ripple could lead to local overheating of the blanket.

The reversed-field pinch program had its origins in the British device, Zeta. A large toroidal machine of the early 1960s, Zeta was shut down in the middle 1960s as an apparent failure. However, in its later stages of operation, it produced discharges with quiescent periods on the millisecond time scale, far longer than discharges at that time usually endured. Long after the experimental program was over, a careful study of this quiescence was made, revealing that the external toroidal field was reversed relative to the field on axis, creating stabilizing shear.

These startling results triggered a renewal in US efforts and led the British physicist, J. B. Taylor, to the concepts of helicity conservation and minimum energy states in the plasma. In the RFP, the minimum energy state is one with the toroidal field reversed on the outside of the plasma.

West European capabilities in the area of alternate confinement approaches can be summarized as follows:

- The West European experimental program in stellarator research is strong, and roughly comparable to the US effort. Its associated theoretical group is considered the leading theoretical group in stellarator research, although the corresponding theory group in the United States adheres to the same standards.

- The influence of stellarator theory on experiment in the Wendelstein group at IPP-Garching is the strongest in the world program.

- The long-term future for next-generation stellarator experiments will depend, to a large extent, on the confinement results of the new Wendelstein device, W-VII-AS, and the corresponding US stellarator, ATF.

- Problems arise from the fact that IPP-Garching is also the site of NET and ITER tokamak design activities. The decisions to be made concerning the future of these tokamak projects will have a major impact on the prospects for W-VII-X, the proposed next step in the Wendelstein experimental program.

- In reversed-field pinch work, the West European effort has been seminal, and continues to be a relatively healthy program among alternative confinement concepts.

- The early West European leadership in RFP physics has been maintained. During the 1980s, however, significant programs in the United States and Japan have risen to challenge that leadership.

- International collaboration has been vital in the reversed-field pinch program, with the United States, Japan, and Western Europe all making important contributions.

b. Outlook

- The latest generation of stellarator devices, in both Western Europe and the United States, are just entering the period of productive operation and should produce interesting results in the early 1990s.

- The W-VII-AS experiment is just beginning a productive program that should be successful, barring worse-than-expected results from the present restudy of the mechanical capabilities of the coils.

- The future of W-VII-X is intimately tied up with such imponderables as the future for NET and ITER, since both these organizations are based at IPP-Garching. There is some concern that construction of either NET or ITER will rule out a possible W-VII-X experiment.

- The reversed-field pinch programs of Western Europe, Japan, and the United States have each been below a funding level sufficient to develop the concept on their own. Since this situation is not likely to change in the next five years, international collaboration and coordination of research effort will be essential to realizing the potential of the RFP.

- Two new RFP machines, comparable in size and current, are being built: the RFX in Italy, and the ZT-H in the United States. Because the RFX is scheduled to be completed in 1990, several years before the ZT-H, its commissioning could move the West European program well ahead of the United States.

- Collaboration between the United States and Western Europe will be especially important to further progress in RFP research. Scientifically, the RFX and ZT-H differ: the former is subject to loss of equilibrium on a slow time scale, while the latter may have instability problems, as did HBTX-1C with its thin shell. Stability and confinement are major topics of research on both machines, and their complementarity will make collaboration beneficial.

3. Plasma Technology and Engineering

a. Overview

Fusion experiments are only as good as the technologies they incorporate; the ability to advance the science of fusion depends as much on that technology as it does on the conception of individual experiments. Three technologies have special importance to progress in magnetic fusion research: auxiliary heating, superconducting magnets, and noninductive current drive.

The importance of auxiliary heating in tokamaks stems from the fact that ohmic heating alone limits electron temperatures to 1 to 2 keV. In the early 1980s, the advent of large positive ion beam systems allowed, for the first time, fusion temperatures of 5 to 10 keV. These beam systems are now giving way to less expensive and less technologically demanding RF heating systems. Such multimegawatt systems have become the current choice of heating systems, and few new positive ion neutral beam systems are being built.

JET has the largest RF heating system in the world, and one of the largest neutral beam systems. Lower hybrid systems, 10 MW at 3.7 GHz for JET and 8 MW at 8 GHz for FT-U (Frascati Tokamak Upgrade), will be built in the next few years. There are plans to install 8 MW of lower hybrid power and 9 MW of ion cyclotron power (30 s pulses) on Tore Supra. All large European experiments have major heating systems installed on them, and they are operating well.

The future heating method of choice may be electron cyclotron heating, if the technology can be developed in the requisite millimeter wavelength range. Since RF systems require launching antennas in close proximity to the edge of the plasma, they pose serious interface problems when the antennas must be large (at lower frequencies); high-frequency ECH systems largely eliminate those problems and offer other advantages as well. In this technology, Western Europe lags behind the United States somewhat, but major industrial development efforts are underway in Europe and are broad-based.

Superconducting magnets are being developed for both fusion and high-energy physics applications in Western Europe, and the industrial capability is impressive. Experience in constructing coils for the International Atomic Energy Agency's Large Coil Task and ongoing applied superconductivity research in several laboratories has positioned Western Europe well for any future requirements.

One of the important future directions in the program is towards long-pulse or steady-state operation in tokamaks. This requires noninductive current drive technologies. The present methods of choice are MeV negative ion beams and high-frequency lower hybrid systems. As in the United States, the negative ion beam development effort in Europe is small, but the expertise is there and capable of quickly reviving development efforts to meet future needs. In the RF area, Western Europe has more advanced lower hybrid systems than the United States.

Coordination of technology development in Europe is done partly through the Commission of the European Communities, which has established a Fusion Technology Steering Committee for EURATOM-funded activities. The EURATOM technology program is directed primarily towards NET, and involves all the major technology centers in Europe.

West European capabilities in the area of fusion technology and engineering can be summarized as follows:

- Western Europe brings to fusion technology a broad research base, involving universities and research laboratories, that is able to make relatively long-term commitments. This base, in combination with an industrial capability that can manufacture any item it develops, has produced an excellent track record in building and operating large fusion experiments.

- The broad industrial manufacturing base in Western Europe is second to none in producing both conventional and high technology components (computer hardware excepted) as well as systems vital to building major devices.

- Success in fusion technology development requires continuity of effort: the five-year funding and planning cycle in Western Europe is an important part of the European success. In this respect, the West European program has had some advantage over that in the United States.

- Western Europe has passed the United States by building and operating a major superconducting tokamak (Tore Supra).

- Western Europe is on a par with the United States on 1- to 2-MW RF tubes for ion cyclotron heating, but lags in gyrotron development for electron cyclotron heating. Its capability in high-power klystrons for lower hybrid heating may exceed that of the United States.

- West European capability on positive and negative ion beams is similar to that of the United States.

- In a more minor technology, plasma fueling, European development lags. However, work on the next generation of fast pellet (2 to 5 km/s) fueling devices is in evidence.

b. Outlook

- In the area of negative ion beams, the United States may be better placed at the moment to meet an early development schedule, but the West European effort would not lag far behind if needs arise. It is driven primarily by ITER for steady-state operation, and by NET.

- The accelerator for negative ion beams requires development. At present, that effort is small in Europe, but it could expand if a time scale were set for building negative ion beam systems.

- Western Europe has the experience and industrial capability to build magnet systems for future fusion experiments. Its capability is equal to that in the United States, and West European researchers have taken the further step of incorporating superconducting magnets into a major new facility, Tore Supra.

- As in the United States, there are no large projects for building superconducting magnets on the near horizon; the expertise is available but underused. However, the level of fundamental R&D on large-scale superconducting magnets for future generations is higher in Western Europe, where there is more institutional commitment to continuity in programs.

- The outlook for future West European RF technology remains excellent and very competitive. The immediately upcoming RF projects are significantly larger than those in the United States.

- Western Europe will procure future RF sources almost exclusively from European manufacturers. Chances are high that the Thomson gyrotron will be chosen as the final winner for the 8-MW FT-U lower hybrid system.

- Western Europe is on a par with the United States in high-power ICRH tetrode manufacturing capability at high power levels, and has a larger number of manufacturers than the United States. Europe has bypassed the United States in the lower-hybrid (klystron) development area.

- In the ECH area (gyrotrons), Western Europe is rapidly catching up with US capabilities. The present West European gyrotron effort is twice the size of that in the United States. Thus, in a few years, Europe may bypass the US manufacturing capabilities in the ultra-high frequency ($f \geq 100$ GHz) high-power, gyrotron area.

- In the area of ECH transmission line and component development, the University of Stuttgart is continuing with its pioneering research and development program, and it is planning the world's first high-power, millimeter-wave quasi-optical transmission system. Europe will be a prime competitor to provide the RF heating systems in all frequency ranges for ITER if such a device is built by the world community.

4. Fusion Nuclear Technology and Materials

a. Overview

In a fusion reactor, both the fusion energy recovery and the tritium breeding will be accomplished in a component designated the "blanket" which surrounds the plasma. Fusion nuclear technology deals primarily with the development of the blanket and its associated components. In addition, fusion nuclear technology addresses operational issues such as remote maintenance and safety, arising from neutron-induced activation and tritium handling. In this report, fusion reactor studies will also be considered under fusion nuclear technology.

During the past five years, the West European fusion nuclear technology program has undergone a major transformation. Prior to this period, the West European fusion nuclear technology program was generally behind the United States; currently, it appears to be surpassing the United States in several areas. This transformation has been driven by the commitment to NET.

The commitment to the NET project has added a mission orientation and a goal-specific character to the West European fusion nuclear technology program. Presently, the West European fusion nuclear technology program gives relatively little attention to the long-term needs of fusion power development. By contrast, the emphasis of the US fusion nuclear technology program is more evenly balanced between near-term needs and long-term needs.

It appears that Western Europe currently spends about three times as much per year on fusion nuclear technology as does the United States. However, these differences in levels of expenditure cannot be directly translated into judgements on the relative effectiveness or quality of the two programs. As noted earlier, prior to the NET commitment, the West European fusion nuclear technology program lagged behind that of the United States. Support for the West European effort has been gaining considerable momentum, while support for the US program has been declining.

About 75 percent of the West European program appears to be concentrated at three institutions: the KfK in Karlsruhe (West Germany), the EURATOM Joint Research Center at Ispra (Italy), and the CEA Laboratories in France.

West European capabilities in the area of fusion nuclear technology and materials can be summarized as follows:

- In general, activities in the West European fusion nuclear technology program are of very high quality, and Western Europe appears to be surpassing the United States in several areas.

- The higher current level of support for the West European fusion nuclear technology program is somewhat counterbalanced by the greater base of fusion-specific experience and superior organization of the more mature US program.

- Collaborations between the West European and the US programs have been excellent.

- West European industry is heavily involved in the fusion nuclear technology program; the United States has essentially no industrial involvement in its fusion nuclear technology program. On the other hand, universities do not appear to play major roles in the West European program, while universities have significant responsibility in the US program.

- The West European effort focuses more on near-term issues, while the US effort is more evenly balanced between near-term and long-term issues.

- Western Europe has de-emphasized reactor studies in its program, while the United States has maintained an active reactor studies effort. This is an area where the United States is clearly the world leader.

- National parochial interests sometimes result in duplicative efforts within the West European fusion nuclear technology program. Nevertheless, the success of the JET project indicates that the West Europeans can effectively carry out major technical collaborations in fusion research.

- Western Europe is currently supporting blanket development at a much higher level than the United States. Thus, it appears that Western Europe will surpass the United States in this area during the next several years.

- With regard to plasma-facing component development, the West European and US efforts are comparable; the West European effort appears stronger in terms of testing capabilities in existing tokamaks, while the US effort appears stronger in terms of R&D and test-stand capabilities.

- The West European effort in structural material development is currently about twice as large as that in the United States. The United States still appears to have a technological edge, but if current funding trends continue, Western Europe could surpass the United States in this area within several years.

- Currently, Western Europe is devoting more support to tritium technology development than the United States. However, support derived from a joint US-Japanese collaboration makes the effort in the United States comparable in size to that in Western Europe. The United States is currently well ahead of Western Europe in post-JET tritium technology and integrated tritium-testing facilities.

- At present, the West European fusion nuclear data effort is somewhat larger than that of the United States. However, the US fusion nuclear data files are in a relatively good state, and the West European effort should be viewed as being in a catch-up mode.

- The West European effort in remote operations is significantly greater than that in the United States. The JET remote maintenance activity is the most advanced fusion effort in the world.

- The West European level of support for fusion safety activities is substantially greater than that in the United States. However, the United States benefits from greater experience in fusion safety matters, and furthermore, the US effort appears more efficient and better coordinated.

b. Outlook

- If present trends in support continue, Western Europe will surpass the United States in both liquid-metal and ceramic blanket development in the next several years. This situation would not necessarily represent a concern if the United States maintains viable blanket development programs that allow continued collaboration.

- While the United States still appears to have a technological edge in structural material development, continuation of current trends suggests that this edge could be lost in several years.

- The US advantage in the areas of technology and integrated facility capabilities should continue until about 1995, at which point the new West European tritium laboratories should be producing valuable and competitive results.

- Western Europe will maintain its current level of effort and scope in the area of nuclear data and code development. The United States should maintain a relative advantage in this area, although there is some concern about declining support for fusion-specific data evaluations.

- The West Europeans have an edge in fusion remote operations development, and this edge is expected to be sustained into the 1990s. The JET operating experience will be of fundamental importance to this area of development.

- Western Europe appears to be surpassing the United States in fusion safety programs relating to near-term devices. If support for the US fusion safety program were to decline relative to the West European program, the excellent collaborations in this area might be compromised.

- Given the current emphasis on NET by the West Europeans, it is unlikely that they will initiate any significant activity in the area of reactor studies.

5. Plasma Confinement Theory

a. Overview

The international magnetic fusion program has come full circle with regard to magnetic confinement theory. One can distinguish an early European phase that included Alfvén's Nobel prize for astrophysical plasma research and Chandrasekhar's early investigation of plasma transport. A second phase, after the 1958 Geneva conference, included Pfirsch and Schlüter's collisional transport theory in toroidal magnetic fields, Mercier's magnetohydrodynamics (MHD) theory, and Taylor's discovery of minimum-B stability.

A third phase began in 1969, when, at a conference in Novosibirsk, the tokamak principle rose to prominence. The next 16 years were marked by the phenomenal rise of the tokamak approach in the West, under the leadership of the US fusion program. Finally, with the operation of JET and ASDEX (Axisymmetric Divertor Experiment) over the last few years, a fourth phase has seen the pendulum swing back towards Western Europe. Today's frontline European fusion research program no longer depends on the crucial support and flow of information from the United States.

Compared to their colleagues in the United States, West European theorists (including those employed at the major laboratories) have relatively secure positions. Their EURATOM salaries follow them wherever they work, and, at least until recently, their efforts were typically driven more by scientific issues rather than by programmatic needs. One result is a certain tenacity and persistence in West European theory, even regarding problems whose fusion benefit may be remote. The fundamental knowledge gained from such persistence is in some cases bringing rewards at the present time. On the other hand, such long-range research attitudes may be associated with an apparently diminished level of scientific communication, compared to theorists in the United States.

The theory program in Western Europe has had less central coordination than that in the United States, although this situation is changing. This is partly a result of having two distinct fusion funding sources, local (national) and the

EC. This circumstance can help the theory program, but also hinder it through administrative complications.

Several major European experimental programs do not have dedicated theory groups. Indeed, until recently, the JET organization had no provisions for a theory group. However, this unusual practice is changing, with the development of theory groups dedicated to a specific program or device, as in the United States.

West European capabilities in the area of plasma confinement theory can be summarized as follows:

- While the West European theory program has been smaller than the US program in the past, its growth over the past four years well exceeds (about 10 percent per year) theory growth in the United States. Yet West European theory production still lags behind that of the United States, especially when both are weighted according to fusion-program relevance.

- Recent growth of EC theory is traceable, in part, to strong interaction with, as well as manpower influx from, the US program. Such interaction has also benefited the United States.

- West European coverage of fusion theory topics is uneven. Ideal and resistive MHD theory, RF heating and current drive theory, and transport phenomenology are represented strongly, while plasma ignition physics and impurity transport and fundamental turbulence theory receive less attention than in the United States.

- The NET design team in Garching is at approximate parity with US reactor study groups. However, West European contributions to alpha particle physics and ignition have been following, not leading, the United States.

- West European university-based theorists play a lesser role in the overall program than do their counterparts in the United States. Laboratory-based theorists are given the freedom to pursue fundamental plasma problems as well as directly applied problems.

- EC theorists seem to have a smaller impact on the program than the experimentalists. Partly because most West European plasma theoreticians have lifetime positions, their devotion to magnetic fusion is sometimes less direct and exclusive than in the United States.

- In general, the theory program in Europe is less coordinated than the US program: theorists in different laboratories have traditionally interacted infrequently. However, this situation is changing. Furthermore the West European theory program benefits from the rich mixture of national research styles and preferences.

b. Outlook

- The remarkable capabilities recently demonstrated by the EC in plasma transport theory promise substantial near-term contributions to our understanding of transport phenomena. The historical preference of the West Europeans for basic fusion plasma research can be considered a natural advantage in this difficult area. With JET, NET, and ITER programs now in dire need of a better physical understanding of energy and particle confinement, the EC theorists should find it relatively easy to increase their level of effort.

- The present scarcity of West European turbulent-transport calculations and particle transport simulations will not be remedied overnight. But, in view of the excellent West European access to supercomputers and the almost immediate international transfer of methods, the transport theory gap is likely to be filled within the next few years.

- In view of the long European tradition in MHD theory, the nearly complete parity with the United States, and the widely available MHD codes, there is no doubt that the big and small West European experiments alike will continue to have complete state-of-the-art coverage. Leading analytic work in MHD will also continue.

- Alpha-particle theory is slowly receiving more interest in the West European program: a small but competent ensemble of workers is emerging. But, overall, the US program still provides essential leadership and momentum in this area.

- While in the past the United States has dominated the area of RF heating and current drive theory, rapid improvements in West European RF theory have brought it close to the US level.

- The most recent West European contributions to pellet theory demonstrate sufficient originality and competence to imply the coming of age of Western Europe in this previously US-dominated area.

- Recent observations in ASDEX and JET have led to a revival of interest in neoclassical impurity theory and increased collaboration with the United States. Thus, while the United States is exerting leadership in H-mode theory and impurity transport, the outlook is positive for increasingly important West European contributions.

- Fewer West European papers concern fundamental theory, including such topics as Hamiltonian dynamics or modern mathematics applications, than MHD or RF theory. Yet the fundamental work contains a number of very high-quality contributions.

- Finally, although West European theorists still draw substantially from the maturity and variety of US codes and applications, West European magnetic fusion theory has now attained the competence and breadth to continue entirely on its own.

6. Fusion Computations

a. Overview

The West European magnetic fusion program has made extensive use of computing since the formative days of EURATOM. Indeed, several key fusion computational researchers played important roles in post-war West European nuclear weapons and fission reactor development. These researchers established a tradition both of sophisticated computing aimed at resolving complex issues of experimental analysis, and of open collaboration with researchers from the United States. Thus, fusion computational work in Western Europe started at a high level of excellence.

It is also notable that there was a significant flow of computational researchers from Europe to the United States during this period. Many productive researchers contributing to this field who were trained in West European laboratories relocated "permanently" to the United States during the period preceding this assessment. That is, they contributed significantly to work at the indicated US institution for periods significantly longer than the typical guest or postdoctoral assignment.

The West European approach to the use of computing in solving problems arising in magnetic fusion research is very similar to that in the United States. Some of the founders of computational activity in Western Europe were either educated in the United States in the post-war period (for example, F. Troyon, University of Wisconsin-Madison) or participated in joint US activities in the nuclear field (for example, K. V. Roberts, Culham Laboratory, United Kingdom).

The differences in approach exist primarily in the study of basic processes, where US activity in particle simulation and turbulence studies is not matched by a similar West European effort. Rather, the West European codes are focused on applications to solving pressing experimental and engineering problems which arise in the conduct of the confinement programs.

West European capabilities in the area of fusion computations can be summarized as follows:

- The West European computational effort is approximately equal to that of the United States in most of the areas considered. Especially at the beginning of the period surveyed, the West European computational effort can be described as fundamentally collaborative with the United States and of comparable quality.

- The major hindrances to expansion at the beginning of the period were due to the lack of availability to West European researchers of Cray-1-level mainframe computers. There has been a significant increase in West European use of present-generation hardware during this period, and the absence of a Cray-2-class device has not significantly hampered the West European effort.

- The West European expansion in computational capability has been accompanied by an expansion of experimental activity. Thus, computational collaboration with the United States has had to compete with a more inward-looking focus on the problems of the West European experiments.

- The computational activity in analyzing basic processes is directed toward the study of generic processes seen to influence tokamak confinement: sawtooth oscillations, wave absorption, and edge processes. In contrast to US activity, computational study of anomalous transport is neglected.

- Predictive and interpretative modeling of confinement results is similar in scope and outlook to that of the United States. The Princeton Plasma Physics Laboratory data analysis code has been adopted as a standard for use on JET and other West European tokamaks.

- The West European program has assumed a leading position with regard to divertor modeling. This situation could be reversed if new activities in the United States in the divertor area are pursued.

- Outside collaborators have experienced relative difficulty in communication with JET. This is intentional and means that JET cannot benefit fully from international participation in its experimental program. The technology for significant remote participation from anywhere in the world exists; however, the JET group cannot use even the contracted contributions of its associated members in an efficient manner because of access problems.

- The West European dependence on US mainframe computers (Cray, IBM) and data acquisition (DEC) hardware is a weakness in principle, but since there are no restrictions in obtaining this hardware, the weakness has few practical consequences.

b. Outlook

- The West European computational program has made a transition from collaboration with the United States to independence. This transition will be reinforced by the West European need to attend to the complex problems arising from expanded experimental activity. The most challenging and relevant computational problems arise in the attempts to improve upon the highest confinement performance, and this is now to be found in Western Europe.

- The success of the JET group in fashioning large integrated codes from individual contributions by different national groups is likely to continue. The United States has been able to establish such integrated, mutually supportive efforts only sporadically, most recently involving studies for CIT (Compact Ignition Tokamak).

- The rapid expansion of economic integration in West European engineering firms is thought, by leading NET participants, to foretell a corresponding increase in the sophistication of computational support for NET/ITER-level design activities.

- The excellent coordination between working experiments in West European laboratories and the designers has already resulted in a leadership role in many areas such as poloidal field design and position control. The adoption of US codes in structural, magnetics, and neutronics analysis is a remnant of large-scale US activity in the corresponding areas in the late 1970s and early 1980s, and this activity has been sharply reduced. The West European position in this area, along with that of the Japanese ITER participants, is likely to be dominant.

CHAPTER III: ASSESSMENT OF WEST EUROPEAN MAGNETIC FUSION RESEARCH
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CHAPTER IV
ASSESSMENT OF JAPANESE MAGNETIC FUSION RESEARCH

A. INTRODUCTION

A detailed assessment of the status and outlook for magnetic confinement fusion research and development in Japan is presented in the recent FASAC report *Japanese Magnetic Confinement Fusion Research*.[1] This chapter summarizes the principal findings described in that report.

During the 1960s and 1970s, Japanese fusion research was in a formative stage in which the institutional commitments, the manpower training and technological capabilities, and the national priority for fusion research and development were being established. As a result of a concerted national effort during the past decade, Japan has emerged as a world leader in fusion research and development. Within the framework of a vigorous national policy for fusion energy development, Japan's universities, national laboratories and industries have developed a coordinated capability in terms of human resources and facilities which place Japan at the forefront in the development of advanced technologies such as superconducting magnets and neutral beams, and in the development of the tokamak and stellarator/torsatron confinement approaches.

With a sustained national commitment, Japan may surpass US and West European capabilities in the early to middle 1990s in several important areas of fusion research and development. For example, successful operation of the planned upgrade of the JT-60 tokamak would surpass both TFTR (United States) and JET (Western Europe) in the usual measures of plasma performance in the 1992 to 1993 time frame. In the absence of correspondingly major improvements to JET or TFTR, the JT-60 upgrade will take a clear international lead in large-tokamak research by 1994 to 1995.

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1 R. C. Davidson, M. A. Abdou, L. A. Berry, C. W. Horton, J. F. Lyon, and P. H. Rutherford, *Japanese Magnetic Confinement Fusion Research,* Foreign Applied Sciences Assessment Center, Science Applications International Corporation, McLean, Virginia, January 1990.

The Japanese fusion program has the human and technological resources required to build and operate a fusion engineering test reactor without external participation. By the same measure, Japan would be a highly desirable partner in the bilateral or multinational undertaking of such a project.

Following a brief description of the organization and planning of fusion research in Japan in Section IV.B, the status and outlook for Japanese fusion research and development is summarized in Section IV.C in the following five areas:

- tokamak confinement;
- alternate confinement approaches;
- plasma theory and engineering;
- fusion nuclear technology and materials; and
- basic and applied plasma physics.

The reader is referred to the FASAC report *Japanese Magnetic Confinement Fusion Research* for more detailed assessments and the associated bibliography.

B. ORGANIZATION AND PLANNING OF FUSION RESEARCH IN JAPAN

As illustrated in Figure IV.1, university fusion research in Japan is funded through the Ministry of Education, Science and Culture (MOE), whereas fusion research at the Japan Atomic Energy Research Institute (JAERI) is funded through the Science and Technology Agency (STA). The STA and MOE are parallel organizations reporting to the Office of the Prime Minister. The prestigious Nuclear Fusion Council, an arm of the Atomic Energy Commission (which also reports to the Office of the Prime Minister), plays an important role in formulating national fusion policy and in developing a consensus on the priorities for fusion research and development in Japan (Postma and Rosenthal, 1983).

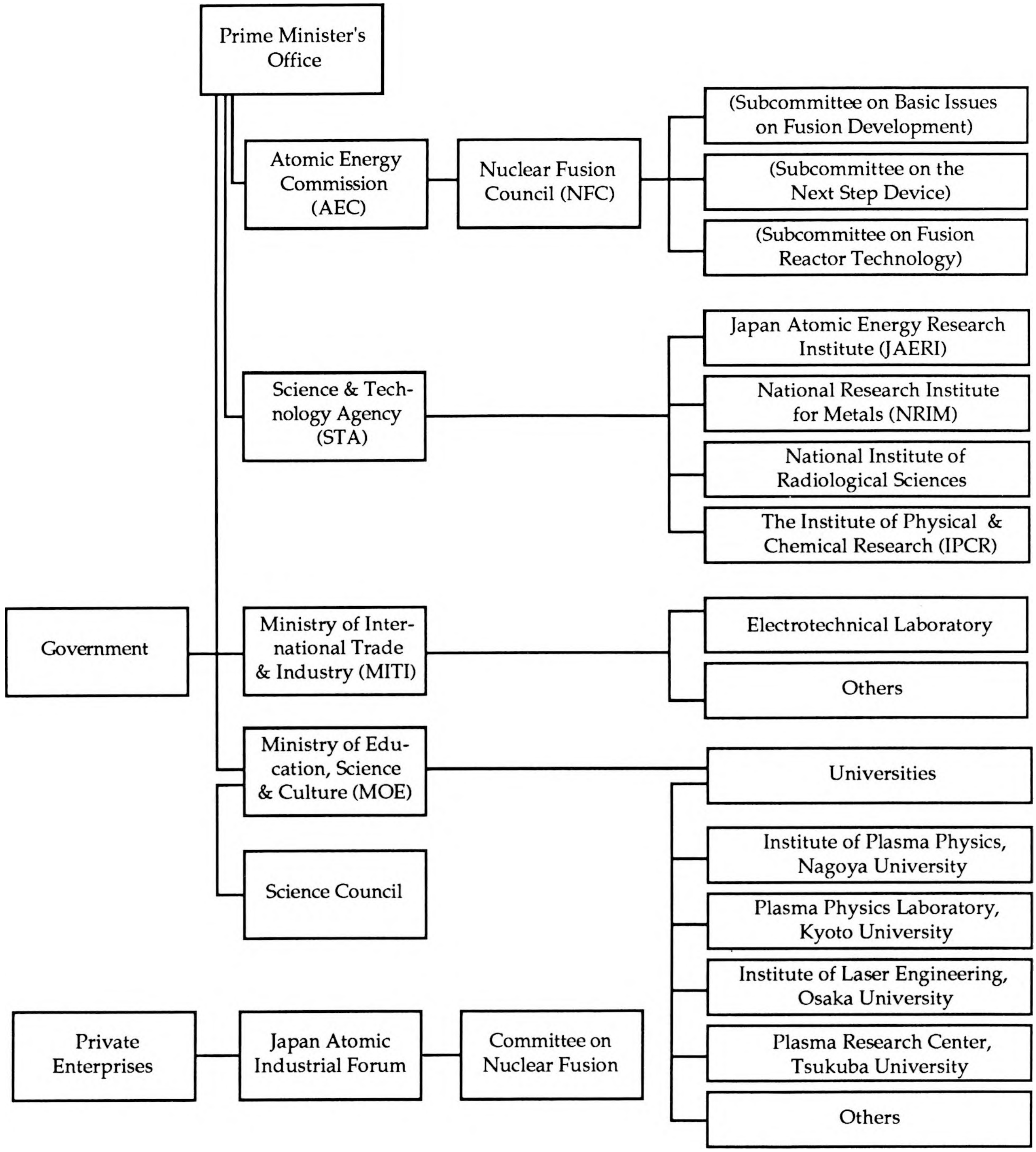

Figure IV.1
Organization of Fusion Research in Japan

The Science and Technology Agency is a cabinet-level department headed by the Minister of State for Science and Technology. Under the Atomic Energy Bureau (one of six major units within STA) is the Institute's Administration Division, which oversees JAERI, an independent, nongovernment organization. JAERI receives a significant fraction of Japan's funding for fusion R&D (see Figure IV.2), and places primary emphasis on developing the tokamak confinement approach and the related reactor technologies. While the present major tokamak facility is JT-60 and its upgrade at the JAERI Naka site, large-facility construction plans call for a next-step device, which presumably integrates deuterium/tritium burning plasma physics and long-pulse reactor technologies, and eventually a demonstration (DEMO) fusion reactor (see Figure IV.3). Of course, plans and schedules, such as those illustrated in Figure IV.3, are updated on a regular basis, depending on the rate of technical progress on fusion facilities in Japan and elsewhere.

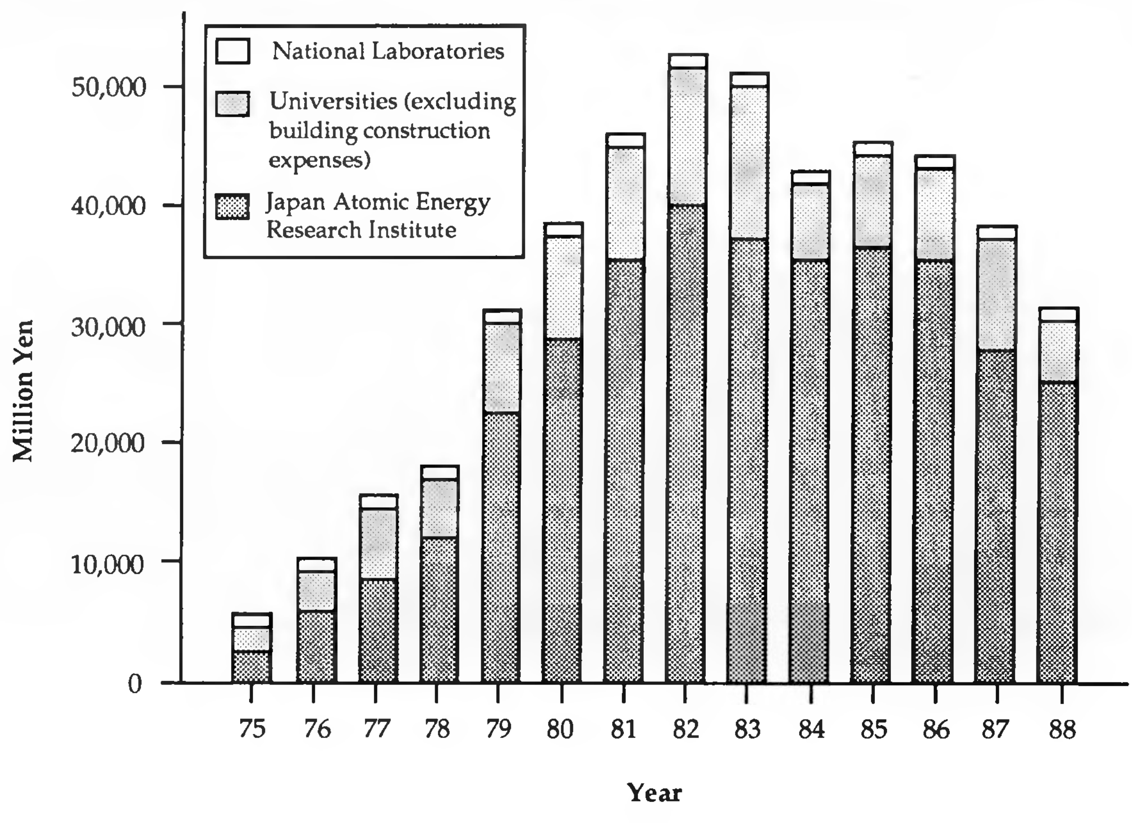

Figure IV.2
Recent Trends in Fusion Funding in Japan
(Excluding Personnel and Administration Fee)

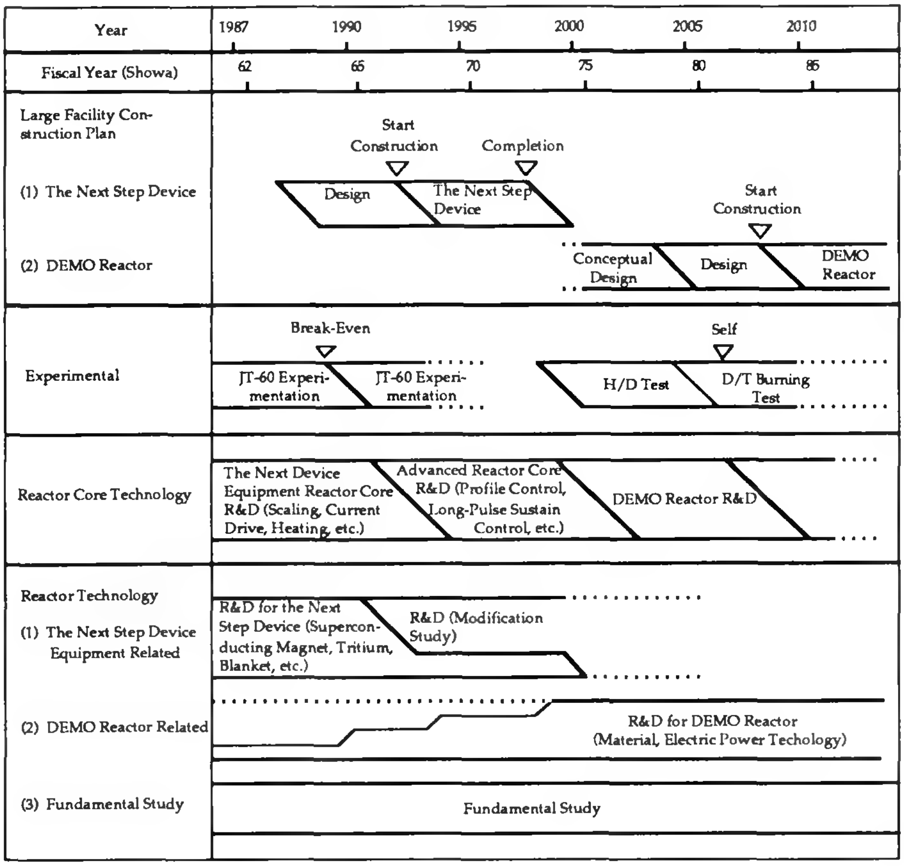

Figure IV.3
Nuclear Fusion Development Plan in Japan

As a general remark, referring to Figure IV.2, the decrease in funding for fusion R&D in Japan since 1983 correlates somewhat with US trends, and is also connected with the "roll-off" in funding for JT-60 construction. What is most remarkable, however, is that the funding levels illustrated in Figure IV.2 do not include salary costs for technical and administrative personnel (except for subcontracts to industry). Therefore, the resources in Figure IV.2 represent a very significant capability in terms of the materials and services expended on fusion R&D.

The Ministry of Education, Science, and Culture supports a broadly-based university research program in plasma science, materials research, technology development, and manpower training related to fusion. MOE plans call for the university fusion research effort to concentrate on the design, construction, and operation of a major new stellarator/torsatron experiment called the Large Helical Device (LHD), which will be located at the new MOE National Institute for Fusion Science at Toki (near Nagoya). While the fusion research activities at Nagoya University, Kyoto University, and Hiroshima University will be absorbed by the Toki laboratory, the impact on other university confinement physics programs remains unclear at this time. However, it is anticipated that more than one-half of the MOE fusion budget for plasma physics will be required for the Toki laboratory and the LHD project.

Fusion research and development play a prominent role in the Japanese Atomic Energy Commission's *Long-Term Program for the Development and Utilization of Nuclear Energy* (June, 1987). The following excerpt from this policy and planning document clearly delineates the national context and priority for fusion R&D in Japan:

> Research and development of nuclear fusion, high temperature engineering studies, etc., has been promoted from a long-range viewpoint towards the target of attaining a stable supply of energy. Since this original target is to be accomplished by concentrating and combining numerous advanced technologies, these [sic] R&D must play a leading role as a locomotive for technical innovation. Bearing in mind their importance in the advance of science and technology, such leading projects will be promoted effectively and efficiently.
>
> Research and development in nuclear fusion has the possibility of opening the path for humans to secure a permanent energy source through the practical use of this technology. Furthermore, it defines clear targets and gives vitality to many fields of ultra-high technology, advanced technology, and evolves by absorbing the results attained in these fields. Therefore, it is also very important from the standpoint of the role it plays as a leading project leading a wide variety of technological fields.
>
> Therefore, Japan, which is a large consumer of energy with little energy resources, will actively promote research and development of nuclear fusion towards the practical utilization of the technology.

Not only is fusion an integral part of Japan's plans for long-term energy security, there is notable emphasis on international cooperation in fusion R&D, as well as in other advanced energy technologies.

Cooperation between the United States and Japan in fusion began officially in 1978 with an initiative, agreed upon by President Carter and Prime Minister Fukuda, which opened the way for Japanese partnership in operating the Doublet-III tokamak at General Atomics. On 24 August 1979, the US-Japan Agreement on Cooperation in Fusion Research was signed. The agreement provided for bilateral cooperation in four areas: (i) the general exchange of fusion scientists; (ii) the Doublet-III tokamak experiment; (iii) joint planning on tokamak alternatives; and (iv) a Joint Institute for Fusion Theory (JIFT) program. Overall, US-Japanese cooperation in fusion has been highly beneficial to both parties in a wide range of experimental, theoretical, and technological areas.

Japan and the European Community have recently (January 1990) established a broadly based accord on nuclear fusion research.

C. SUMMARY OF ASSESSMENTS

1. Tokamak Confinement

a. Overview

The Japanese tokamak program began in the early 1970s, when a small tokamak was brought into operation at JAERI almost concurrently with the first generation of tokamak devices in the United States and Western Europe. All of these devices came into being as part of a major reorientation of world fusion research toward the tokamak concept, brought about by the experimental successes of the T-3 tokamak at the Kurchatov Atomic Energy Institute (Soviet Union) in 1968-1969.

By the middle 1970s, a second small tokamak was in operation at JAERI, and a small toroidal device had been constructed at the Institute of Plasma Physics (IPP) at Nagoya, that was capable of operating either as a tokamak or as a stellarator. The Japanese program did not make any major or fundamental contributions to world tokamak research during this period. However, the early devices provided valuable experience in the methods of operating tokamaks, and they served as suitable test beds for the radio frequency (RF) heating and current drive techniques that became an important emphasis of the Japanese program.

By 1975, the development of fusion had become a major objective of the Japan Atomic Energy Commission (AEC). The focus of the fusion program was a large tokamak, the JT-60, to be constructed at a new JAERI site at Naka. The basic objective of JT-60—to provide an integrated evaluation of the plasma physics and associated heating and fusion technologies at break-even plasma conditions—was originally established in 1975 as part of the AEC's second-phase program of fusion development, and it was reconfirmed in the AEC's long-term program plan of 1982. The JT-60 project was formally initiated in 1975, and construction began in 1978. Initial plasma operation occurred in 1985.

Early in the construction phase of JT-60, the United States and Japan executed an agreement for collaboration in fusion research, and this agreement provided JAERI with access to a major fraction of the experimental run-time on the Doublet-III tokamak at General Atomics (GA) in San Diego in return for a five-year contribution of about $70 million for upgraded hardware and incremental operating expenses. A JAERI experimental team took up residence at GA and was able to participate directly in major advances in tokamak research. The Japanese team, which included industrial as well as JAERI personnel, returned to Japan in 1984 to form the core of the present JT-60 experimental group.

Although JAERI retained full responsibility for the direction of the JT-60 construction project, the machine was designed and built by Japanese industry, with Hitachi playing the role of coordinating company. A large-scale research and development program preceded the start of construction. The industrial involvement in JT-60 has continued throughout its operating phase.

Construction of the JT-60 device was completed on schedule, and all major auxiliary systems reached full capability soon after their installation. A major modification of the JT-60 was implemented in 1987-1988 and required a shutdown of only seven months—a remarkable feat, again brought about by the efforts of a large Hitachi-led industrial team.

The JT-60 device is generally similar in design to the other two large tokamaks that also came into operation in the early 1980s, namely, the TFTR at Princeton University's Plasma Physics Laboratory and EURATOM's JET at the Culham Laboratory. A unique feature of the JT-60 was the outer-null magnetic divertor, but in this respect the design seems to have been influenced more by engineering than by physics considerations, and the divertor configuration was changed as part of the 1987-1988 modification.

The JT-60 is the only one of the three large tokamaks that has been equipped with a high-power radio-frequency system operating in the lower hybrid range of frequencies. This capability has allowed JT-60 to demonstrate long-pulse non-inductive current drive for the first time in a large tokamak, with an efficiency that exceeds that obtained in smaller tokamaks. The operating costs of JT-60 are similar to those of JET, but much higher than those of TFTR.

Overall, the JT-60 has achieved plasma parameters roughly similar to those obtained in JET and TFTR. A serious limitation, however, has been the inability to operate with deuterium—the result of a commitment made both to the AEC and to the local authorities at Naka that neither neutron shielding nor the ability to handle activated components would be required at the JT-60 facility. The impact of this restriction could not have been anticipated at the start of the JT-60 project, since the superior performance of deuterium plasmas in tokamaks, relative to hydrogen plasmas, was discovered only in the 1980s, and is still lacking a theoretical explanation.

Because of the restriction to hydrogen operation, the parameters achieved in JT-60 by 1987 fell short of those required to demonstrate breakeven plasma conditions, which was the original objective of JT-60. Nonetheless, by adjusting the parameters to their deuterium-equivalent values, the JT-60 team could claim that the objective had been met, and this well-publicized success led to the authorization of a major upgrade of JT-60, the JT-60U.

The restriction on deuterium operation at Naka will be lifted for JT-60U. Although the JT-60U will place Japan at the forefront of world tokamak research in the early 1990s, its capabilities will fall far short of those of the more ambitious

Fusion Experimental Reactor, which was previously intended to be the immediate successor to JT-60.

In parallel with JT-60, the Japanese have continued to operate small-to-medium size tokamaks at Toki (JFT-2M), Nagoya University (JIPP-T-IIU), and Kyoto University (WT-2/3). Indeed, the programs on these smaller devices—operated in a more informal, research-oriented style than JT-60—have tended to be quite inventive.

The niobium-tin superconducting tokamak, TRIAM-1M, at Kyushu University represents a major engineering accomplishment, but the physics program on this device is not yet well defined. However, Japan lacks a broad university-based program of tokamak research, such as is found in the United States. As the MOE program focuses increasingly on the stellarator/torsatron concept, there presumably will be even fewer opportunities for university faculty and graduate students to participate directly in tokamak research.

The AEC's long-term program plan of 1982 focused fusion reactor design studies in Japan on a single reactor-like device with comprehensive objectives, patterned closely on the multi-national INTOR device and called the Fusion Experimental Reactor (FER). A large, JAERI-led (but industry-dominated) FER design team has been at work since the early 1980s and has produced a series of designs for a superconducting, D-T-burning reactor-like device that would not only achieve plasma ignition (or near-ignition) but would also demonstrate all essential fusion technologies, including tritium breeding.

Two principles that appear to have guided the FER design effort have been a desire to achieve sufficient flexibility to adapt to an evolving physics data base and a willingness to introduce advanced physics features if these could result in a significant reduction in capital cost. Although cost estimates were generally not presented, it seems that JAERI has been anxious to keep the cost of FER lower than the projected cost of INTOR or its successor, the quadripartite International Thermonuclear Experimental Reactor (ITER).

In 1988, the FER effort was largely absorbed into the ITER Activity, to which, after some early hesitancy, Japan now appears to be fully committed. The

Japanese contributions to ITER are at least equal to those of the other participants.

b. Outlook

It is perhaps regrettable that the present JT-60 device has been unable to identify conclusively the reason for not achieving a larger enhancement of confinement in the H-mode regime. Nonetheless, the prospects for greatly superior results in JT-60U are very favorable. Indeed, because of its larger toroidal field, JT-60U will have a higher performance potential than JET at the same 6-MA current.

Specifically, if both devices succeed in obtaining confinement times of 0.7 seconds at beta-values corresponding to a Troyon coefficient of 3.5, the JT-60U will surpass the requirement for Lawson break-even (thermonuclear reactions only, excluding beam-plasma contributions), whereas JET will fall slightly short of this requirement. However, the conventional H-mode scalings predict that the confinement time in JT-60U could be limited to about 0.5 to 0.6 seconds.

Even in the first stage of operation, the upgraded device will maintain JT-60's position at the forefront of research in lower hybrid current drive (LHCD). The new LHCD launchers are projected to be capable of driving the full 6-MA current at densities up to 5×10^{18} m^{-3}.

It seems likely that negative-ion-beam heating and current drive will be selected for the second-stage experiments on JT-60U, and there is every indication that the present negative-ion-beam development program will be successful in producing a 20-MW system by the middle 1990s. In summary, there is a distinct possibility that JT-60U will surpass both TFTR and JET in the usual measures of overall plasma performance by 1992-1993, and an even better chance that it will take a clear lead in world tokamak research by 1994-1995.

A decision to proceed with construction of the FER is likely to be taken only after favorable results have been obtained on JT-60U, and not before all reasonable possibilities for international collaboration within the framework of ITER have been thoroughly explored.

At first, the Japanese seemed somewhat lukewarm toward participation in ITER—either because they still expected early authorization of a national FER-like project, or because they feared the dominance of the Western partners in an ITER constructed in Europe. After the first year of joint design studies, however, the Japanese enthusiasm for the ITER activity appears to have increased markedly. Certainly, the quality and breadth of the Japanese technical contributions are easily equal to those of the other participants.

The bulk of the effort of the FER team is now directed at the ITER activity. Japan is seen as likely to join any future phase of the ITER activity, even to the extent of joining an international construction project if this were to materialize. However, the ITER activity will meanwhile increase further the experience and capabilities of an already-impressive FER team, which will remain ready to design and construct a national engineering test reactor, should such a project be authorized by the Japanese government.

The Japanese fusion program certainly has the human and technological resources to build an engineering test reactor of the FER/ITER class without external help. However, the $4-5 billion cost of a device designed on the basis of a conservative extrapolation of the present database is probably perceived to be too much for Japan alone, at least in the present economic and political climate. Accordingly, Japan is almost certain to favor a continuation of the ITER activity and may even be willing to participate in multinational construction of an ITER-like device. On the other hand, if the outlook for fusion funding in Japan were to become sufficiently favorable, there is little doubt that Japan would prefer a national device.

With regard to medium-scale tokamaks, it is generally recognized within JAERI that JFT-2M fulfills an important role in providing a testbed for exploratory ideas that might eventually be employed in the mainline program, especially JT-60 or its upgrade. Moreover, the JFT-2M device has considerable flexibility in regard to plasma configuration and operating conditions, and it has been equipped with a wide range of auxiliary capabilities, especially for heating and current drive. Thus, it seems likely that support for JFT-2M will be maintained at least for several more years.

In the near term, the program on JFT-2M will emphasize lower hybrid current drive studies, with an upgraded LHCD system and a new fast wave current drive (FWCD) system, which was completed in 1988 and has 200-MHz, 180-kW sources feeding each of four phased loop antennas for 0.5-s pulses. A 10-shot, higher-speed pellet injector is under construction for JFT-2M.

A plan has also existed for some years to move the JFT-2M device to the Naka site. With the power supplies available at Naka, the JFT-2M toroidal field could be increased to the range of 3.0 to 4.5 T, and the plasma current could be increased to 1.0 MA, in both cases for pulse lengths in the range of 2 to 3 seconds. Operation at these parameters would require correspondingly upgraded RF systems. Although the relocation to Naka has been tentatively set for 1991, it has not yet received formal approval. Indeed, as JAERI fusion budgets flatten or decline slightly in the face of an ambitious JT-60U project, the view seems to be growing that JFT-2M may, in fact, remain at Toki.

Although the main thrust of the MOE's future program of fusion research will be on the heliotron/torsatron concept, it has apparently been decided that the JIPP-T-IIU tokamak at Nagoya University will remain in operation for at least another two years. The emphasis of the program will continue to be RF heating and current drive. Since the JIPP-T-IIU has a circular cross-section plasma bounded by a limiter, it is not expected to contribute significantly to enhanced confinement research, although it has achieved marginally improved limiter H-modes.

The TRIAM-1M superconducting tokamak is regarded as a major accomplishment in fusion magnet technology, and it will certainly represent an element of growing importance in the Japanese fusion program. However, the confinement physics capabilities at Kyushu University are regarded as somewhat weak relative to those at the other tokamak sites, and this may tend to limit the research output from TRIAM-1M. On the other hand, the device is highly reliable, and the extraordinarily long pulses will provide a unique opportunity for experimental studies relevant to the steady-state operation of tokamaks. A higher-power lower-hybrid system presently nearing completion should be capable of driving currents up to the device limit of 500 kA.

The small WT-3 tokamak will remain in operation at Kyoto University. Non-inductive current drive, using various combinations of electron cyclotron and lower hybrid waves, will continue to be the main emphasis of the program, although current drive by electron cyclotron heating (ECH) alone is not regarded as very promising.

The TNT-A tokamak in the Physics Department at Tokyo University is now regarded as useful primarily for student-oriented experiments, and its operation may not be continued. The TORIUT sequence of low-q tokamaks in the Nuclear Engineering Department at Tokyo University was replaced by a reversed-field-pinch program based on the REPUTE device, but REPUTE worked poorly in this mode and is being operated as an ultra-low-q tokamak.

Overall, however, the small tokamaks in Japan will soon all but vanish. Except for WT-3 at Kyoto, graduate students will have very limited opportunities for experimental work on tokamaks, unless they can arrange to do their research on JFT-2M at JAERI, on TRIAM-1M at Kyushu University, or—for another few years—on JIPP-T-IUU at Nagoya.

2. Alternate Confinement Approaches

a. Overview

Study of alternate confinement (non-tokamak) approaches in Japan during the 1980s has been carried out by relatively small university groups funded by the MOE, at a level much lower than that for tokamak research and development at JAERI. The confinement approaches being studied (in order of decreasing effort) are stellarators (or helical systems), tandem mirrors, reversed-field pinches, and compact tori (spheromaks and field-reversed configurations).

The small size of the university research groups is limited by the number of available faculty positions and related support positions. This is especially true in the relatively small theory area. However, the funding of university experimental activities (separate from salaries) allows purchase of turnkey machines that are usually well-engineered (but very conservatively designed) from

Hitachi, Mitsubishi, or Toshiba. The universities also rely on these companies for all phases of an experiment, including R&D, concept development, detailed design, construction, commissioning, repairs, and upgrading both of the device and its auxiliary equipment.

This process works well when there is good coordination between the experimental group and the company (for example, Heliotron-E), but there have been some failures when good communication was lacking (for example, the initial GAMMA-10 configuration). The arrangement also tends to limit the continual evolutionary improvements and upgrading that occur on US experiments. A side benefit is that new devices are partially subsidized by the companies, and engineers from the companies work with some of the experimental groups, especially in the development of new devices.

Both experimental and theoretical groups in Japan tend to be conservative in their approach. In general, they are much better at adapting to developed ideas and implementing them quickly and well, with attention to detail, than they are at original, innovative research. Examples are the designs of the CHS, SHATLET M, Asperator-H, LHD, GAMMA 10, and NBT experimental facilities, and many of the theoretical studies in computations on magnetohydrodynamics (MHD) and transport. There are, of course, some notable exceptions. Among these are the Heliotron set of stellarator experiments, the TPE-1RM-15 reversed-field pinch, the ponderomotive-plugged mirror experiments, the SPAC series of relativistic electron ring experiments, and some theoretical studies of MHD, orbit confinement, and stabilization of the $n = 2$ rotational instability in field-reversed configurations.

The resources available for alternate confinement research in Japan are significant. The experiments are well designed and reliable. The plasma heating power and diagnostics are limited only by funding and are comparable to or better than those available to alternate confinement researchers in the United States and Europe. The computing facilities (per researcher) are greater than those available in the United States and Europe and they have a large collection of computational tools (MHD, transport, orbit, and configuration codes) that are well exercised. Although computer acquisition of experimental data is established, routine on-line integrated analysis of data is not well developed.

b. Outlook

A major change is taking place in alternate confinement research in Japan. One approach, the stellarator (or helical system) has been selected for a large next-step facility, and more than one-half of the funding for alternate concepts in Japan will be devoted to one project, the Large Helical Device to be built at the new MOE-operated National Institute for Fusion Science near Nagoya. The device cost is estimated at ¥62 billion (about $460 million) and the project at more than $750 million. However, budget pressures may reduce the device cost by 10 to 20 percent.

Staff for the new laboratory will be drawn from the now-defunct Nagoya University IPP, the Hiroshima University Institute for Fusion Theory, and part of the Kyoto University Plasma Physics Laboratory (PPL). There are no definite plans for any major upgrades or new experiments in the other alternate confinement approach areas, due in large part to the major resource commitments needed for the LHD. In addition, MOE has decided that the activities on the other types of plasma systems (tandem-mirror, laser and particle-beam, ICF, and RFP) should be maintained, as far as possible, for future possible innovative developments.

The Heliotron-E experiment at Kyoto PPL is presently the leading stellarator facility in the world. It is a mature experiment with significant plasma heating and diagnostic capability and it has achieved some of the highest-performance plasma parameters obtained in stellarators. Its more recent program has shifted from improving parameters to better understanding of stellarator physics in support of the LHD.

After a seven-year hiatus in stellarator research, IPP Nagoya has built the low-aspect-ratio CHS torsatron, a unique helical facility. These groups are presently among the best in the world. However, there will be a decline in research on these projects in the next few years as these experiments are cut back (or terminated) and more resources are shifted to the LHD project. In the long term (after startup of the LHD in 1995), Japan will dominate the world stellarator program. Their stellarator theory is internationally competitive but undermanned.

It should become stronger in a few years with the consolidation of the theory effort at the new MOE laboratory at Toki.

In the tandem mirror area, the GAMMA-10 experiment at Tsukuba University is now one of two mirror programs in the world studying concept improvement. (The second major research program on mirrors is located at the Institute for Nuclear Physics in Novosibirsk.) It has made significant contributions, especially in the study of thermal barriers, and has excellent people and capabilities. There are plans for improvements and continued operation for the next few years, but no definite plans for a major upgrade or new experiment.

In the reversed-field pinch (RFP) area, the TPE-1RM-15 facility at the Electrotechnical Laboratory (ETL) is an excellent facility that has made contributions to the basic understanding of confinement scaling. It has obtained the highest current density and electron temperature achieved in RFPs. The REPUTE-1 RFP at Tokyo University has not performed satisfactorily as an RFP because of inherent field errors; recent studies have shifted to ultra-low-q tokamak operation. While TPE-1RM-15 will remain competitive in the short term, it will be overshadowed by the larger RFX (Italy) and Z-TH (United States) reversed-field pinch devices in the middle 1990s.

In the compact torus area (field reversed configurations and spheromaks), the facilities are relatively modest, although some significant contributions have been made in this area. A major contribution has been the experimental and theoretical work on stabilization of the $n = 2$ rotational instability. Interesting physics studies can still be done on the present experiments but they are subcritical in size for studying the key physics issues needed (on larger devices) to advance the concept.

3. Plasma Technology and Engineering

a. Overview

Capability in developing plasma technologies is determined not only by specific skills within a particular research program, but also by the existence of a much broader external infrastructure. For example, a successful ion cyclotron heating (ICH) effort requires specific knowledge and experience on how to design, fabricate, and operate effective RF launching structures, as well as the existence of laboratories and industries that can provide the required RF power sources, high-voltage power supplies, and high-power coaxial-line components. Both factors must be addressed in order to evaluate Japanese programs in the plasma technologies.

In those areas with active development programs in the laboratories and universities (for example, the heating systems on the JT-60 tokamak—especially the neutral beams—and superconducting magnet development), the Japanese have made significant contributions. The advancements reflect improvements in the underlying technology base and the production of high-quality, reliable components by industry.

In other areas, for example, pellet injection and millimeter-wavelength, high-power, long-pulse to steady-state microwave sources, R&D programs have not been established. Even then, Japanese industry has been able to produce useful components; but they are based on existing technology and have not advanced the state of the art.

As is evident from the preceding discussion, supporting industry in Japan is singularly capable. Strong and effective relationships exist between the laboratories and industry, which are reinforced by the broader national commitment of Japan to advanced technology development as a means to commercial advancement.

b. Outlook

Plasma technology development efforts are closely tied to the support of major fusion facilities. Thus, most of the work has been carried out in JAERI and that effort has been focused on JT-60 and the Fusion Engineering Reactor. The recent decline in budgets in plasma technology is probably tied to the completion of JT-60 (even though an upgrade is now under way) and the uncertain nature and timing of Japanese participation in engineering test facility development and fabrication.

For example, decisions on long-planned neutral beam and superconducting magnet test facilities are being delayed. Thus, future contributions in areas of present strength depend on national and international decisions on FER and ITER, and on the extent of Japan's participation. This could range from an independent, national FER to multilateral or bilateral participation in ITER.

Fusion superconducting magnet development in Japan is consistent both with national policy to develop superconductivity, and the policy to use fusion technology development as a means to enhance industrial capability. Thus, continued significant development activity in this area is likely. The pace of this work will be strongly influenced by Japanese participation in national and/or international engineering test reactor projects. This continued development, combined with the underlying industrial capability, will help Japan maintain its position as a leader in the field and strengthen its position as a magnet supplier.

Neutral beam technology based on positive ions will be used in the planned upgrade of JT-60, which includes increasing the neutral beam energy to 120 keV and 40 MW with deuterium operation. Progress in the development of MeV-class beam systems depends on the schedule and role that Japan assumes with respect to an ITER-type facility. Decisions have been delayed on construction of a high-current 500-kV facility and a lower-current system is now planned in its place. This will probably receive higher priority and increased funding when plans for FER/ITER are established.

The plans for JT-60 Upgrade call for doubling the installed ICH capability to a total of 10 MW. While less than the 40 MW of neutral beam power and the 15

MW of lower hybrid power, this will certainly allow a significant ICH program. It is unlikely that ICH will become a major focus of JT-60 research, given the stated emphasis on current drive and the relatively modest power level compared to the neutral beam systems. Japanese industry could readily support a much larger effort if program priorities should change. The present use of US power tubes is not a limitation and could probably be eliminated within a few years if it proves expedient.

Pellet injectors have been used in fueling experiments on the JFT-2M tokamak, the Heliotron-E stellarator, and most recently, on JT-60. These injectors were designed and built by Japanese industry, Lobe and Mitsubishi, and are based on concepts developed at the Oak Ridge National Laboratory. Performance parameters of the injectors are similar to those attained in the United States with velocities of 2.3 km/s being reported for hydrogen pellets on the JT-60 injector.

High-velocity pellet injection, or more broadly speaking, central fueling, has not been identified as a critical development item in the ITER concept definition process. In part, this is due to the fact that the fueling technique does not have any significant impact on the device conceptual design, and the add-on nature of fueling systems. A major thrust in advanced fueling system development is unlikely in the next several years unless such a system becomes necessary for JT-60U. If a system is needed, then Japanese industry would attempt to build on US and/or European technology rather than embarking on an independent development effort.

Prospects for those plasma technology areas which are not presently competitive with the United States are dependent on the priority given them within the Japanese fusion program. With program commitment, effective programs could be established within two to four years because of the strong industrial capability in component design and fabrication. If, for example, gyrotrons become a program objective because of the need for megawatts of power in the 100-GHz range on the LHD, then Toshiba has a good chance of becoming an alternative supplier to Varian.

4. Fusion Nuclear Technology and Materials

a. Overview

Fusion nuclear technology and materials research includes the reactor blanket, neutronics, tritium processing, neutron-interactive materials, and plasma-interactive materials. JAERI has the primary responsibility for project management and the development of key fusion nuclear technologies and materials. Universities emphasize fundamental research and support the national technology development effort. Industry plays a unique role in Japan's fusion technology R&D. Industry has the primary responsibility for hardware construction not only for large projects but also for small-scale facilities, including practically all of the activities at JAERI, the national laboratories, and the universities. Personnel from industry normally participate from the beginning of the conceptual design stage for research projects at JAERI and the universities. One consequence of this practice is that technology transfer occurs naturally and efficiently within the existing fusion technology R&D programs.

The role of universities in Japan is unique among the world fusion technology R&D programs. The fusion nuclear technology and materials program in the Japanese universities is comparable in funding with that in JAERI, and larger in terms of the number of researchers. The combination of the mission-oriented technology programs at JAERI and the broad-based, fundamental and long-term programs at the universities gives the Japanese fusion nuclear technology and materials program a unique aspect of strength.

Solid breeder blankets are considered the primary option in Japan, with the R&D carried out mainly at JAERI and with some support activities at universities. Liquid metal blankets are considered as an alternate approach and the research is performed only in Japanese universities with no effort at JAERI. JAERI's solid breeder program is further focused on one ceramic breeder—Li_2O. JAERI's research includes measurements of basic material properties, fission reactor irradiation, and development of manufacturing technology. Japan has participated in collaborative international programs, BEATRIX-I and -II, for exchange of materials, information, and irradiation of solid breeders in fission reactors in the United States and Europe.

The Japanese fusion program has designated the development of a tritium production capability as a national priority and is completing the design for an integrated breeder blanket unit test in the Japan Material Test Reactor (JMTR). This is an example of targeting a sensitive technology for which no capabilities presently exist in Japan. Also, a plan is being finalized for construction at JAERI of a blanket manufacturing technology facility with a special laboratory for handling beryllium. The liquid metal blanket R&D program in the universities is diverse, with a number of existing facilities and a large number of researchers. However, this liquid metal program suffers somewhat from a lack of focus and close coordination.

Japan now has the largest fusion neutronics program in the world. This remarkable progress from a modest program in the 1970s to the leading world program in the 1980s has been achieved in part by constructing simultaneously in the early 1980s the two largest fusion neutronics facilities in the world. These are the Fusion Neutronics Source (FNS) facility at JAERI and the OKTAVIAN facility at Osaka University. Both have a yield of ~3 x 10^{12} n/s, pulsed and steady-state operation, and other important experimental capabilities. These facilities adapted many technologies developed in the United States and West Germany.

It is interesting to note that the United States has presently no fusion neutronics facility in operation. There is a US-JAERI collaborative effort using FNS for fusion neutronics experiments. There is also a JAERI-West Germany agreement for neutronics instrumentation development using FNS.

Tritium handling technology has been targeted for an extensive R&D effort in Japan since the early 1980s. Prior to this effort, Japan had no significant tritium technology. The Tritium Processing Laboratory (TPL) was constructed at JAERI with the first tritium operation (three-gram level) occurring in March 1988. Also, Japan is participating in the operation of the Tritium Systems Test Assembly (TSTA) at the Los Alamos National Laboratory to gain direct experience with tritium handling technology. The operating cost is shared equally between the United States and JAERI (about $2 million each). A number of smaller-scale facilities for fundamental tritium studies are also in operation at Japanese universities. In addition, one of MOE's Grant-in-Aid groups is carrying out an extensive research program on the effects of tritium on environment and safety.

The materials program in Japan has three elements: fundamental research, the development of structural materials, and the development of plasma-facing (high-heat-flux) components. The progress made in Japan on fusion materials during the past five years has been significant. Major areas of strength are non-neutron testing capabilities. Testing of materials in the neutron environment is accomplished through bilateral collaboration with the United States and Europe. Materials development concepts originating in the United States and Europe find immediate application in Japan.

The collaboration between universities, JAERI, the National Research Institute for Metals, and industry is product-oriented and results in highly developed applications. There are two major weaknesses in the Japanese materials program. First, the theory and modeling of radiation effects are not as sophisticated as the experimental work. This may explain the apparent lack of original concepts of materials development and data analysis. Second, the neutron irradiation facilities are not convenient for materials testing. At present, extensive collaboration with other countries in this area is being pursued. However, plans are being developed for a national high-energy, high-fluence fusion materials test facility in order to gain flexibility in the national program.

System and design studies have been carried out principally at JAERI, with a much smaller effort at the universities. During the 1980s, JAERI's system and design activities have focused on three large areas: the design of the FER; major participation in international projects for the next-step fusion experimental reactor, such as INTOR (1980 to 1987) and ITER (beginning in 1988); and power reactor system studies. All of these efforts have been on tokamaks.

A few observations are important in this area. JAERI's system and design activities have always involved very extensive (> 50 percent) participation by personnel from industry, residing at JAERI for the duration of the design project. The effort on FER has been the largest (comparable only to the West European NET effort) such activity among the world programs. The Japanese program has also faithfully and seriously participated in international activities such as

INTOR and ITER. A general characteristic of the system and design studies in Japan is that more emphasis is placed on engineering credibility and engineering details than on concept and performance improvement.

Japan has consistently promoted international collaboration on fusion R&D and some examples in the fusion nuclear technology, materials research, and system studies areas were cited above. It is also important to note that Japan has been the only country that is willing to make significant direct payment for participation in other countries' technology programs and the use of their facilities. It is concluded that the return on investment for Japan has been extremely high.

b. Outlook

The Japanese fusion program made an early selection of solid breeders as the blanket option and focused on Li_2O as the primary material. JAERI has a large, well-focused program in this area. Furthermore, Japan has invested in international collaborative programs to use facilities not available in Japan. The five-year plan for 1990 to 1995 includes major facilities, such as the construction of an integrated blanket test for fission reactor irradiation in JMTR, and the construction of a manufacturing and processing facility with a beryllium handling laboratory. Thus, the Japanese program appears to be moving toward a world leadership role in solid breeder blanket technology, at least for the Li_2O option.

Liquid metal blanket R&D is pursued only by Japanese universities and not by JAERI. At the present time, the liquid-metal blanket option is considered only as an alternate to solid breeder blankets in Japan. The past few years have witnessed a surge in liquid-metal activities in Japanese universities. There are many diverse facilities, and a large number of capable university researchers are active in the field. The five-year plan for 1990-1995 calls for an expanded effort in this area. However, the program now lacks focus. There is no clear goal with observable milestones.

Furthermore, existing facilities in Japan, although diverse, cannot address integrated thermomechanical issues for liquid metals. Some Japanese universities (Tokyo University, for instance) have proposed constructing a new facility with high magnetic field, large test volume, and high surface-heat-flux capabilities. If such a facility is constructed and the Japanese university program on liquid metals is more effectively coordinated, Japan can become a major contributor to liquid-metal blanket development. Without this, the Japanese program will probably continue to make significant research contributions but not become a major contributor to liquid-metal blanket development.

In the 1980s, the Japanese fusion neutronics program succeeded in advancing much faster than similar efforts in the rest of the world. At present, JAERI is finalizing a plan to upgrade the FNS facility, increasing the neutron yield to 1×10^{13} n/s and providing additional experimental capabilities. The new research project on nuclear fusion by the Grant-in-Aid of MOE will start in 1990. The plan for the next five years is to expand fusion neutronics activities in universities, to expand the nuclear database, and to perform new integrated experiments.

Given the achievements in the 1980s and Japan's serious commitment to implement the R&D plan, it is expected that Japan will gain and strengthen its leadership in the world fusion neutronics program. There have been proposals for international collaboration among Japan, the United States, and Western Europe for performing radiation shielding and blanket neutronics integral experiments at FNS. Such proposals provide for the effective pooling of international fusion resources. Since Japan has the best facilities, such international collaboration will undoubtedly extend the leadership held by the Japanese in this area.

The Japanese program made significant progress during the past five years in developing hardware capabilities and initiating research projects related to tritium processing, handling, and containment. In the late 1970s Japan had practically no capabilities in this area; at the end of the 1980s, Japan's capabilities are not far behind those of the United States. It is planned to upgrade TPL, to build a tritium mock-up test laboratory, to build other small-scale experiments dealing with various aspects of tritium physics and chemistry, interaction with materials, and to develop the technology for tritium recovery from the blanket.

Given the customary strong commitment in Japan to five-year plans, it should be anticipated that such plans will be implemented. Such capabilities and activities, together with the experience Japanese scientists are gaining at TSTA at

Los Alamos, should make Japan able to handle all aspects of tritium fuel processing and containment in fusion systems. However, Japan's ability to produce large quantities (hundreds of grams) of tritium is likely to remain limited.

An advanced infrastructure of materials science and engineering, with a mature manufacturing technology, has helped Japan to make significant strides towards world leadership in fusion materials research over the past five years. The style of Japanese research in this area has several characteristics, perhaps dictated by the educational training of Japanese researchers and the industrial drive to market products of immediate value.

Other constraints, for example, the lack of high-energy and high-fluence neutron test facilities and the availability of advanced optical and electronics industries, have shaped the directions of research. Universities and national institutes have concentrated on the use of electron and ion irradiation facilities to simulate fundamental aspects of radiation effects and to draw conclusions on the expected nature of radiation damage under fusion conditions.

It is evident that experimental work on fundamental damage mechanisms has already placed Japan at the forefront of research in this area. However, the technical training of Japanese materials scientists is seriously lacking in strong theoretical foundations. This will place some limits on the level of future accomplishments, even in experimental areas. It is anticipated that the vast experimental parameter space will be scanned in a disciplined and systematic fashion. However, their ability to identify and perform new experiments designed specifically to develop new fusion materials is in doubt.

The Japanese program on the development of structural materials and ceramics for fusion applications has been primarily based on European and US efforts. Their development of swelling-resistant steels, low-activation steels, and vanadium alloys are testimonials to this fact.

In several areas, nonetheless, the newly-established materials manufacturing capabilities have helped the development of improved materials properties. Examples are the production of superior C/C graphite composites, and SiC/SiC and SiC/Al composites for fusion applications. In many instances, the ideas generated by US researchers are pursued to perfection, even after such ideas are discarded in the United States. One can observe this from Japanese efforts on the development of refractory metals.

Future Japanese efforts on fusion materials research are expected to continue the vigorous and dedicated path already established. Aided by rising manufacturing capabilities and advanced materials characterization technology, it is expected that more systematic materials tests will be conducted for the development of fusion components. The combination of university training and the newly-established industrial capability will most probably encourage Japanese research to be more innovative. Collaboration with the West, particularly the United States, will continue to be sought in order to provide key ideas for future research.

At least during the next decade, Japan is expected to lead the United States in most of the research areas outlined above. If the materials community in Japan is successful in building a national fusion neutron test facility, as planned at JAERI, this will accelerate and widen the lead even further. Their acquired leadership is not only a product of increased Japanese funding and personnel training, but is also due to the effects of recent funding cuts in the US fusion materials programs.

5. Basic and Applied Plasma Physics

a. Overview

Japan has achieved international prominence in plasma physics and fusion research during the past decade, from a technical base built on theoretical physics, experimental research, and applied engineering. Japanese theoretical physics, which grew from fundamental nuclear research, has led to the development of a small, high-quality group of theoretical physicists with expertise in statistical plasma physics, nonlinear dynamics, and plasma turbulence theory.

A still larger influence on the Japanese fusion program comes from the engineering community, which places the highest emphasis on the practical applications of research and development. From these two directions—fundamental physics and practical engineering—a unique applied plasma physics program has matured rapidly in Japan.

Compared with the United States, applied plasma physics research in Japan lacks strength in the middle ground of broad-based theoretical physicists working on the design and analysis of experimental facilities.

In applied plasma physics, the Japanese university program has made significant contributions in three areas: (i) development of alternate fusion approaches; (ii) statistical plasma physics; and (iii) the innovation of advanced computer simulation techniques.

Alternate fusion approaches are magnetic confinement configurations that operate on principles different from the mainline tokamak. The Japanese program has developed the toroidal fusion approach called the helical system into the most important alternate approach to the tokamak fusion reactor. The research and development of the helical system, which began about 30 years ago at Kyoto University, is the most widely recognized success of the Japanese applied plasma physics program.

In recognition of the significant accomplishments in this area, a large new laboratory located at Toki, near Nagoya, is being established to pursue the further development of the helical confinement approach. This laboratory, called the National Institute for Fusion Science, will be the site of the LHD, which will be the world's premier stellarator facility in the 1990s.

In theoretical plasma physics, Japan makes significant technical contributions to the understanding of coherent structures in plasma, including solitons and vortices. The properties of solitons and vortices are extensively investigated in the Japanese literature. Theory, basic laboratory experiments, and computer simulations have often been carried out first in Japan on the propagation, interaction, and collision of these self-organized coherent structures in plasmas.

Japanese accomplishments in theoretical plasma physics include the development of statistical plasma physics for high-density plasmas, plasma physics effects in strongly correlated systems, and calculations of the characteristic space-time fluctuations in plasmas, with emphasis on the effects of intermittency and universal dynamical features in both Hamiltonian and dissipative systems.

Japanese plasma research has also developed international prominence in the areas of advanced computer simulation techniques. Innovation in both the fundamental approach of solving the nonlinear, self-consistent field problem describing the electromagnetic interactions of charged particles, and the approach of solving nonlinear MHD equations for large-scale plasma dynamics are rapidly advancing in Japan. Other applied and engineering computational capabilities are also advancing rapidly in the Japanese applied plasma physics program.

b. Outlook

During the next five years, Japanese plasma physicists will make extensive use of large-scale computers to advance both basic and applied plasma theory and their application to confinement devices, particularly helical systems. The availability of supercomputers to plasma physicists, especially at the universities, may become greater in Japan than in the United States. Already it appears that the amount of supercomputer resources per research physicist in Japan is greater than in the United States. Some US physicists believe that their Japanese counterparts are able to carry out large-scale multidimensional simulations more easily.

On the other hand, a strength of the US program is that the larger number of plasma physicists working with adequate computer resources tends to foster more inventiveness in the use of computers.

Establishment of the new fusion laboratory at Toki will provide a new state-of-the-art computer center networked to many Japanese researchers. It is expected to have a supercomputer with a speed in the ten gigaflop range in one to two years. The theory and simulation division of the new laboratory is expected to have high-quality computer scientists with the freedom to work on a variety of current plasma research problems.

Regarding the computer hardware, it is expected that Japanese manufacturers will be able to provide multiprocessor supercomputers which are comparable in speed to the CRAY-3, or faster, in a few years. NEC has announced SX-3 with peak performance of about 20 gigaflops with four processors. In 1990, Fujitsu, NEC, and Hitachi are expected to announce next-generation computers with speeds in the range of many tens of gigaflops. In view of these developments, US manufacturers may have difficulty in keeping pace with the performance of Japanese computers from the point of view of the research physicist.

During the next five years, Japan should maintain its present position of a strong international presence in statistical physics and soliton research. It is not considered likely that Japan will surpass the United States in this area in any broad measure. Japanese scientists are capable of making major discoveries in statistical and nonlinear physics in the next five years.

Fundamental physics problems being addressed in Japanese research on helical systems include increasing the plasma pressure limit and investigations of the anomalous transport induced by resistive interchange modes and drift modes below the beta limit. The role of the nonambipolar radial electric field in determining the plasma transport and edge fluctuations is also a critical problem. The outlook for the next five-year period is that Japan will continue to make significant technical advances in the physics of helical systems.

The active collaboration with the Advanced Toroidal Facility (ATF) team at the Oak Ridge National Laboratory will provide important basic physics results until the Large Helical Device is operational. The technical qualifications of the Japanese theorists are high in this area, presently comparable to those of US theorists working on similar problems. With a strong commitment to the LHD, it is likely that Japan will become the world leader in both the basic plasma physics and experimental research on helical systems by the middle 1990s.

During the next five years, Japanese theory and simulation of RFPs may also surpass the US theory effort in this area, provided the groups at Hiroshima University and Tokyo University continue to grow and develop their theoretical and computational capabilities. Experimental RFP research in Japan is funded only for small-scale experiments.

Japan has traditionally made significant contributions in research related to the use of RF heating methods in plasmas. Expectations are that Japan will continue to develop the basic science of applying high frequency electromagnetic waves with various types of antennas for the purpose of plasma heating, driving currents, and controlling plasma instabilities and transport. Japan is in a position to become a world leader in this area during the next five years.

Increasing emphasis and manpower are being directed towards the development of new computer simulation techniques in Japan. During the next five years, the implicit particle code and the gyrokinetic codes will become production codes and important new computational techniques will assuredly be introduced by Japanese researchers in the area of computational plasma physics.

CHAPTER IV: ASSESSMENT OF JAPANESE MAGNETIC FUSION RESEARCH

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APPENDIX A
ABOUT THE AUTHORS

Ronald C. Davidson *(Co-Chairman)*. Dr. Davidson has been Professor of Physics and Director of the Massachusetts Institute of Technology (MIT) Plasma Fusion Center since 1978. He received a BSc from McMaster University in 1963 and a PhD in plasma physics from Princeton University in 1966. He was an Assistant Research Physicist at the University of California/Berkeley (1966-1968) and a member of the physics faculty at the University of Maryland (1968-1978), where he was also an Alfred P. Sloan Foundation Fellow (1970-1972). He has made numerous fundamental theoretical contributions to several areas of pure and applied plasma physics, including nonlinear effects and anomalous transport, kinetic equilibrium and stability properties, nonneutral plasmas and intense charged particle beams, advanced accelerator concepts, and coherent radiation generation by relativistic electron beams. Dr. Davidson is the author of two advanced research monographs: *Methods in Nonlinear Plasma Theory* (Academic Press, New York, 1972), and *Theory of Nonneutral Plasmas* (W. A. Benjamin, Reading, MA, 1974). From 1976 to 1978, he served as Assistant Director for Applied Plasma Physics, Office of Fusion Energy, US Department of Energy (DOE). He also served as the first chairman of the DOE Magnetic Fusion Advisory Committee (MFAC) from 1982 to 1986, as chairman of the American Physical Society (APS) Plasma Physics Division from 1983 to 1984, and has participated in numerous national and international committees on plasma physics and fusion research. He is a Fellow of APS and a member of Sigma Xi.

Richard D. Hazeltine *(Co-Chairman)*. Dr. Hazeltine is a professor of physics at the University of Texas at Austin. He specializes in theoretical plasma physics, especially with regard to controlled fusion, and is best known for his work in plasma transport, magnetic confinement stability, and nonlinear plasma modeling. A graduate of Harvard College (AB, 1964) and the University of Michigan (PhD, 1968), he spent two postdoctoral years at the Institute for Advanced Study in Princeton before joining the University of Texas in 1971. In 1980, he helped to establish the Institute for Fusion Studies at Texas; he served for several years as Assistant Director of the Institute, under Marshall Rosenbluth, and later as Acting Director. Dr. Hazeltine has participated in numerous government and professional panels, including, most recently, the Technical Planning Activity of the US DOE's Magnetic Fusion Program Plan. A previous member of the editorial boards of *The Physics of Fluids* and *Physical Review*, he is presently an associate editor of *Reviews of Modern Physics*. He is a Fellow of APS.

Mohamed A. Abdou. Dr. Abdou is a Professor in the Mechanical, Aerospace, and Nuclear Engineering Department at the University of California/Los Angeles (UCLA). He also directs the fusion technology research at UCLA. Formerly, he was the Associate Director of the Fusion Power Program at Argonne National Laboratory. He has been active in fusion technology research and system design studies for the past 20 years, and has contributed over 300 publications in this field. Dr. Abdou has made major contributions to international technical and programmatic fusion activities. He was the leader of the US nuclear systems for the International Tokamak Reactor (INTOR) (1980-1983) and is now the leader of the US test program for the International Tokamak Experimental Reactor (ITER). He has received several awards including the American Nuclear Society (ANS) Young Members Engineering Achievement Award (1982), the DOE Distinguished Associate Award (1988), and the ANS Fusion Energy Outstanding Achievement Award (1988). He was elected Associate Fellow of the Third World Academy of Sciences.

Lee A. Berry. Dr. Berry received a BS in mathematics and physics (1966) and a MS (1969) and PhD (1970) in physics from the University of California/Riverside. He was awarded a Regent's scholarship, a Woodrow Wilson Fellowship, a National Science Foundation Open Fellowship, and was elected to Phi Beta Kappa and Pi Mu Epsilon. He joined the Oak Ridge National Laboratory (ORNL) in August 1970, and worked initially in the turbulent heating and tokamak research programs. From December 1974, until his appointment in November 1977 as ORNL Fusion Program Director, he served as Head of the Tokamak Experiment Section, Fusion Energy Division. Dr. Berry played a key role both as a scientist and technical director in the pioneering research on neutral injection heating for tokamak plasmas at the laboratory. In 1980, he was appointed Director of the Laboratory's EBT Program and served from September 1984 to May 1988 as Associate Division Director for Development and Technology in the Fusion Energy Division. He is presently assisting the Division Director as Senior Technical Analyst. He is a Fellow of APS and has served on various professional and technical committees, including appointment to DOE's Magnetic Fusion Advisory Committee. Dr. Berry's work on EBT was recognized by a DOE Distinguished Associate Award.

John T. Hogan. Dr. Hogan is a research staff member of the Fusion Energy Division at Oak Ridge National Laboratory. He received a BS in Aeronautical Engineering from St. Louis University in 1963, a PhD from the Technological Institute, Northwestern University, in 1967, and completed post-doctoral work at the Courant Institute of Mathematical Sciences, New York University, in 1970. His research in magnetic fusion has centered on the interpretation of confinement experiments, requiring ancillary research on stability, collisional transport theory, atomic physics data, and plasma-wall interactions. Dr. Hogan is a Fellow of APS. He is currently working in international collaborations with the ITER reactor study, with the TEXTOR and Tore Supra particle control experiments, with JET high-beta experiments, and on DIII-D advanced divertor design.

Paul H. Rutherford. Dr. Rutherford received a BA (1959) and a PhD (1963) in theoretical physics from Cambridge University. After postdoctoral positions at Princeton and the Culham Laboratory, he returned to the United States to join the staff of the Princeton Plasma Physics Laboratory in 1965, serving as Head of the Theoretical Division from 1974 to 1980. In his current position as Associate Director for Program and Research, he is responsible for the scientific direction of the laboratory's experimental and theoretical research program. In addition, he is Lecturer with rank of Professor in Princeton University's Department of Astrophysical Sciences. Since 1986, he has co-taught an undergraduate course in plasma physics offered by Princeton's Physics Department. His research interests include a variety of topics in tokamak theory, especially resistive instabilities and processes of anomalous cross-field transport. In 1983, Dr. Rutherford was the recipient of the E. O. Lawrence Memorial Award in physics for his contributions to the basic theory of plasma confinement and to the toroidal reactor concept. He served as a member of the Panel on the Physics of Plasma and Fluids, and chairman of its subpanel on Fusion Plasma Confinement and Heating, for the Physics Survey Committee's report, *Physics Through the 1990s,* published by the National Academy Press (1986). He is a member of the Editorial Board of *Nuclear Fusion,* and is currently a member of the International Scientific and Technical Advisory Committee for ITER.

APPENDIX B
GLOSSARY OF ABBREVIATIONS AND ACRONYMS

AEC	Atomic Energy Commission
ANS	American Nuclear Society
AN SSSR	*Akademiya nauk Soyuza Sovetskikh Sotsialisticheskikh Respublik* (USSR Academy of Sciences)
APS	American Physical Society
ASDEX	Axisymmetric Divertor Experiment (Garching, West Germany)
ASDEX-U	ASDEX Upgrade (Garching, West Germany)
AS USSR	USSR Academy of Sciences
ATF	Advanced Toroidal Facility (Oak Ridge National Laboratory)
AWH	Alfvén wave heating
CAD	computer-aided design
CEA	*Commissariat à l'Énergie Atomique-Institut de Recherche Fondamentale* (Cadarache/Fontenay-aux-Roses/Grenoble/Saclay, France)
CEC	Commission of the European Communities (Brussels, Belgium)
CHS	Compact Helical System, torsatron (Nagoya, Japan)
CIT	Compact Ignition Tokamak—proposed in the United States
cm	centimeter
CPRF	Confinement Physics Research Facility (Los Alamos)
CPU	central processing unit
CRPP	*Centre de la Recherche en Physique des Plasmas (Ecole Polytechnique Fédérale,* Lausanne, Switzerland)
D	deuterium
DEC	Digital Equipment Company (United States)
DEMO	demonstration reactor
D-III-D	Doublet III-D tokamak (General Atomic, San Diego)
DOE	US Department of Energy
D-T	deuterium-tritium

EC	European Community
ECCD	electron cyclotron current drive
ECH	electron cyclotron heating
EML	ergodic magnetic layer
ETL	Electro-Technical Laboratory (Japan)
EURATOM	European Atomic Energy Agency
eV	electronvolt
FEL	free electron laser
FER	Fusion Experimental Reactor (Japan)—proposed tokamak
FNS	Fusion Neutronics Source (Japan)
FNT	fusion nuclear technology
FRC	field reversed configuration
FRM	field reversed mirror
FT	Frascati Tokamak (Frascati, Italy)
FT-U	Frascati Tokamak Upgrade (Frascati, Italy)
FWCD	fast-wave current drive
GA	General Atomics
GDT	Gas Dynamic Trap
GHz	gigahertz
GJ	gigajoule
HBTX	High Beta Toroidal Experiment (of RFP type)
H-mode	high mode
Hz	hertz
IAEA	International Atomic Energy Agency
ICRF	ion cyclotron resonance frequency
ICH	ion cyclotron heating
ICRH	ion cyclotron resonance heating
INTOR	International Tokamak Reactor (joint study effort)

IPP	*Institut für Plasmaphysik* (see MIPP; Garching bei München, West Germany); Institute of Plasma Physics (Nagoya, Japan)
ISTAC	International Science and Technology Advisory Committee (to ITER)
ITER	International Thermonuclear Experimental Reactor
JAERI	Japanese Atomic Energy Research Institute
JET	Joint European Torus—tokamak at Culham, United Kingdom
JFT-2M	medium-size Japanese tokamak
JIFT	Joint Institute for Fusion Theory (Japan)
JIPP-T-IIU	Japanese tokamak (Nagoya)
JMTR	Japan Material Test Reactor
JRC	Joint Research Center (Ispra, Italy)
JT-60	large Japanese tokamak (Naka)
JT-60U	JT-60 Upgrade (successor to JT-60)
K	Kelvin
kA	kiloamperes
kCi	kilocurie
keV	kiloelectronvolt
KfK	*Kernforschungszentrum Karlsruhe GmbH* (Nuclear Research Center, Karlsruhe, West Germany)
km	kilometer
kV	kilovolt
kW	kilowatt
LANL	Los Alamos National Laboratory
LCT	Large Coil Task
LH	lower hybrid
LHCD	lower-hybrid current drive
LHD	large helical device (Toki, Japan)
LHH	lower-hybrid heating
LLNL	Lawrence Livermore National Laboratory
L-mode	low mode

mA	milliampere
MA	mega-ampere
MB	megabyte
MeV	megaelectronvolt
MFAC	US DOE Magnetic Fusion Advisory Committee
MHD	magnetohydrodynamic
MHz	megahertz
MJ	megajoule
MIT	Massachusetts Institute of Technology
MITI	Ministry of International Trade and Industry (Japan)
MOE	Ministry of Education, Science, and Culture (Japan) (see *Monbusho* below)
MOTA	Materials Open Test Assembly
ms	millisecond
MTX	Microwave Tokamak Experiment
MW	megawatt
NBI	neutral beam injection
NET	Next European Torus
NFC	National Fusion Council (Japan)
NRIM	National Research Institute for Metals (Japan)
OH	ohmic heating
ORNL	Oak Ridge National Laboratory
OTR	Soviet experimental thermonuclear reactor (proposed)
PBX	Princeton Beta Experiment
PDX	Poloidal Divertor Experiment (Princeton)
PF	poloidal field
PFC	plasma facing component
PLT	Princeton Large Tokamak/Torus
PPPL	Princeton Plasma Physics Laboratory
RF	radio frequency
RFP	reversed-field pinch
RFX	Reversed-Field Experiment (Padua, Italy)

s (sec)	second
STA	Science and Technology Agency (Japan)
T	Tesla
T	tritium
T-10/T-11/T-14 (TSP)	medium-size Soviet tokamaks (Kurchatov Institute)
T-15, T-20	large Soviet tokamaks
TEXT	Texas Experimental Tokamak (United States)
TF	toroidal field
TFR	*Tokamak de Fontenay-aux-Roses* (France)
TFTR	Tokamak Fusion Test Reactor (Princeton, United States)
TO-1/TO-2	Soviet tokamaks (Kurchatov Institute)
Tore Supra	superconducting tokamak (Cadarache/Fontenay-aux-Roses, France)
TPL	Tritium Processing Laboratory (Japan)
TSP	Soviet tokamak (Kurchatov Institute)
TSTA	Tritium Systems Test Assembly (United States)
UCLA	University of California at Los Angeles
v	volt
W-VII-A (-AS, -X)	Wendelstein stellarators (Garching, West Germany)
ZETA	zero-energy thermonuclear assembly
ZT-H	reversed-field-pinch machine at Los Alamos National Laboratory

APPENDIX C

FASAC REPORT TITLES

(* asterisk before the title indicates report is classified)

(completed)

FY-82/83

* * Soviet High-Pressure Physics Research
* Soviet High-Strength Structural Materials Research
* Soviet Applied Discrete Mathematics Research
* * Soviet Fast-Reaction Chemistry Research

FY-84

* Soviet Physical Oceanography Research
* Soviet Computer Science Research
* Soviet Applied Mathematics Research: Mathematical Theory of Systems, Control, and Statistical Signal Processing
* Selected Soviet Microelectronics Research Topics
* * Soviet Macroelectronics (Pulsed Power) Research

FY-85

* FASAC Integration Report: Selected Aspects of Soviet Applied Science
* Soviet Research on Robotics and Related Research on Artificial Intelligence
* Soviet Applied Mathematics Research: Electromagnetic Scattering
* * Soviet Low-Energy (Tunable) Lasers Research
* Soviet Heterogeneous Catalysis Research
* Soviet Science and Technology Education
* Soviet Space Science Research
* FASAC Special Report: Effects of Soviet Education Reform on the Military
* Soviet Tribology Research
* Japanese Applied Mathematics Research: Electromagnetic Scattering
* Soviet Spacecraft Engineering Research
* Soviet Exoatmospheric Neutral Particle Beam Research
* Soviet Combustion Research
* Soviet Remote Sensing Research and Technology
* Soviet Dynamic Fracture Mechanics Research

(completed/cont.)

FY-86/89

- Soviet Magnetic Confinement Fusion Research
- Recent Soviet Microelectronics Research on III-V Compound Semiconductors
- Soviet Ionospheric Modification Research
- Soviet High-Power Radio Frequency Research
- Free-World Microelectronic Manufacturing Equipment
- FASAC Integration Report II: Soviet Science as Viewed by Western Scientists
- Chinese Microelectronics
- Japanese Structural Ceramics Research and Development
- System Software for Soviet Computers
- Soviet Image Pattern Recognition Research
- Japanese Magnetic Confinement Fusion Research
- West European Magnetic Confinement Fusion Research
- * Soviet Research in Low-Observable Materials
- Comparative Assessment of World Research Efforts on Magnetic Confinement Fusion

(in production)

FY-86/89

- Soviet Oceanographic Synthetic Aperture Radar (SAR) Research
- Soviet and East European Research Related to Molecular Electronics
- Soviet Phase-Conjugation Research
- Soviet Atmospheric Acoustics Research
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