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FOREIGN APPLIED SCIENCES ASSESSMENT CENTER
TECHNICAL ASSESSMENT REPORT

# JAPANESE MAGNETIC CONFINEMENT FUSION RESEARCH


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January 1990

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# FOREIGN APPLIED SCIENCES ASSESSMENT CENTER

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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.

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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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## ABSTRACT

This report is the work of six US scientists who surveyed and assessed Japanese research and development in magnetic fusion. All of the panelists are very familiar with Japanese fusion research through their knowledge of the published scientific literature and through personal contacts with Japanese colleagues and with US colleagues who have visited Japanese research facilities. This report concentrates on the period from the early 1980s through June 1989. The technical accomplishments during this period are reviewed, and the Japanese capabilities and outlook for future contributions are assessed. Detailed evaluations are provided in the areas of basic and applied plasma physics, tokamak confinement, alternate confinement approaches, plasma technology, and fusion nuclear technology and materials.

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 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 will surpass US and West European capabilities in the early to middle 1990s in several important areas of fusion research and development. For example, it is expected that the planned upgrade of the Japanese JT-60 tokamak will surpass both the US Tokamak Fusion Test Reactor (TFTR) and the Joint European Torus (JET) in the usual measures of plasma performance in the 1992 to 1993 timeframe, and will take a clear international lead in large-tokamak research by 1994 to 1995. 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 undertaking of such a project.

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## FOREWORD

This report, *Japanese Magnetic Confinement Fusion Research,* is one in a series of technical assessment reports (TARs) produced by the Foreign Applied Sciences Assessment Center (FASAC), which Science Applications International Corporation operates for the Federal government. Appendix E, at the end of this report, lists the titles of FASAC reports completed or underway.

The report focuses on Japanese research in:

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

The report was prepared by a panel of six internationally recognized US scientists and engineers who are active participants in magnetic confinement fusion research. The panel membership is:

| | |
|---|---|
| • Dr. Ronald C. Davidson (Panel Chairman) | Professor of Physics<br>Plasma Fusion Center<br>Massachusetts Institute of Technology |
| • Dr. Mohamed A. Abdou | Professor<br>Department of Mechanical, Aerospace, and Nuclear Engineering<br>University of California at Los Angeles |
| • Dr. Lee A. Berry | Senior Technical Analyst<br>Fusion Energy Division<br>Oak Ridge National Laboratory |
| • Dr. C. Wendell Horton | Professor of Physics<br>Department of Physics<br>University of Texas at Austin |

- Dr. James F. Lyon — Stellarator Program Coordinator<br>Fusion Energy Division<br>Oak Ridge National Laboratory

- Dr. Paul H. Rutherford — Associate Director<br>Plasma Physics Laboratory<br>Princeton University

All of the panelists have had extensive contacts with Japanese fusion scientists and engineers at international conferences. Moreover, all of the panelists have been personally involved in US/Japanese fusion exchange activities. Between November 1988 and June 1989, the panelists spent approximately one working month each reviewing and assessing several thousand articles obtained from published technical journals, preprints from Japanese research institutes, international conference proceedings, and US government databases of Japanese technical publications.

The panel acknowledges the help of Professor Nasr Ghoneim of the University of California/Los Angeles, who contributed information in the areas of materials and plasma-interactive components.

# EXECUTIVE SUMMARY

This technical assessment of Japanese magnetic fusion research and development concentrates on the period from the early 1980s through June 1989. The report presents detailed evaluations of Japanese accomplishments and capabilities and the outlook for future contributions in five areas: basic and applied plasma physics; tokamak confinement; alternate confinement approaches; plasma technology; and fusion nuclear technology and materials.

By way of background, during the 1960s and early 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 it 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 will surpass US and West European capabilities in the early to middle 1990s in several important areas of fusion research and development. For example, it is expected that the planned upgrade of the Japanese JT-60 tokamak will surpass both the US Tokamak Fusion Test Reactor (TFTR) and the Joint European Torus (JET) in the usual measures of plasma performance in the 1992 to 1993 timeframe, and will take a clear international lead in large-tokamak research by 1994 to 1995.

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 undertaking of such a project.

The following brief summary highlights the panel's findings.

## A. BASIC AND APPLIED PLASMA PHYSICS

The Japanese university program has emerged as a world leader in basic and applied plasma physics with significant contributions and capabilities in these three areas: (i) the development of alternate (non-tokamak) confinement approaches, (ii) statistical plasma physics, and (iii) advanced computer simulation techniques.

Japanese theorists have used statistical physics to study such problems as the nature of transients near the instability threshold of plasmas and the structure of plasma turbulence. The Japanese plasma research program has developed innovative methods within their strong program in advanced computer simulation techniques. This already impressive program will be enhanced as Japanese manufacturers provide multiprocessor supercomputers which are comparable in speed to the CRAY-3, or faster, in the next few years. NEC Corporation has announced the 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. As a general remark, US manufacturers may have difficulty in keeping pace with the performance of Japanese computers in typical calculations done by the research physicist.

## B. TOKAMAK CONFINEMENT

With a sustained national commitment, it is anticipated that the planned upgrade of the JT-60 tokamak will surpass both TFTR (US) and JET (Europe) in the usual measures of plasma performance in the 1992 to 1993 timeframe. It is expected that Japan will likely take a clear international lead in large-tokamak research by 1994 to 1995, barring major improvements to JET or TFTR.

The intermediate-scale JFT-2M tokamak at the Japanese Atomic Energy Research Institute and the superconducting TRIAM-1M tokamak at Kyushu University fulfill important roles in providing testbeds for exploratory ideas that may eventually be employed in the mainline program. Apart from the small

WT-3 tokamak (Kyoto University) and TRIAM-1M, Japanese graduate students will have very limited opportunities for experimental research on tokamaks.

## C. ALTERNATE CONFINEMENT APPROACHES

The stellarator (or helical system) has been selected for a large next-step experimental facility, presently called the Large Helical Device, to be sited at the new National Institute for Fusion Science at Toki (near Nagoya) operated by the Ministry of Education, Science and Culture. More than one-half of the funding for alternate concepts in Japan will be devoted to the Large Helical Device project (total estimated project cost $\gtrsim$ \$750 million).

With a strong commitment to the Large Helical Device, Japan is likely to become the world leader in both the basic plasma physics and experimental research on helical systems by the middle 1990s. Official Japanese policy, while somewhat uncertain, is to maintain, as far as possible, research on other alternates for future possible innovative developments.

## D. PLASMA TECHNOLOGY

The Japanese have made significant contributions in those areas where there are active plasma technology 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 advancements reflect improvements in the underlying technology base and in the production of high-quality, reliable components by industry.

In other areas (for example, pellet injectors and millimeter wavelength, high-power, long-pulse to steady-state microwave sources), research and development programs have not been established. Even then, Japanese industry has been able to produce useful components which are based on existing technology.

Supporting industry in Japan is singularly capable. Strong and effective relationships exist between the laboratories and industry and are reinforced by the broader national commitment of Japan to advanced technology development as a means to commercial advancement.

## E. FUSION NUCLEAR TECHNOLOGY AND MATERIALS

Fusion nuclear technology and materials have been areas of particularly rapid growth and strong national commitment in the Japanese fusion program. During the next decade, it is expected that Japan will lead the world effort in several related areas: (i) integrated blanket tests in the Japan Material Test Reactor; (ii) construction of a manufacturing and processing facility with a beryllium handling laboratory; (iii) upgrade of the Fusion Neutronics Source facility to increase the neutron yield; (iv) upgrades of the Tritium Processing Laboratory and tritium test laboratories; and (v) continued strengthening of materials science and engineering programs, including the development of structural materials and plasma-facing (high-heat-flux) components. As a general remark, a mature Japanese manufacturing technology exists in the materials area.

## F. INTERNATIONAL COOPERATION

As a final point, international cooperation on fusion research and development is being actively pursued by Japan. US-Japanese cooperation in fusion officially began in 1978 with an initiative, agreed upon by President Carter and Japanese Prime Minister Fukuda, which opened the way for Japanese partnership in operating the Doublet III tokamak at General Atomics in San Diego. 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 program.

Overall, the US-Japan cooperation in fusion has been highly beneficial to both parties in a wide range of experimental, theoretical, and technical areas. In addition, Japan and the European Community have recently established a broadly based accord on nuclear fusion research.

# CHAPTER I
# ASSESSMENTS

## A. INTRODUCTION

Magnetic fusion research and development (R&D) is one highly visible measure of a nation's capabilities in advanced technology and the physical sciences. During the past decade, Japan has emerged as a world leader in fusion R&D. 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 will surpass US and West European capabilities in the early to middle 1990s in several important areas of fusion R&D. For example, it is expected that the planned upgrade of the JT-60 tokamak will surpass both the Tokamak Fusion Test Reactor (TFTR) at Princeton University and the Joint European Torus (JET) at Culham Laboratory in England in the usual measures of plasma performance in the 1992-1993 time frame, and will take a clear international lead in large-tokamak research by 1994-1995. The Japanese fusion program certainly 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 undertaking of such a project.

After description of the organization of fusion research in Japan and Japan's fusion policy, the remainder of this chapter summarizes the panel's assessments in the following five areas:

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

Chapters II through VI provide a more thorough evaluation and delineation of accomplishments and capabilities, as well as the outlook for future Japanese contributions.

## B. ORGANIZATION OF FUSION RESEARCH IN JAPAN

As illustrated in Figure I.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).

The Science and Technology Agency (STA), which is a cabinet-level department, is 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, which is an independent, non-government organization. JAERI receives a significant fraction of Japan's funding for fusion R&D (see Figure I.2), and places primary emphasis on developing the tokamak confinement approach (Chapter III) and the related reactor technologies. As follow-ons to the present major tokamak facility 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 I.3). Of course, plans and schedules, such as those illustrated in Figure I.3, are updated on a regular basis, depending on the rate of technical progress on fusion facilities in Japan and elsewhere.

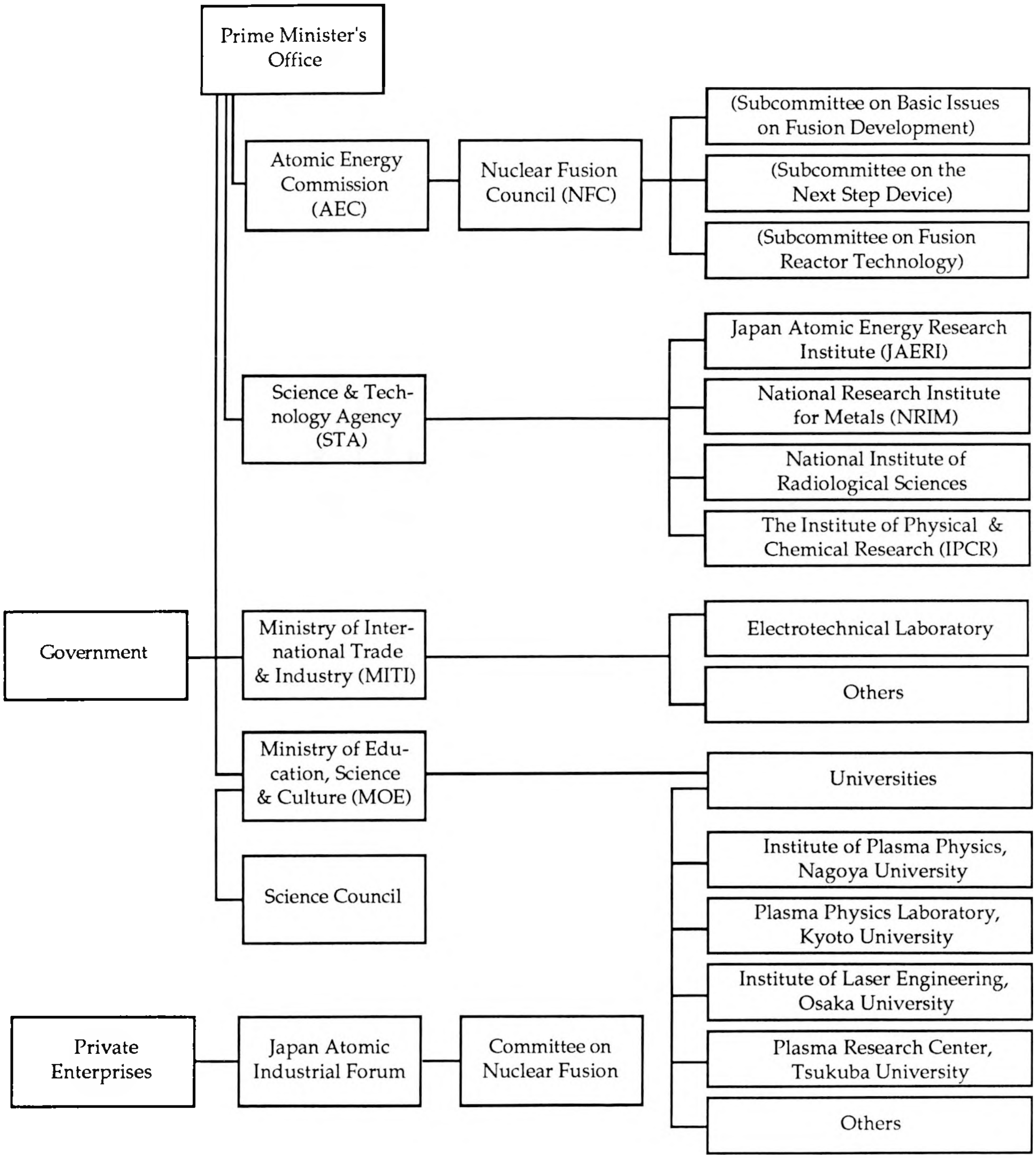


**Figure I.1**
**Organization of Fusion Research in Japan**

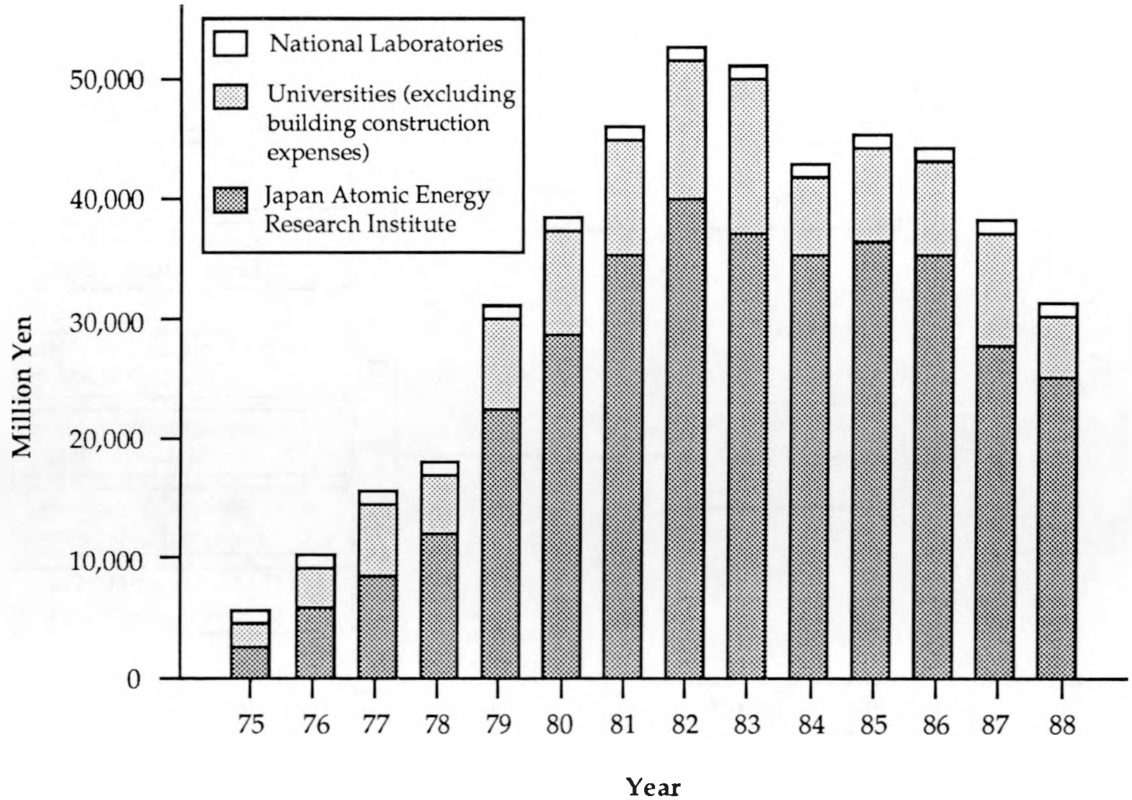


**Figure I.2**
**Recent Trends in Fusion Funding in Japan**
(Excluding Personnel and Administration Fee)

As a general remark, referring to Figure I.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 I.2 do not include salary costs for technical and administrative personnel (except for subcontracts to industry). Therefore, the resources in Figure I.2 represent a very significant capability in terms of the materials and services expended on fusion R&D.

MOE supports a broadly-based university research program in plasma science, materials research, technology development, and manpower training related to fusion. This is illustrated in Figure I.4, which shows a cross-cut of research activities on different confinement approaches at various institutions involved in fusion research. (The JAERI tokamak facilities, JFT-2M and JT-60, are also included in Figure I.4.) As discussed in Chapter IV, 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.

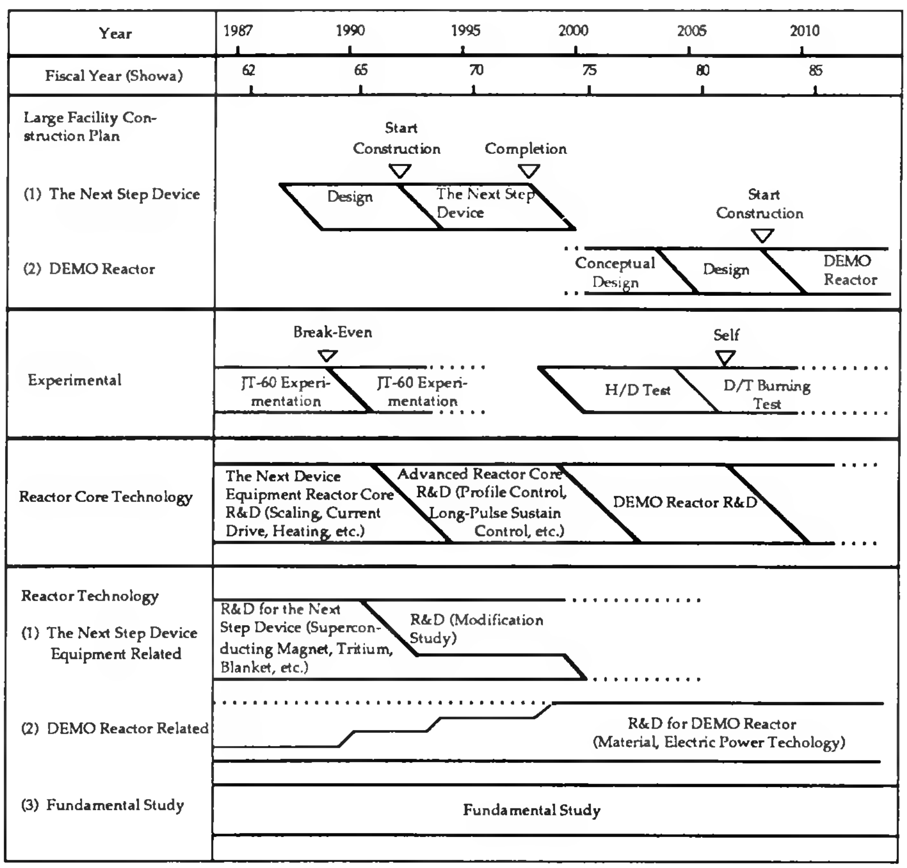


**Figure I.3**
**Nuclear Fusion Development Plan in Japan**

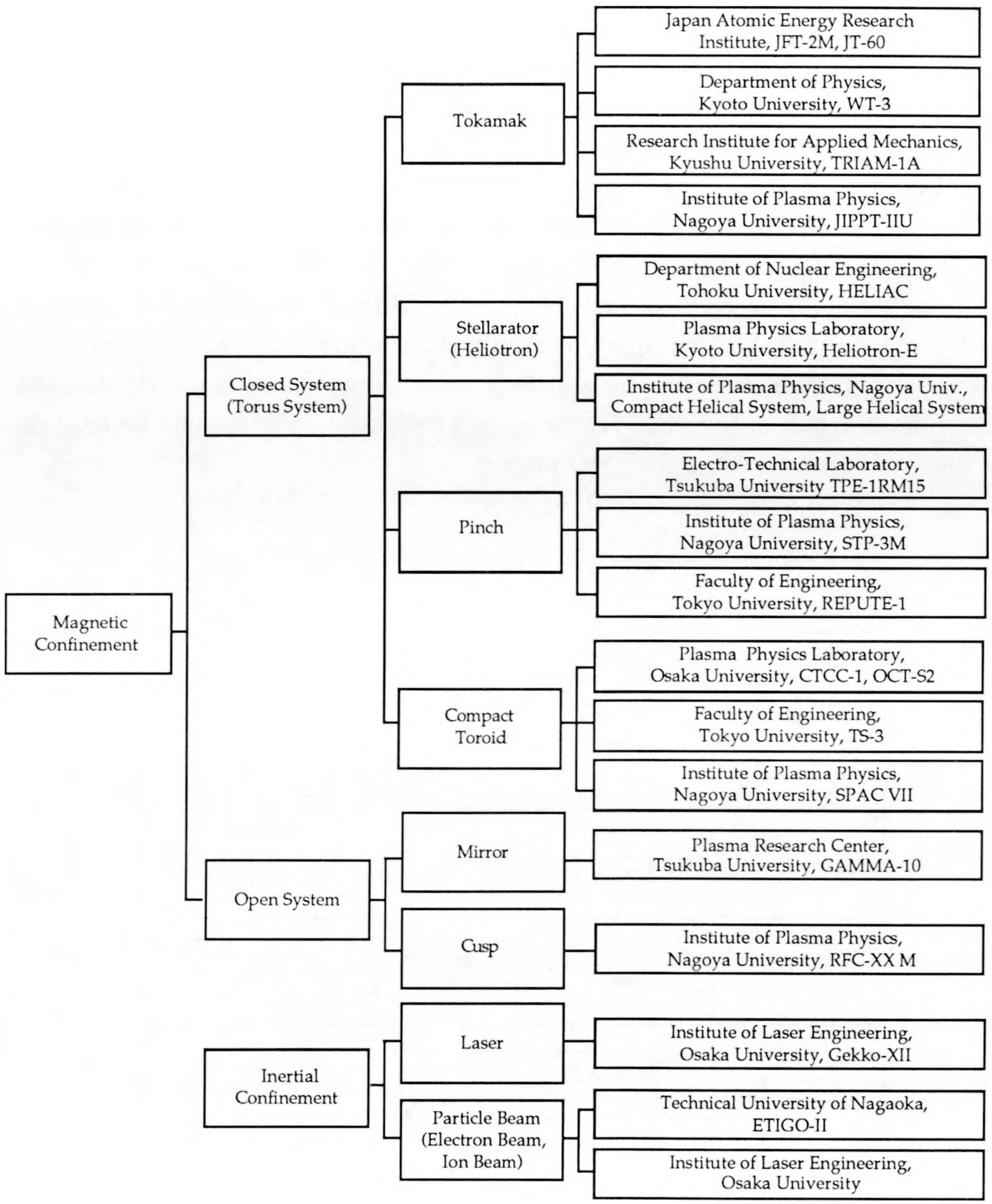


**Figure I.4**
**Plasma Confinement Research Activities in Japan**

## C. JAPAN'S NATIONAL POLICY ON FUSION RESEARCH AND DEVELOPMENT

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

Fusion R&D plays an important role in Japan's goal for long-term energy security and in the development of advanced technologies:

> 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.

The plan calls for a next-generation tokamak beyond JT-60 and an increased emphasis on the development of reactor-related technologies:

> . . . the next-generation large-size nuclear fusion equipment will be indispensable for promotion of the relevant R&D activities in

> Japan, and the same Tokamak system as the JT-60 will be adopted. The relevant R&D will be started after attaining the break-even plasma condition of the JT-60, by taking into consideration the evaluation of the generation, control, and other aspects related to the reactor core plasma. A concrete plan for construction of the new equipment will be defined by taking into consideration such factors as research on improvement of the Tokamak system at home and abroad, the state of development of the reactor engineering technology, and the international trends related to the matter, by keeping in mind the schedule, which aims at starting construction of new equipment in Japan in the first half of the 1990s.
>
> Regarding reactor engineering technology, the importance of which will increase hereafter, research and development of technologies related to such fields as materials, tritium, superconductivity, remote control, and heating, will be actively carried out with the long-range viewpoint towards practical application of the technology.

The roles of JAERI, the universities, and national research institutions are well defined in a nationally coordinated effort to develop fusion as a practical energy source:

> In promoting such R&D, JAERI will make efforts to attain the break-even plasma condition by means of the JT-60 and to improve the performance of Tokamak equipment through improvement and remodeling of the JT-60, and other applicable measures. Furthermore, JAERI will play a leading part in the research and development in the next stage based on the knowledge obtained from the R&D carried out so far and the operating results of the existing equipment. The universities and national research institutions, etc., are expected to carry out fundamental and creative research on plasma confinement methods of various kinds and on reactor engineering, and to develop human resources required in this field.
>
> In implementing the comprehensive development of nuclear fusion mentioned above, the relevant R&D will be carried out in conformity with the control and coordination scheme, in the domestic context, defined by the Nuclear Fusion Council of the Atomic Energy Commission, by taking into consideration international cooperation, and by paying attention to the compatibil-

ity between and mutual coordination and cooperation among JAERI, national research institutions, and universities.

International cooperation on fusion R&D is to be actively pursued:

> International cooperation, including studies of the possibility of joint construction of nuclear fusion facilities through new international cooperation projects, will be actively promoted, on the premise of mutual benefit, by taking into consideration the compatibility with the programs being implemented in Japan, and from the standpoints of expansion of the scope and efficient implementation of the R&D, and reduction of the new development risk.

Japan's bilateral cooperation in the development and utilization of nuclear energy covers a wide range of advanced technologies with potential long-term benefits:

> Responsible and active international cooperation will be promoted with Japan's initiative in such fields or key technology areas where collaboration with other advanced countries is considered necessary from the standpoint of a common benefit of the world, and where Japan possesses a certain level of technological achievement. Moreover, as for cooperative programs initiated by other countries, Japan will, from the same standpoint, positively participate in such programs. In implementing the cooperation, special attention will be paid to the state of affairs and other relevant factors in the counterpart countries, as well as to securing reciprocal benefit and responsibility.

Four specific areas for cooperation are then listed, one of which is:

> Strengthening of cooperation related to key technologies of nuclear fusion, and participation in the joint design and examination of the possibility of joint construction of next-generation facility.

Japan actively promotes the peaceful use of nuclear energy on world-wide basis through international organizations such as the IAEA:

> In order to make responsible contributions to our own initiative, and for proper improvement of the international environment

necessary for the promotion of peaceful uses of nuclear energy in the world, Japan, as one of the main members, will positively devote itself to the activities of such institutions as the International Atomic Energy Agency, and the Nuclear Energy Agency of the Organization for Economic Cooperation and Development, so that each of these institutions will give fullest play to its characteristics. At the same time, Japan will strive to promote international understanding of its activities in the field of nuclear energy through the activities of those international organizations.

In this connection, Japan will be an active participant in international conferences, promote its participation in international organizations by sending personnel, and offer appropriate voluntary contribution to international organizations in connection with themes of special interest to Japan. Besides such areas as safeguards in which Japan has been active, special importance will be attached to cooperation related to activities in the safety area, and in the feasibility surveys of new technologies.

To summarize, 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 Fuduka, 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 program (centered at Hiroshima University). Overall, as discussed in Chapters II through VI, US-Japanese cooperation in fusion has been highly beneficial to both parties in a wide range of experimental, theoretical, and technological areas.

In January 1989, the European Community/Council approved a broadly based accord with Japan on nuclear fusion research.

## D. SUMMARY OF ASSESSMENTS

### 1. Basic and Applied Plasma Physics

#### a. Overview

Japan has emerged as an international leader in plasma physics and fusion research during the past decade, with 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 numbers 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 thirty 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.

Japanese accomplishments in statistical 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.

Japan also 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 plasma research has also developed international prominence in the areas of advanced computer simulation techniques. Innovations 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 magnetohydrodynamic equations for large-scale plasma dynamics occurring 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 its 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. The laboratory 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 the SX-3 system with peak performance of about 20 gigaflops using 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 the Japanese computers available to Japanese research physicists.

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

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 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 reversed field pinches 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 reversed field pinch research in Japan is funded only for small-scale experiments.

Japan has traditionally made significant contributions in research related to the use of radio frequency (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.

## 2. Tokamak Confinement

### a. Overview

The Japanese tokamak program began in the early 1970s, when a small tokamak was brought into operation at the Japan Atomic Energy Research Institute (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 Institute 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 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 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 General Atomics in San Diego 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 had 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 (FER), 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-moderate size tokamaks at Tokai (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, DT-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 multinational 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.

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 high confinement (so-called 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 theoretically predicted beta-values, the JT-60U will surpass the requirement for Lawson criterion for energy 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-60 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 device heating. The new lower hybrid current launchers are projected to be capable of driving the full 6-MA current at densities up to $5 \times 10^{18} m^{-3}$.

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 probability 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 intermediate-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 (LHCD) 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-sec pulses. A ten-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 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 Tokai.

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 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.

### 3. 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 size of the small 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 (for example, Heliotron-E) when there is good coordination between the experimental group and the company but there have been some failures (for example, the initial GAMMA-10 configuration) when good communication was lacking. This 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 in a few areas. 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 well 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 LHD to be built at a new MOE-operated laboratory at Toki, 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 confinement systems (tandem-mirror, laser and particle-beam inertialconfinement, and reversed field pinch) 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 the only tandem mirror in the world studying concept improvement. 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 Electro-Technical Laboratory 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 and 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 ZT-H (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.

### 4. Plasma Technology

#### a. Overview

Capability in developing plasma technologies is determined by specific skills within a particular research program and 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 which, however, 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 (FER). The recent decline in budgets in plasma technology is likely 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 the FER and the International Thermonuclear Experimental Reactor (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 likely receive higher priority and increased funding when plans for FER/ITER are established.

The plans for JT-60 Upgrade call for doubling the installed ion cyclotron heating (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 likely 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, Kobe 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 certainly 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.

### 5. 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 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. 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 $\sim 3 \times 10^{12}$ 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 presently has 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 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 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 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 the Japan Material Test Reactor, 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 to increase the neutron yield to $1 \times 10^{13}$ n/s and to provide 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 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 they 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 some characteristics 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, 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.

## CHAPTER I: ASSESSMENTS
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# CHAPTER II
# BASIC AND APPLIED PLASMA PHYSICS IN JAPAN

## A. OVERVIEW

Japan has emerged as an international leader in plasma physics and fusion research during the past ten years from a scientific base built on theoretical physics, experimental research, and applied engineering. Japanese theoretical physics, which grew from fundamental nuclear research (Yukawa, 1935), 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 has arisen from the engineering community, which places the highest emphasis on the practical usefulness of research and development. From these two directions, fundamental physics and practical engineering, a unique plasma physics research program has rapidly matured in Japan.

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

In applied plasma physics, the Japanese program has developed leadership in three areas: (i) development of so-called "alternative concept" fusion approaches, (ii) statistical plasma physics, and (iii) the innovation of advanced computer simulation techniques.

Alternative concepts are magnetic fusion configurations that operate on different principles from the mainline tokamak (see Chapter III). The Japanese program has developed the toroidal fusion approach called the "helical system" into the most important alternative approach to the tokamak fusion reactor. The research and development of the helical system, which began about 30 years ago at Kyoto University, is probably the most widely recognized success of the Japanese applied plasma physics program (see Chapter IV).

In recognition of their success 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 will be one of the major fusion facilities in the world, as described in Chapter IV.

Advances in other alternative approaches have constituted important accomplishments in the Japanese plasma fusion program. The field reversed configuration (FRC) has benefited from a series of Japanese contributions on the control of the rotational instability and the first experiments on plasma translation. The toroidal reversed field pinch (RFP) configuration has benefited from the research and development of three-dimensional resistive magnetohydrodynamic computer simulations showing the dynamical processes for the relaxation of the plasma to a self-organized dynamo state. Research in this area began with basic studies of driven magnetic reconnection, a fundamental process in laboratory and astrophysical plasmas.

In addition, the Japanese program has the world's largest operating and best-performing tandem mirror confinement device located at Tsukuba University. Although the plasma performance parameters in tandem mirrors are far behind those of tokamaks and helical systems, a fact leading the United States to abandon this approach, the tandem mirror has unique properties that make it an important plasma physics confinement approach.

In theoretical plasma physics, Japan makes a strong international contribution to the understanding of coherent structures in plasma, including solitons and vortices. The properties of solitons and vortices are extensively explored 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 calculations 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.

Finally, the Japanese plasma research program has developed a leading international role in the area of advanced computer simulation techniques. Innovations 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 magnetohydrodynamic (MHD) equations for large-scale plasma dynamics are rapidly advancing in Japan. Other applied and engineering computer capabilities are also rapidly advancing in the Japanese applied plasma physics program.

## B. FUSION AND PLASMA PHYSICS IN THE JOURNALS AND INSTITUTIONS OF JAPAN

### 1. Accomplishments and Capabilities

a. Survey of Physics Journals

The principal Japanese journal for both experimental and theoretical plasma physics is the *Journal of the Physical Society of Japan*, published in English. Each issue contains works in condensed matter; nuclear, atomic, and molecular physics; classical and general physics; and fluids and plasma physics. During the period from 1981 to 1988, each volume of the journal contained from 4,000 to 5,000 pages with approximately five percent devoted to plasma theory. Averaged over a year, there are approximately two significant plasma theory works per month, split about evenly between fusion theory and basic plasma theory.

Two other important Japanese physics journals are *Progress of Theoretical Physics* and the *Japanese Journal of Applied Physics*. *Progress of Theoretical Physics* was initiated at the Yukawa Institute in Kyoto, and is a prestigious physics journal in Japan. Although this journal contains sections on condensed matter and statistical physics, astrophysics, plasma physics, relativity, and mathematical physics, it is dominated by nuclear physics, elementary particle physics, and high-energy physics. While there are occasionally articles on general aspects of nonlinear dynamics or statistical plasma physics, there are essentially no fusion theory articles published in this journal. The *Japanese Journal of Applied Plasma Physics* contains typically one to three articles (out of 25 to 30) each month on the experimental aspects of plasma diagnostics, heating, surface and edge plasma physics, or other general areas of practical laboratory plasma behavior. Both of these journals have a few European and US contributions, but are dominated by Japanese and other Asian contributions.

In addition, there are journals such as *Kakuyugo-Kenkyu* and *Laser-Kenkyu,* which are mostly written in Japanese, with occasional articles in English. The first journal is primarily for magnetic fusion, and the second journal is primarily for laser fusion and related applications.

The distribution of articles over the fields of physics published in the *Journal of the Physical Society of Japan* is shown in Figure II.1 for the year 1985. The journal is dominated by research on condensed matter physics. The distribution of topics in *Progress of Theoretical Physics* is shown in Figure II.2, and the distribution in the *Japanese Journal of Applied Physics* is shown in Figure II.3. The journal *Progress of Theoretical Physics,* initiated in Kyoto and edited by Yukawa until his death in 1981, is now published by the Japanese Physical Society and primarily contains articles on advances in nuclear and high-energy physics. Experimental and technological advances in condensed matter and plasma physics are typically reported in the *Japanese Journal of Applied Physics.*

Complementary to basic plasma theory are the basic plasma physics experiments performed principally at the universities with the purpose of isolating one or a few physical processes. The *Journal of the Physical Society of Japan* contains typically about 20 articles on the results of such experimental studies. In relation to theory, this approximately one-to-one ratio is considerably higher than the ratio published in the plasma physics section of the US journal *Physics of Fluids.* Universities with strong basic plasma physics experimental programs include Tohoku University at Sendai, Tsukuba University, Utsunomiya University, Nagoya University, Kyoto University, Osaka University, and Kyushu University. As typical of these publications, we cite the work by Yamamoto et al. (1975) on the stabilization of the interchange instability in a simple mirror with the use of the ponderomotive force produced by radio frequency fields.

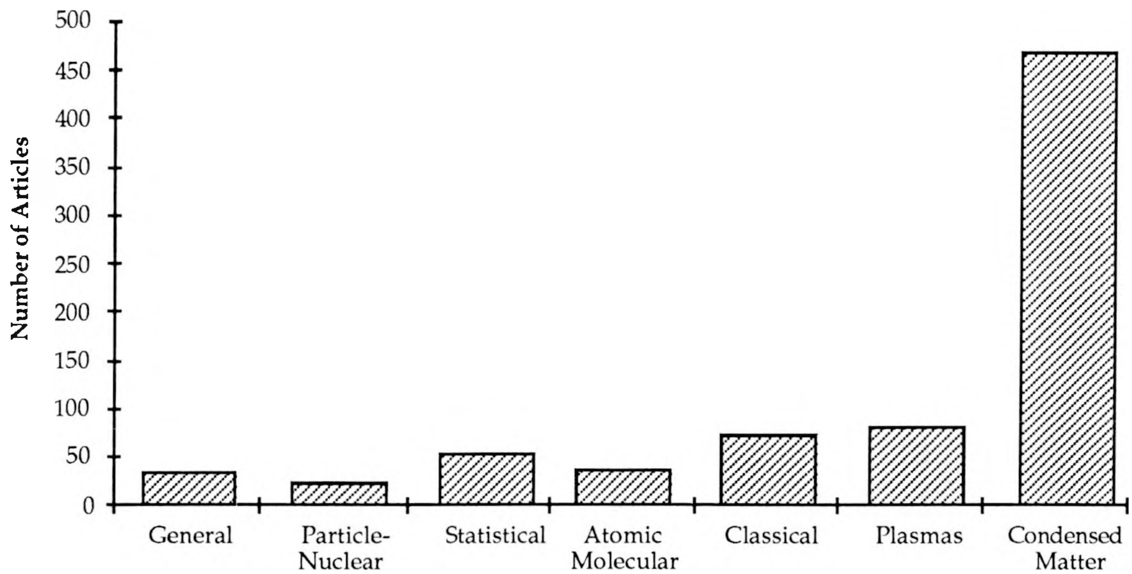


**Figure II.1**

**DISTRIBUTION OF ARTICLES IN THE**

***JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN, 54* (1985)**

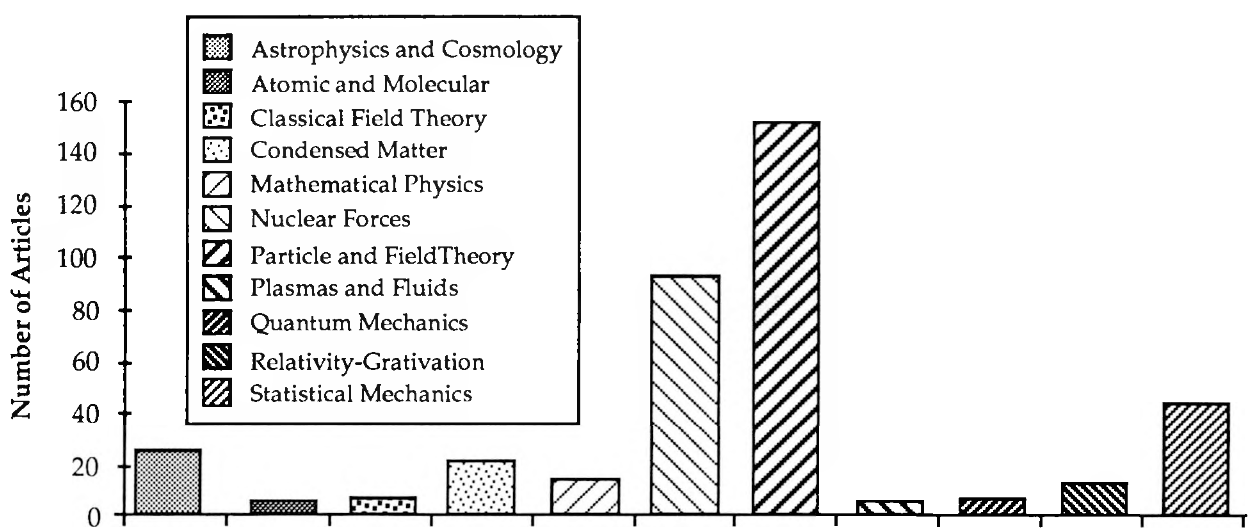


**Figure II.2**

**DISTRIBUTION OF ARTICLES IN**

***PROGRESS OF THEORETICAL PHYSICS, 73/74* (1985)**

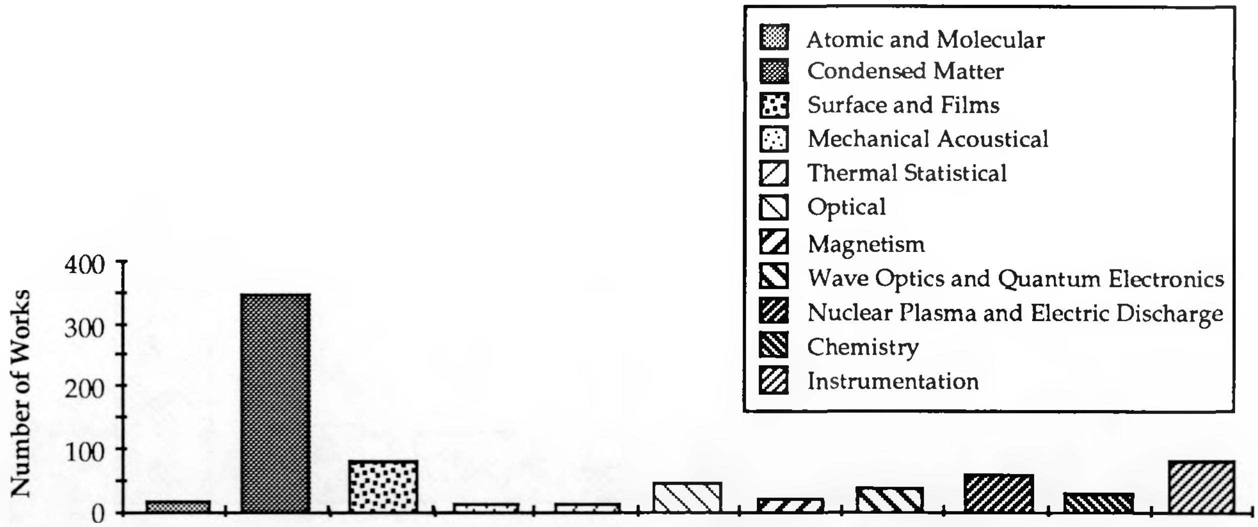


**Figure II.3**
**DISTRIBUTION OF ARTICLES IN**
***JAPANESE JOURNAL OF APPLIED PHYSICS, 24* (1985)**

The number of Japanese scientists actively publishing in plasma theory is about 80 at the present time (1988). The distribution of physics contributions at the annual meeting of the Physical Society of Japan is presented in Table II.1 and shows that 15 percent of the contributions were in magnetic and inertial fusion, compared with 44 percent in condensed matter and statistical physics, and 33 percent in nuclear and high-energy physics. As illustrated in Table II.2, the membership in the Japan Society of Plasma Science and Nuclear Fusion Research is 10 percent of the membership of the total Physical Society.

The *Journal of the Physical Society of Japan* is a highly regarded journal for research publications. The research published therein is almost all from Japanese scientists working in Japan. Because of the national character of this journal, the Japanese fusion theorists tend to publish their most important findings in international journals, principally those published by the American Institute of Physics, and in the European plasma physics and fusion journals. Occasionally, however, an important new plasma physics result is first published in the *Journal of the Physical Society of Japan*. One example is the first demonstration of the soliton character of the Rossby drift wave dipolar vortex published by Makino, Kamimura, and Taniuti (1981).

**Table II.1**
**1988 AUTUMN MEETING OF THE PHYSICAL SOCIETY OF JAPAN—DISTRIBUTION OF CONTRIBUTIONS OVER FIELD OF PHYSICS**

| Number of Works | Fields of Physics |
|---|---|
| 243 | Plasma and Fusion (Magnetic and Inertial) |
| 180 | Statistical Physics and Fundamental Condensed Matter |
| 531 | Condensed Matter Physics (Magnetism, Semiconductor, Metals, etc.) |
| 123 | Quantum Electronics and Atomic Molecular Physics |
| 527 | Nuclear and High-Energy Physics |

**Table II.2**
**MEMBERSHIP NUMBERS FOR KEY JAPANESE SOCIETIES (1988)**

| Membership Numbers | Affiliation |
|---|---|
| 14927 | Physical Society of Japan |
| 16721 | Japan Society of Applied Physics—mainly work in condensed matter physics, electronics, and high-vacuum physics |
| 1258 | Japan Society of Plasma Science and Nuclear Fusion Research |
| ~80 | Active researchers in plasma theory |

In summary, examination of the Japanese publications in plasma theory and computer simulations shows that 15 to 20 articles per year in magnetic fusion are published in Japanese journals, with an equal or larger number published by Japanese scientists in the leading US and European physics journals.

In addition to fusion theory articles, there are works in applied mathematics and statistical physics motivated by general plasma theory questions. The quality of the contributions in the nonlinear physics of solitons, Hamiltonian dynamics, fluid turbulence and vortex dynamics, and self-organized dissipative structures is high, and the number of contributions equals or exceeds the number in magnetic fusion theory. Examples of works in these areas are Toda (1967a-b, 1970), Mori (1965, 1983a-b), Wadati et al. (1980), and Hirota (1973). While Japanese physicists in these areas often contribute to the plasma theory meetings in the United States and Japan, these physicists tend not to publish works that directly address the problems of magnetic confinement. In this survey of Japanese plasma theory related to magnetic fusion, only those articles directly related to plasma confinement are included in the numbers of published papers. This division between general theory and plasma theory corresponds closely to the division used by the *Journal of the Physical Society of Japan.*

b. Style of Plasma Theory Publications and the Attitude of Japanese Theorists

Japan emerged as an international force in theoretical physics with the publication by H. Yukawa (1935) of the theory for the nuclear force binding neutrons and protons by the exchange of a new intermediate-mass particle called the pi-meson. Prior to Yukawa's predictions, the dominant view was that of scientists in Germany, particularly Heisenberg, that the nuclear force should be explained with a neutron-proton-electron model. The experimental confirmation of the pi-meson theory of the nuclear force launched Japan as a scientific leader in theoretical physics and set the direction of Japanese physics institutions, and their administration.

The typical publications by Japanese theorists are shorter and simpler in construction (typically less than 10 pages and less than 30 equations) than the corresponding US publications, which often contain 10 to 20 pages and 50 or more equations. Making up for the shorter articles, Japanese researchers often show a spirit of persistence—called *yamato damashii*—where a series of studies is published, each dealing with different aspects of a research problem (Sanders, 1975). Examples of these serial publications are easily found in the RFP theories of Yoshizawa (1988) and Yoshizawa and Hamba (1988), the recent RF ponderomotive potential publications of Kono et al. (1980, 1987) and Kono and Sanuki (1987), and the mode coupling calculations of Akama and Nambu (1987) and Nambu (1988), to cite a few examples. Each individual publication deals carefully with one aspect of the research problem. In contrast, leading US theorists tend to publish a more global article dealing with several aspects of a particular problem.

Keeping this in mind, the basic plasma publications in Japan tend to be more clearly contained within the categories of theoretical analysis, numerical simulation, and basic plasma experiments. There are relatively few Japanese publications that contain analytical theory combined with numerical simulations aimed at supporting the theory. These types of publications, prevalent in the United States, tend to be lengthy and complex, and do not generally appeal to Japanese theorists.

The best Japanese simulation articles, typical of those from Sato and Hayashi (1979) at Hiroshima University on magnetic reconnection and magnetic turbulence, develop the physics of the problem almost exclusively by computer. Only when the results can be interpreted by simple, easily derivable theoretical formulas will a direct comparison between experiment and theory be given. This is in contrast to the US use of computer simulations which aim rather specifically at confirming the results of a difficult and approximate theoretical calculation. Both approaches have their advantages and disadvantages with respect to developing an understanding of the nonlinear, self-consistent physics of plasmas.

### c. Size of Plasma Physics Working Force and Institutions

A study of the plasma physics literature indicates that the total number of fusion theorists working in Japan in both magnetic and inertial confinement is about 100. Professor Y. H. Ichikawa, the director of the International Center for Fusion Theory (ICFT) at IPP-Nagoya and past president of the Physical Society of Japan estimates that there are 80 active researchers in plasma theory. There are

1,300 members of the Physical Society of Japan belonging to the Plasma and Fusion Division, which is about 10 percent of the total membership of the Physical Society representing all areas of physics (Ichikawa, 1988). In addition, there is the relatively new Japan Society of Plasma Science and Nuclear Fusion Research whose membership is approximately 1300. Membership is approximately 50 percent from universities, 25 percent from government and public laboratories, and 25 percent from industry.

The distribution of contributed works by fields of physics at the annual general meeting of the Physical Society of Japan for the 1988 Autumn general meeting is shown in Table II.1. At this meeting, there were 243 contributions in magnetic and inertial fusion, accounting for about 15 percent of the total contributions over all areas of physics. Also shown is the approximate number of members in 1988 (Ichikawa, 1988).

The new National Institute for Fusion Science at Toki is supported by the Ministry of Education, Science, and Culture (MOE, or commonly referred to by the Japanese acronym, Monbusho), and contains a new Center for Fusion Theory and Simulation. The total manpower at the new institute will be about 150 scientists with an additional comparable number of support personnel. The National Institute for Fusion Science is projected to have a total permanent staff of about 20 in the Theory Division, including five professors, five associate professors, and 10 research associates. The visiting domestic and foreign staff will add six research associates and a total of six short-term professors and associate professors (Nishikawa, 1988a-b). About 80 percent of the center's staff will come from the Hiroshima and Nagoya theory groups that will relocate at Toki. The remainder represents new positions. In addition, the Large Helical Device Group will contain a Division for Theory and Data Analysis with about 12 theorists, and there will be a separate Computer Center with some numerical simulation theorists.

An important but small theoretical division is located at the Japanese Atomic Energy Research Institute (JAERI) in Tokai. The JAERI theory group is responsible for the theory and simulation support for the large JT-60 Tokamak described in Chapter III (JAERI, 1988).

## 2. Outlook

Japanese research in basic and applied plasma physics is growing steadily in the number of physics-trained scientists retained from the new PhD students graduated from universities with plasma physics faculties, which include Kyoto, Hiroshima, Nagoya, Kyushu, Osaka, and Tokyo, as well as numerous smaller university programs such as those at Niigata and Koriyama. Scientists in the age group of 30 to 50 years are having a strong influence on the international recognition of the growing strength of fusion plasma physics in Japan and the computer simulation of basic plasma processes. Scientists with backgrounds originally in condensed matter, physics, nuclear physics, and electrical engineering in the age group of 50 to 65 years dominate the administration of plasma research in Japan. These administrators of scientific research appear to take a pragmatic approach that emphasizes the experimental and engineering aspects of plasma physics relative to the theoretical approach.

The distribution of plasma fusion resources among theorists, experimentalists, engineers, and technicians described in Section II.B.1.c shows a dramatically smaller fraction of theorists than in the US and European plasma fusion research programs. In other areas of Japanese physics, such as condensed matter physics and high-energy nuclear physics, the ratio of theorists to the total research staff, while not as small as in plasma fusion research, is still more heavily weighted toward the experimental and technological side than in the United States and Europe (Udagawa, 1989). It is projected that the number of fusion theorists in Japan will slowly increase over the next 10 years as a fraction of the total human resources in fusion research from the 1988 level. The increase is expected because the number of doctoral students graduating from the current fusion programs at the universities is steadily growing. These new students are more likely to stay in fusion research than their US counterparts, who often enter defense-related research at the national laboratories or in the private sector. In Japan, many of the best plasma physics and fusion engineering students find employment in the universities and at JAERI.

As evidenced by the large number of scientists working in nuclear and condensed matter theory, Japan is capable of supporting several times the current (1988) number of 80 fusion theorists. With 80 theorists being less than one percent of the membership of the Physical Society of Japan and the steady supply of PhDs from the universities, Japan could double its theoretical effort in a short period of time in the event that scientific or economic conditions were to shift in favor of fusion research. Tempering this observation, however, is the fact that Japan in the past has shown a proclivity for supporting experimental activities in preference to theoretical physics. This tendency for supporting experimental activities is also apparent in such fields as astrophysics. For example, a large respected staff for radio and X-ray telescopes exists while few theorists are supported in Tokyo Observatories—the largest astrophysics institution in Japan.

Looking at the older field of high-energy physics as a guide, one finds that large projects such as the 30 x 30 GeV electron-positron collider and the large neutrino counter in Kamioka are the world's largest facilities for these particular experiments, while no corresponding expansion has taken place in the theoretical programs of nuclear and high-energy physics. The decisions of scientific and governmental administrators in MOE and the Science and Technology Agency (STA) to emphasize experimental research may be rooted in the reaction to the pre-modern era (prior to 1868) emphasis on metaphysical philosophies. This tendency may be more pronounced in the present post-war era. The decision of Monbusho to concentrate the fusion efforts, previously spread over numerous smaller efforts, in a new large facility at Toki 20 kilometers outside of Nagoya may be another example of the preferential support of experimental hardware relative to human resources. The objective reason for the consolidation and move is to provide a facility capable of reaching reactor-grade plasma conditions at a site environmentally capable of operating with radioactive materials.

## C. ROLE OF LARGE COMPUTERS IN BASIC PLASMA PHYSICS

### 1. Accomplishments and Capabilities

It is generally recognized that the Japanese plasma physicists are leaders in the use of computers for developing an understanding of plasma dynamics. During the 1970s, the Japanese developed the techniques for efficient solutions of hydrodynamic and particle descriptions of plasmas. Perhaps the most widely cited and pioneering work in the first category is the development of the two-dimensional resistive MHD codes by Sato and Hayashi at Hiroshima University for the study of driven magnetic reconnection. The basic results are given in a remarkably clear and widely-cited publication (Sato and Hayashi, 1979). The problem of driven reconnection is a classical and fundamental problem in plasma physics. The reconnection process appears to occur in various forms in most laboratory confinement experiments as well as in space and astrophysical plasmas. Prior to the Sato and Hayashi simulations, there were two highly idealized theoretical models: one based on the existence of a collisionless MHD shock front and the other model based on an enhanced resistive diffusion boundary layer. Addressing this problem with numerical simulations required the development of reflectionless inflowing and outflowing plasma boundary conditions in a mixed hyperbolic-diffusive nonlinear system. While this type of problem was also being studied computationally in the United States and in West Germany, the Japanese results gave the first general simulation of the problem from an overall physics point of view. Many subsequent works have appeared in the United States and Europe which follow the general approach developed in the work of Sato and Hayashi.

During the past five years, there have been numerous exchanges of theoretical computer scientists between the United States and Japan in magnetic fusion research. Although the lack of English language computer documentation has been an obstacle to direct use of the Japanese computers by visiting exchange scientists from the United States, collaborative computational projects have given visitors access to the computers and an understanding of the capabilities of the latest Japanese computers, such as the Fujitsu FACOM VP200 (where VP designates vector processing). Although experiences vary with individual computer codes, the Fujitsu VP200 computers perform on a par with the CRAY-2 computers at the National Magnetic Fusion Energy Computer Center (NMFECC) at Lawrence Livermore National Laboratory (LLNL). The central processing unit (CPU) timings and overall comparisons reported by US computer scientists visiting Japan are given in the following subsections (Matsuda, 1989).

a. Numerical Techniques and Plasma Theory Software

During the 1980s, the Japanese theorists developed computer codes that appear to be generally comparable with or, in some cases, faster than the corresponding US computer codes. The computer simulation areas that stand out are listed below by type and location.

- Hiroshima University: Vlasov equilibrium and stability codes and resistive-viscous three-dimensional MHD codes describing reconnection in tokamaks, reversed field pinches, and spheromaks.

- Kyoto University, Uji Campus (the Heliotron site): Three-dimensional resistive MHD, stellarator beta-limit (derived from the Beta code developed at New York University in the 1980s), and nonlinear collisional drift wave codes.

- Kyoto University, Faculty of Engineering Department: RF heating codes with antenna details and the capability of predicting ponderomotive potential stability effects.

- Ohayama University: Ion cyclotron heating and stochastic heating theory codes of Fukuyama (Fukuyama et al., 1977).

- IPP-Nagoya: Advanced variable space-time scale implicit particle simulation codes, and long-time-scale stochastic map codes and shock wave acceleration codes.

- Nagoya University; Nihon University, Koriyama: Drift-wave vortex and driven-damped soliton dynamics codes.

Less is known at the present time about the particle simulation codes used at Kyushu University to study beam-plasma interaction for the theory of soliton development and phase-space clumps.

Advanced finite element codes for solving MHD equilibrium and stability problems have been developed at Nihon University (Kawakami, 1987), and at JAERI.

The inertial confinement theory section of the Institute of Laser Engineering (ILE) at Osaka University has a two-dimensional fluid-particle code with dynamical adjusting grid that is an important development and research tool among many other codes developed at ILE. A new particle simulation code for the free electron laser (FEL) is being developed at ILE. Computer-specific aspects of ion beam inertial fusion are being developed both at the new Supercomputer Center at Tokyo Institute of Technology and at ILE at Osaka University.

b. Supercomputer Machine Parameters

Two supercomputers, the VP-200 and the VP-200E, at IPP-Nagoya have a fast memory capacity of 64 MB (megabytes) (or 16 million 32-bit words), and 256 MB (or 64 million 32-bit words), respectively. The clock time of these machines is 7.5 ns, and the peak performance is 0.57 and 0.95 gigaflops for the VP-200 and VP-200E machines, respectively. (Gigaflops is the computer's speed measured in billion floating point operations per second.) Although these machines are usually run with 32-bit single-precision, the arithmetic operations are performed with double precision. Taking into account these differences, the CPU timings indicate little difference (less than 10 percent) between single-precision and double-precision calculations.

These parameters compare with 512 MB (or 64 million 64-bit words) and 1 GB (gigabytes) (or 128 million 64-bit words) of memory on the CRAY-2 B-machine and F-machine at the NMFECC, respectively. The CRAY-2 has a clock time of 4.1 ns and the peak performance of 2 gigaflops. Another CRAY computer, the X-MP, at the NMFECC has a clock time of 8.5 ns and a peak performance of 0.84 gigaflops.

These performance numbers, which are summarized in Table II.2, indicate that the Japanese and US supercomputers currently employed in magnetic fusion research possess comparable capabilities, although the United States is ahead in performance, but not by a significant margin. However, in December 1988, Fujitsu announced production plans for the so-called VP2000 series of computers; it is claimed that the fastest model, the VP2600/20, runs at 4 gigaflops with a maximum memory capacity of 2 GB. With plans for delivery of the new machine later this year or next, this would introduce a single-processor machine with peak performance comparable to a CRAY Y-MP with eight processors. (See Table II.2.)

As shown in Table II.3, the CRAY-3, to be announced this year, is expected to surpass the VP2000's performance with a 2-ns clock time and 16 processors.

**Table II.3**
**SUPERCOMPUTER PARAMETERS**

| Type | Clock Time (ns) | Peak Performance (GFLOPS) | Memory Capacity (MB-GB) | Number of Processors |
|---|---|---|---|---|
| Hitachi S-810/20 | 15 | 0.80<br>0.84 | 256 MB | 1 |
| NEC SX-2 | 6 | 1.3 | 256 MB | 1 |
| Fujitsu VP-200 | 7.5 | 0.57<br>0.533 | 64 MB | 1 |
| Fujitsu VP-200 E | 7.5 | 0.95 | 256 MB | 1 |
| Fujitsu VP-2600/20 | 4 | 4 | 2 GB | 1 |
| CRAY-1 | 12.5 | 0.16 | 32 MB | 1 |
| CRAY X-MP | 8.5 | 0.84 | | 4 |
| CRAY Y-MP | 6 | 4 | 256 MB | 8 |
| CRAY-2 | 4.1 | 2 | 2 GB | 4 |
| CRAY-3 | 2 | 16 | 16 GB | 16 |

It should be noted that all Japanese supercomputers available so far are single-processor machines, while the US computers are multiprocessor machines (except for the original CRAY-1). When Japan introduces a new supercomputer with each processor capable of performing at the levels indicated in

Table II.3, it is likely that these machines will be superior to their US counterparts with an equal number of processors.

c. Compilers

Some of the magnetic fusion theory calculations most demanding of the computer hardware in terms of size and speed are multi-dimensional simulations, such as three-dimensional toroidal helical systems computations, and two- and three-dimensional particle simulations. During 1988, problems have been encountered in converting codes that run efficiently on the Fujitsu VP-200 to the CRAY-2 at the NMFECC. The Fujitsu codes are written in the standard ANSI77 FORTRAN, but the workhorse compiler on the CRAY-2, CIVIC, is not entirely ANSI77 compatible. Combined with the lower vectorization capabilities of CIVIC compared to the Fujitsu compiler, FORT77VP, these differences caused the converted codes to run several times slower (in terms of CPU time) on the CRAY-2 than on the VP-200. One example is the Helical Toroidal Fat Coil Code developed in Japan for stellarator systems (Leboeuf, 1988).

One of the reasons for the lower performance on the CRAY-2 is that IF-statements, branching, and subroutine calls inside a do-loop prevented CIVIC from vectorizing the loop, while the FORT77VP compiler was able to vectorize such a loop without difficulty. The Fujitsu compiler performs automatic vectorization of "casually" written or scalar FORTRAN codes much more efficiently than either the CIVIC or the CFT compiler. Another reason for the difference is the faster scalar operation by the VP-200 than by the CRAY computers.

These features also caused a scalar version of a three-dimensional particle code to run two to three times slower on the CRAY-2 than on the VP-200 (Decyk, 1988; Matsuda, 1989). A vectorized version of the code, however, was only about 50 percent slower on the CRAY-2 B-machine. For a highly optimized version, the CRAY-2 and the VP-200 perform equally well (Decyk, 1988). The vectorized machine code produced by the FORT77VP compiler can take considerably more machine real memory than the vector machine code produced by CIVIC or CFT from a well-written vector FORTRAN program.

In addition to vectorization, there is an important issue of multi-tasking or multi-processing. In the above comparisons the multi-processing capability of the CRAY-2 was not utilized. Currently, because of the considerable rewriting necessary to make use of the multi-processing capability, a typical user tends not to multi-process the code. Therefore, it is possible that the maximum capability of the CRAY is not currently utilized.

In summary, it appears that a typical physicist-user of these supercomputers at present gains more on the VP-200 than on the CRAY-2. Equal performance can be achieved by working significantly harder on the programming on the CRAY-2 than on the VP-200, which is a disadvantage for the US scientists.

In a more recent comparison of timings for a "scalar" particle code, however, a new CFT77 compiler produced a code that is comparable in speed on the CRAY-2 F-machine to that of the VP-200E (Matsuda, 1989).

d. Operating Systems and Software

The interactive features (user interface) on the Japanese computers are well behind the US computer systems (for example, the CTSS operating system on the NMFECC computers). At the Japanese computer center equivalent to the NMFECC, the IPPCC Nagoya, the Fujitsu M380 is the front end to the two VP200s running the transmitted work as batch jobs. As it is implemented at present, the Nagoya TSS (Time-Sharing System) is primitive, although a more user-friendly interactive system is available. According to one researcher at IPP, the Japanese scientists do not show much interest in changing to a more user-friendly system. Apparently, the Japanese are reluctant to accept a new system. This is somewhat surprising. An exception to the higher level of user-friendliness on the US system is the presence of a good screen editor on the Japanese system, as compared with the line editor on the US NMFECC system. The Fujitsu system also offers a more advanced debugger with more user-friendly features than that on the NMFECC system. The Fujitsu debugger is similar to the one offered on an IBM system.

The new VP-2000 series offers an operating system based on UNIX. Therefore, the interactive features of the future Japanese machines will certainly improve. The United States has a widespread availability of computing resources as a utility for scientists and engineers through university and laboratory computer centers that is well ahead of the corresponding Japanese computer service facilities.

### 2. Outlook

During the next five years Japanese plasma physicists will make extensive use of the large-scale computers to advance both basic and applied plasma theory and its application to confinement devices, especially with regard to helical systems (see Section II.E).

The availability of supercomputers to plasma physicists, especially at the universities, may possibly become greater in Japan than in the United States during the next five years. Already it appears to some computational plasma physicists that the amount of supercomputer resources per research physicist in Japan is greater than that 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.

Establishing the new fusion laboratory in Toki city outside of Nagoya 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 10 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 hardware, it is thought that Japanese manufacturers will be able to provide multiprocessor supercomputers which are comparable in speed to the CRAY-3 or faster in the next several years. In April 1989, NEC Corporation announced the SX-3 with peak performance of about 20 gigaflops with four processors with shipment scheduled in June 1990. 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 the cooperation in technology for the new machines between these strong companies, the US manufacturers may have difficulty keeping pace with the performance of Japanese computers.

## D. STATISTICAL PLASMA PHYSICS

### 1. Accomplishments and Capabilities

There is a long, rich tradition of research on statistical physics in Japan, and this tradition has a strong influence on the Japanese plasma physicist working in areas related to statistical physics and plasma turbulence theory. The two preeminent names in Japan in statistical physics are R. Kubo and M. Toda. Kubo (1957) first derived the linear response matrix directly from microscopic theory showing the relationship of the linear susceptibility to the spectral density, establishing a microscopic form of the fluctuation dissipation theorem. The classical statistical physics as done by the Kubo school is continued today with applications to plasma theory by H. Mori (1958, 1965, 1983a-c), M. Suzuki (1983), Iyetomi and Ichimaru (1987), and Ichikawa et al. (1980, 1983, 1987). Projection operators, which are powerful tools in statistical mechanics and were made famous by the Brussels group led by Professor Prigogine, were first introduced in Japan by H. Mori (1965). While the Japanese statistical plasma physicists' publications generally address statistical physics questions, they are often motivated by plasma physics issues or have applications to a plasma physics problem. Japanese statistical plasma physicists are frequent participants in plasma physics meetings devoted to nonlinear dynamics and turbulence problems.

The area of soliton physics and, more generally, of solitary waves and long-lived coherent structures, is a large area of mathematical physics research in Japan. A pioneering figure in this area is T. Taniuti, who, in early work, developed a general theory called the reductive perturbation method for deriving the reduced equations of the soliton type for nonlinear waves in plasmas, lattices, and fluids (Taniuti, 1974). His work, while principally mathematical, has historically centered around plasma equations, especially as described in MHD or other fluid descriptions. Taniuti has educated a large number of students in nonlinear plasma and classical physics, many of whom now work in universities and research laboratories in Japan. Recently, Taniuti and his associates have investigated the response features of dissipative-dispersive nonlinear media when driven by external sinusoidal forces.

Classical soliton research outside of plasma physics is a large area of research, probably emerging from the famous exact solution of the nonlinear lattice problem by M. Toda called the Toda lattice (Toda, 1967a-b). The scientists in this endeavor have principally condensed matter or mathematical physics backgrounds.

A number of basic plasma physics experiments in Japan have been carried out to study the properties of ion acoustic wave solitons and other exotic plasma wave solitons (Wadati et al., 1980).

The first measurements of two- and three-dimensional solitons were reported in Japan. An important experiment investigating the resonant three-soliton interaction was carried out by Nishida and Nagasawa (1980), Tsukabayashi and Nakamura (1981), and Tsukabayashi et al. (1983). The results of the resonant three-acoustic-wave experiments were in accord with the theory developed by Yajima et al. (1978). In theory and computer studies, a number of exotic solitons, such as loops and cusps, have been studied.

The statistical properties of area-preserving maps have been studied extensively in Japan. Both the standard map and a twist map that represents the bounce-to-bounce radial excursions of ions in the central cell of a tandem mirror have been studied by Ichikawa et al. (1987) and his colleagues. The long-time correlations due to stable fixed-point orbits have been extensively studied. Recent studies use symmetry properties to find high-order fixed points of the standard map.

Statistical physics is used to study the nature of transients near the instability threshold of plasmas. M. Suzuki (1983) uses scaling theory to describe the time behavior near the instability point of the relative diffusion of nearby test particles in plasmas and relates the time behavior to the lifetime of phase-space clumps as defined by Dupree. Suzuki (1983) also uses the time dependence of the correlation functions in fractional Brownian motion using a geometrical interpretation of critical exponents based on a fractal analysis of phase space structures.

There is a strong statistical physics group led by Hazime Mori at Kyushu University in Fukuoka that studies chaos and the structure of turbulence. Turbulence is often characterized by the presence of a strange attractor in phase space. The multifractal structure and generalized entropies of the strange attractors are analyzed in works of this theoretical group, as in Morita et al. (1987) and Hata et al. (1987).

The fundamental problems of fully-developed turbulence, including the distribution of turbulent energy along the length scales taking into account spatial intermittency, and the problem of the relative diffusion of test particles in time are considered in the works of Mori et al. (1983a-c).

### 2. Outlook

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. In special areas such as the statistical properties of strongly coupled plasmas and the soliton dynamics in plasmas, Japan may become the dominant country. Japanese scientists are capable of making major discoveries in statistical and nonlinear physics within the next five years.

## E. CONFINEMENT THEORY AND EXPERIMENTS

### 1. Accomplishments and Capabilities

The accomplishments and capabilities in basic plasma physics aspects of the confinement of high temperature plasma is investigated here according to the type of confinement system: the helical system, the tokamak, the reversed field pinch, the field-reversed configuration, and the tandem mirror. In international research on magnetic fusion, the tokamak is the mainline approach, and the remaining confinements approaches are "alternative concepts." The Japanese tokamak research program is covered in depth in Chapter III.

a. Helical Systems

Japan has fundamental research programs in the plasma physics of the helical system (called the torsatron in the United States). Japanese research on helical systems originates from the 1950s, when Prof. Koji Uo (1961, 1971) developed his ideas on the heliotron type of magnetic confinement device. Since that time, the Kyoto University group has established a unique, long standing expertise and understanding of the helical system (Uo, 1988). Now a major new laboratory at Toki outside of Nagoya, the National Institute for Fusion Science, will build and operate the world's largest helical system confinement experiment. The rebirth of interest in the helical system architecture in the United States during the past five years can be credited to the encouraging confinement results obtained in the Kyoto and Garching (West Germany) experiments in the period from 1978 to 1982. The new research facility at Toki will house the superconducting Large Helical System (LHS) experiment with major radius $R \approx 4$m and magnetic field $B \approx 4$ Tesla described in detail in Chapter IV.

Theoretical programs in helical systems in Japan are led by relatively young theorists, the most senior of whom is Professor Masahiro Wakatani of Kyoto University. Other theorists are Dr. Kimitake Itoh, Dr. Jiro Todoroki, and Dr. H. Sanuki. Professor Wakatani has developed three-dimensional MHD codes for calculating the critical beta limits and benchmarked these codes with those at New York University. Professor Wakatani is also an expert in the theory and simulation of drift-wave turbulence and resistive g-modes (Sugama et al., 1988a-b). Wakatani collaborates with US theorists, particularly with Akira Hasegawa at Bell Laboratories. Their equations for collisional drift-wave turbulence are often called the Hasegawa-Wakatani equations (Wakatani and Hasegawa, 1984; Yagi et al., 1987, 1988). Dr. Kimitaka Itoh has expertise in kinetic ballooning modes from work on tokamaks at JAERI, and recently has developed with Associate Professor Sanae Inoue Itoh at Hiroshima University a theory of L- to H-mode transitions in tokamaks (Itoh and Itoh, 1988b). Associate Professor Jiro Todoroki has expertise in the areas of MHD equilibrium and neoclassical transport in non-axisymmetric systems (Todoroki et al., 1989). He has designed state-of-the-art computer codes for calculating helical magnetic field structures, taking into account the finite areas of the external current-carrying coils. Dr. J. Todoroki and Dr. J. Johnson collaborated on an integration of the results of the Princeton and Japanese equilibrium calculations for helical systems (Johnson, 1988).

Dr. Hayashi has shown the ergodization of the helical flux surfaces in the outer regions of the $l = 2$ toroidal system (Todoroki et al., 1989). The ergodization of the helical flux reduces the rotational transform and lowers the critical plasma beta. To remedy this problem, extra coils that can have the side effect of degrading the confinement of high-energy particle drift surfaces are required. Therefore, the compatibility between high plasma beta and good high-energy particle confinement becomes a serious trade-off. This problem is addressed by Todoroki et al. (1989) considering the effect of horizontal ellipticity due to quadrupole fields. Todoroki et al. examine the $l = 2$, $M = 10$ and aspect ratio $A = 8$ system to obtain average beta values of five percent and high-energy particle confinement.

b. Tokamaks

Although Japan was not a leading developer of fundamental tokamak theory in the 1970s, as was the Soviet Union, Europe, and the United States, Japanese scientists do have an excellent understanding of these theories and have built extensive computer software for the implementation of tokamak theories. Particularly, at JAERI, the theory support group has developed an extensive software library for the design and interpretation of tokamak experiments. The JAERI computer library covers MHD equilibrium and stability of shaped cross-sections, ballooning and resistive MHD stability codes, transport codes with neutral beam and radio frequency heating deposition, and various atomic and nuclear physics codes needed for tokamak evaluation and design (JAERI, 1988).

Dr. Hamada (1962) developed a widely used set of natural curvilinear magnetic coordinates with special theoretical properties useful for toroidal confinement calculations. The coordinates are based on the magnetohydrodynamic equilibrium of the confined plasma.

Sawtooth activity and disruption phenomena are studied by both the JAERI theory department and the Sato group at Hiroshima University, an MHD theory group described in more detail in the following section on RFPs.

Japanese scientists were involved early in the study of alpha-particle losses due to toroidal ripple. The work of Tani et al. (1983) showed that the stochastic diffusion loss rate increases rapidly with tokamak safety factor, producing a severe limit for ignition unless nonaxisymmetric effects are held unusually small.

Japanese scientists have been actively pursuing the L- to H-mode transition physics associated with the role of the radial electric field. It is argued that the edge transport is not intrinsically ambipolar and that the change from L- to H-mode confinement results from a bifurcation of the particle flux due to a change in the radial electric field $E_r$ (Itoh and Itoh, 1988b). This type of bifurcation in the ambipolar flux is a well-studied phenomenon in helical systems.

Drift waves and trapped particle modes along with the associated transport are actively pursued at Nagoya University, Hiroshima University, and Kyoto University. In the past, these studies were generally academic in nature, but more recently the investigations have included transport modeling (Fukuyama et al., 1989).

Extensive work on ion cyclotron radio frequency (ICRF) heating has been carried out using a finite-element method that includes realistic magnetic configurations and antenna geometry. Fukuyama et al. (1989) extended the code to the integral equation formulation of ICRF wave propagation and analyzed the effects of alpha particles on the higher harmonic absorption in reactor grade plasmas.

Alfvén wave heating of magnetized plasma including kinetic effects on the wave absorption are studied using macro-particle simulations by Tanaka et al. (1989). Lower hybrid heating has been extensively studied with particle simulations by H. Abe at Kyoto University (Nakajima et al., 1982).

c. Reversed Field Pinches

The RFP plasma is a high-beta plasma in a state of strong MHD turbulence and would be expected to show poor confinement properties compared with a tokamak. Experiments, and to some degree three-dimensional resistive MHD simulations, show that the turbulent plasma finds a natural steady-state configuration. While the energy confinement time is short in comparison with that in tokamaks of comparable size, the energy density is much higher for comparable confining magnetic field strengths. The simulation of the RFP is state of the art in computing due to the essential difficulties of three-dimensional magnetic turbulence. It is the turbulence that allows the plasma to convert the externally driven poloidal magnetic flux into a reversed toroidal magnetic flux that is the essential feature of the minimum energy state of relaxed RFP plasma. Efforts to understand why RFP confinement is relatively good from the point of view of anomalous transport theory is a key issue. A key element may be that the relaxed RFP state is one of much stronger shear and shorter connection length than in the tokamak. The disadvantage of the RFP configuration, however, is that it has strong unfavorable magnetic field curvature: this unstable feature is mitigated by the diamagnetic-well stabilizing effect at high plasma pressure occurring for some perturbations that would be strongly unstable in the low beta limit.

Japan maintains a vigorous basic research program on RFPs at the universities. The Japanese RFP program is comparable in strength to the US program in theory and computations, but lags substantially in RFP experiments. The Japanese program has a number of small, high-quality, university experiments, particularly the STP-3 RFP at IPP-Nagoya (recently terminated) and the current TPE RFP at the Electrotechnical Laboratory in Tsukuba. These experiments are well researched but are not competitive with the large US experiments ZT-40 ($R$ = 114 cm, $I$ = 200 A) at Los Alamos National Laboratory (LANL) and the MST experiment ($R$ = 115 cm, $I$ = 800 A) at the University of Wisconsin.

The future ZT-H experiment at Los Alamos with $a$ = 80 cm and $I$ = 2 MA is scheduled for operation in 1992. The capability of ZT-H is well beyond any known plans for future Japanese RFP experiments.

Japanese scientists are providing key ideas in the interpretation of the self-organized relaxation and dynamo activity in the reversed field pinch both through experimental and computational studies. In particular, Professor Kenro Miyamoto of Tokyo University, author of one of the most complete and authoritative textbooks on fusion confinement (Miyamoto, 1980), is leader of a group of scientists working on the development of an experimental understanding of the relationship of MHD activity and relaxation phenomena in RFPs. Miyamoto (1988) has compared the relationship between the observed relaxation oscillations and the reversed field sustainment with the results of the simulation codes. He explains the mechanism by which the $m = 1$ mode converts poloidal flux into toroidal magnetic flux in the RFP dynamo based on earlier Japanese computer simulations.

The theoretical and simulation RFP groups headed by Professor Tetsuya Sato at Hiroshima University from the period 1980 to the present have been international leaders in performing state-of-the-art three-dimensional simulations of the RFP system. Professor Sato and his colleagues Dr. T. Hayashi (Sato and Hiyashi, 1979), Dr. R. Horiuchi (Horiuchi and Sato, 1988), and Dr. K. Kusano (1987), have shown how the $m = 1$ modes of both the resonant type familiar in tokamak physics and the nonresonant or external kink type produce relaxation oscillations in the RFP that sustain the system against the resistive decay of the plasma (Kusano and Sato, 1987). Methods for tracking the modes responsible for the creation of the dynamo electric field have been developed which show the importance of the process of driven reconnection in the dynamo problem. Computationally, this work shows clearly the intrusion of the reversed magnetic flux region into the core plasma, and how the magnetic reconnection allows this outer plasma to be ingested into the core plasma. The dynamics are clearly presented by showing the contours of only the reversed toroidal field flux function. On increasing the temperature of the plasma, it is predicted that the period of the $m = 1$ relaxation oscillations increases but that the amplitude remains constant. Also, it is predicted that the amplitude of the $m = 1$ relaxation oscillations is related to the aspect ratio of the device.

There are differences of scientific opinion between the Hiroshima University theory group and the LANL-SAIC group (Caramana et al., 1983; Schnack et al., 1985) on some of the details of the dynamics of the field sustainment mechanism and the role of driven reconnection in the dynamics. Overall, the Japanese and US RFP theory activities are comparable in strength, but the Japanese program appears to be better equipped with young scientists doing state-of-the-art three-dimensional simulations and turbulence theory in order to explain RFP confinement.

More diverse and academic MHD turbulence work motivated by RFP research in Japan is performed at Tokyo University by Akira Yoshizawa (1988a-b), developing turbulent dynamo models with theory and simulation, and by Zensho Yoshida et al. (1984a-b), investigating the effects of a nonuniform resistivity distribution and a resistance anomaly.

An important issue in future RFP research is to better quantify the transport and confinement scaling in order to compare with the confinement in tokamaks (Yamagishi, 1986a-b). Future RFP theory must determine the intrinsic relations between the turbulent resistivity and viscosity, often called hyper-resistivity, and the electron cross-field transport properties such as thermal diffusivity.

Another forefront research problem is to understand how the RFP with its broader spectrum of MHD turbulence avoids major disruptions that are intrinsic to tokamaks. Part of the answer seems to lie in the strong shear produced by the higher RFP plasma current, which causes a stronger overlapping and competition between the unstable tearing modes. This competition prevents the dominance of a few low $m/n$ modes, for example, the interaction of the 2/1 and 3/2 magnetic islands, which are believed to be the determining factor in the onset of major disruptions in tokamaks. Both Japan and the United States are in good positions to resolve these issues during the next five years.

d. Field Reversed Configurations

The most outstanding technical progress in Japan's basic research on FRCs came with the proposal and demonstration for stabilization of the "rotational instability" that plagues conventional FRCs. The stabilization was achieved by application of a quadrupole magnetic field in the PIACE device at Osaka University (Ohi et al., 1983). The theoretical estimate of the critical value of the quadrupole field was given by balancing the depth of the quadrupole magnetic well with the effective potential hill produced by the centrifugal force. This simple theoretical model for the stability appears to work well, but consistently overestimates the amount of magnetic well needed to stabilize the system (Ishimura, 1984).

The most extensive theoretical modeling and transport studies of FRCs aimed at fusion reactor regimes have been carried out at IPP-Nagoya by Dr.

H. Momota and coworkers, including Dr. M. Okamoto et al. (Momota et al., 1987). Momota et al. have proposed an original scheme using advanced fusion fuels, such as D-$^3$He, which have charged ion products that are preferentially trapped in the direction of the plasma current. Analytical and numerical studies indicate the possibility of a self-sustained burning field-reversed fusion reactor. The proposed configuration has numerous challenging problems associated with maintaining a self-consistent equilibrium and stability, but the potential payoff is substantial, and the proposal is likely to receive considerable attention in the future.

Other important contributions are the first demonstration of FRC translation by the Osaka group (Tanjyo et al., 1984, 1985), and the development of a classic FRC transport model (Hamada and Azevedo, 1988). Dr. A. Ishida of Niigata University is actively researching the rotational and tilt instabilities of the FRC configuration (Ishida et al., 1988). Dr. Ishida has published several important papers in this area of research (Momota et al., 1987; Ishida et al., 1986). Finally, Ohnishi and coworkers have investigated the use of ion beams for stabilizing the rotational instability in FRCs (Ohnishi et al., 1988).

e. Tandem Mirrors

Japan currently leads the world effort in the tandem mirror approach to magnetic confinement. The large high-technology GAMMA 10 tandem mirror device (Inutake et al., 1985) at Tsukuba University has demonstrated the operation of thermal barriers designed to reduce the flow of plasma out of the long axisymmetric central cell plasma (Kiwamoto et al., 1986). The axial and radial plasma potential measurements, as confirmed by a visiting team of US scientists (Foote, 1987) using its own diagnostic equipment, show the establishment of an electron-reflecting potential of a few hundred electron volts in the anchor/ thermal barrier region for low plasma densities. The ion energy flux loss out the ends is low during the thermal barrier operation, and the central cell particle confinement is reported to be of order 100 ms (Inutake et al., 1985).

The design, theory, and simulations for the GAMMA 10 experiment were carried out at Tsukuba University. Particularly in the relative position of the MHD anchor cell and the plug cell, the Gamma 10 configuration differs considerably from that of the earlier less successful tandem mirror experiments TMX and TMX-U performed at LLNL. Early Japanese work demonstrating the principle of the tandem mirror is given by Yatsu (1979).

A number of publications on the theory and computer simulations of the GAMMA 10 tandem mirror experiment are now being published. The theory team is small and relatively young, while the experimental team has considerable plasma physics experience.

The publications by Katanuma and coworkers on different aspects of tandem mirror physics are noteworthy in this area of research (Katanuma et al., 1986, 1987a-b).

### 2. Outlook

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 non-ambipolar 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. The Compact Helical System ($R \approx 100$ cm, $B \approx 2$ Tesla for 2 seconds at IPP-Nagoya) and the active collaboration with ATF in the United States will provide good basic physics results until the LHS is operational. The accomplishments and technical qualifications of the Japanese theorists are high, presently comparable with those of US theorists working on similar problems. With a strong commitment to the LHS (Chapter IV), it appears likely that Japan will become the world leader in both the basic plasma physics and experimental research on helical systems after the mid-1990s.

During the next five years, Japanese theory and simulation of RFPs may also surpass the US theory effort in RFPs, provided the groups at Hiroshima University and the University of Tokyo continue to grow and develop their theoretical and computational capabilities. The experimental aspects of RFP research in

Japan is funded only for small-scale experiments. For the next five years, the United States is expected to maintain leadership in RFP experimental research on intermediate-scale facilities, together with the Italian experiment RFX at Padua University.

## F. RADIO FREQUENCY HEATING AND CURRENT DRIVE

### 1. Accomplishments and Capabilities

#### a. Lower Hybrid Current Drive (LHCD)

Japan has been a pioneer in the development of RF current drive in plasmas. The early work of S. Tanaka and coworkers at Kyoto University on the WT-2 tokamak showed the proof-of-principle experiments for current drive. Shigetoshi Tanaka, Takashi Maekawa, and Yasushi Terumichi of Kyoto University shared the 1984 American Physical Society Award for Excellence in Plasma Physics Research with three scientists from MIT and six scientists from Princeton University, for the demonstration of radio frequency current drive with lower hybrid waves.[1]

Recent major success in current drive in Japan has occurred under the direction of T. Nagashima at the Naka Fusion Research Establishment. At JAERI, an LHCD system was designed that has maintained a current of 2 MA for 2.5 seconds on the JT-60 tokamak without degradation of the plasma properties (Imai et al., 1988). High current drive efficiencies are obtained in ohmic discharges, and the use of simultaneous neutral beam injection (NBI) heating enhances the current drive efficiency. It is found that the current profile during LHCD is broader than in the ohmic heating regime. The result of the current profile change is a net improvement in the energy confinement time over that in the pure NBI regime.

Lower hybrid current drive has broadened the current profiles and thereby raised $q$ on axis and delayed and/or lengthened the period of the central saw-

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1 "Award for Excellence in Plasma Physics Research," *Bulletin of the American Physics Society,* (1984), 1165.

tooth oscillation in the plasma temperature. The high-energy particles created by the LHCD heating may be able to completely eliminate the sawtooth.

### b. Fast Wave Current Drive

Yamamoto and coworkers have carried out detailed calculations of fast wave current drive and obtained good efficiencies (Yamamoto et al., 1989). Their analysis indicates that the density limit seen in PLT (Princeton Large Torus) was due to mode conversion driven by a parametric instability. The parametric instability was seen to disappear at higher densities in JFT-2M, and the Japanese group suggested that the density limit observed in PLT would not occur in this density regime.

High-power ICRF heating combined with neutral beam injection (NBI) creates high energy ion distribution functions as analyzed by Yamagiwa et al. (1988). The high energy ions enhance the fusion reactivity of the plasma and can be used to eliminate or increase the period of the deleterious sawtooth oscillations.

An analytical model for lower hybrid frequency current drive and its efficiency has been developed and applied to experiments on ASDEX by Yoshioka et al. (1988), showing good agreement between theory and simulation.

### c. Ponderomotive Force Theory

The theory and application of an effect known as the "ponderomotive force" is an active area of research in Japan. The high-power radio frequency electric fields produce an effective pressure which can be used as a confinement force—called the ponderomotive force—in a plasma. In most cases, the high-frequency electric field is produced by one of the radio frequency heating methods developed for plasmas.

Experimentally, Japanese scientists recognized early the possible importance of the use of the ponderomotive force for plasma control. Yamamoto (1975) used the radio frequency ponderomotive force to stabilize the interchange instability in a simple mirror. Using particle simulations and theoretical calculations, Abe and Kadoya have evaluated the relative effectiveness of the ponderomotive force for stabilizing the interchange instability in a mirror, for the case where the polarization of the electric field is parallel to (Kadoya and Abe, 1988) and perpendicular to (Abe and Kadoya, 1988) the mirror magnetic field.

The ponderomotive force arises from the particle motion time averaged over the high-frequency electric field in the plasma. The details of the motion, taking into account the onset of stochastic motion of the orbits, is analyzed in the theories of Kono and Sanuki (1987). The description of the ponderomotive force in the hydrodynamic equations and the relation to the exact kinetic description is considered by Kono et al. (1980, 1987) and Skoric and Kono (1988).

### 2. Outlook

Japan has traditionally been a strong leader in research related to the use of radio frequency 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 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.

## G. DEVELOPMENTS IN US-JAPANESE COLLABORATION

The US-Japanese cooperation in fusion began in 1978 with the Carter-Fukuda initiative, opening the way for Japanese partnership in operating the Doublet III experiment at General Atomics. On 24 August 1979, the US-Japan Agreement on Cooperation in Fusion Research was signed. The Agreement provided for 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.

The purpose of the Joint Institute for Fusion Theory is the development of research in the fundamental plasma physics questions associated with magnetic fusion through the planning of workshops, short- and long-term exchange visits, and collaborative research using the NMFECC and IPPCC Nagoya computer facilities through a high-speed computer link.

In 1980, an Institute for Fusion Studies (IFS) with about 20 staff scientists was created at the University of Texas at Austin, for the purpose of advanced research in magnetic fusion and plasma physics. In the period from 1980 to 1989, IFS was the host, or home base, for approximately 27 Japanese plasma physicists. During the same period, IFS arranged for a comparable number of US scientists to spend from one to four months working in Japanese universities and laboratories. There were 34 US-Japanese workshops on topical issues of mutual concern split between the two countries. The US-Japanese exchange activities benefited both fusion programs and have become an important aspect of the research activities at IFS and in the US fusion program.

The JIFT program has led to numerous joint publications, including two workshop proceedings in the area of statistical plasma physics, published by Wiley in the Interscience series. A new volume published in Japan (Ichikawa and Kamimura, 1989) includes the lectures of seven visiting professors from the United States to Japan for the period from 1981 to 1987. Several major joint projects in the area of new plasma simulation techniques were developed during the 1980-1987 period. Major projects have included the development of long-time large-space-scale implicit particle simulation techniques for both the electrostatic and electromagnetic dynamics of plasmas; the development of MHD equilibrium and stability codes for helical systems; and the development of gyrokinetic simulation techniques for the study of anomalous transport in plasmas.

## H. ADVANCED COMPUTATIONAL TECHNIQUES

### 1. Accomplishments and Capabilities

a. Gyrokinetic Simulations

For the study of drift waves and other anomalous transport mechanisms that operate at low frequencies and relatively long wavelengths in magnetized plasmas, advanced computational techniques have been developed in Japan in collaboration with the United States. The first of these is the implicit particle code developed by Barnes, Kamimura, Tajima, and Leboeuf in the IPP-IFS project (Barnes et al., 1983). The second is the gyrokinetic simulation project developed by UCLA-IPP and Princeton University Plasma Physics Laboratory (PPPL) which uses particle simulation techniques to solve theoretical model equations that are strongly simplified versions of the true Lorentz force equations. In the gyrokinetic approach, all gyrophase information is eliminated theoretically; however, this leaves the difficult task of calculating form factors depending on the finite gyroradius factor for each particle and fluctuation.

b. Implicit Particle Codes

Tanaka at Hiroshima University has developed a semi-implicit macroparticle code which retains many kinetic wave-particle effects. The Hiroshima code has a somewhat different approach to the problem of particle simulations of hydrodynamics or large space long time scales than the implicit particle code of Nagoya-Austin. The Nagoya-Austin implicit particle code (Barnes et al., 1983) has a variable space-time window that can be centered on those space-time scales of dominant importance in the particular physical problem.

A new approach to large space scale, long time scale simulations is being developed at IPP-Nagoya by Naitou in collaboration with UCLA and PPPL. The code is based on the gyrokinetic equation.

c. MHD Equilibrium and Stability Codes

Japan has developed MHD equilibrium and stability codes at several laboratories and universities. Both semi-implicit and fully implicit compressible MHD codes are available for three-dimensional geometries. A well-known MHD code with an innovative approach is that of Kawakami (1987) using finite-element methods. Standard tokamak codes are used at JAERI in studies of equilibrium and stability. Accomplishments and capabilities are illustrated in the study of the effect of the free boundary kink mode on the plasma volume by Kurita et al. (1987) and in the study of the effect of divertors on stability by Ozeki et al. (1988). Capabilities in computing MHD tokamak dynamics are illustrated in the calculation of a high-plasma-pressure splitting of an elongated equilibrium in the work of Nakayama et al. (1988). A recent helical system equilibrium study is that of Ichiguchi and Wakatani (1988).

## 2. Outlook

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

# CHAPTER II: BASIC AND APPLIED PLASMA PHYSICS IN JAPAN
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# CHAPTER III
# TOKAMAK CONFINEMENT

## A. OVERVIEW

The Japanese tokamak program began in the early 1970s, when a small tokamak was brought into operation at the Japan Atomic Energy Research Institute (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 Soviet Union's Kurchatov Atomic Energy Institute 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) in Nagoya that was capable of operation 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. 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 device 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 (PPPL) 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 steady-state 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 are 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 break-even plasma conditions—the original objective. 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 (FER), 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-moderate size tokamaks at Tokai (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. Moreover, Japan lacks a broad university-based program of tokamak research, such as is found in the United States. As the Ministry of Education, Science, and Culture 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 DT-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 database 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 multinational 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.

The Japanese fusion program certainly has the human and technological resources required 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 multi-national 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.

## B. INTRODUCTION

This chapter contains a survey of Japanese tokamak research, with emphasis on the period from 1983 to the present. Section III.C, after brief discussions of the principles of tokamak confinement and of the history of tokamak research outside Japan, describes the early Japanese tokamaks that preceded the present (1983 to 1989) generation of devices, and also discusses the initial phase of the collaborative US-Japanese program on Doublet III (1979 to 1984).

The accomplishments of the large Japanese tokamak, JT-60 (operational in 1985), are assessed in some detail in Section III.D, as are prospects for its upgrade, JT-60U, and future large tokamaks, especially the national and international engineering test reactors FER and ITER, respectively. The moderate- and smaller-size tokamaks are discussed in Sections III.E and III.F. Diagnostic capabilities are reviewed in Section III.G.

## C. BACKGROUND

### 1. Principles of Tokamak Confinement

The main magnetic-field component of the tokamak is a strong toroidal field $B_t$, generated by external toroidal-field coils. In addition, there is a weaker poloidal magnetic field $B_p$, generated by a transformer-induced toroidal current within the plasma itself and shaped by external poloidal-field coils. The two magnetic-field components—$B_t$ and $B_p$—together give rise to helically spiraling magnetic-field lines. Each field line lies within an axisymmetric toroidal magnetic surface, and these magnetic surfaces are nested within each other. The axisymmetry of the tokamak geometry forces the orbit of any given plasma particle to remain close to its initial magnetic surface. The quality of overall plasma confinement is correspondingly good, even in the presence of collisions and other microscopic disturbances that can cause particles to skip from one orbit to another.

The poloidal-field component $B_p$ plays the principal role in providing high-quality confinement, but its permissible strength is limited by the need to preserve the gross stability of the tokamak configuration. This stability limit is defined in terms of a safety factor q: gross stability is generally achieved for q somewhat above unity. For a tokamak of circular minor cross-section, the safety factor can be written in the simple form $q = aB_t/RB_p$, where a and R are the minor and major radii. Thus, there is an upper limit on the allowable poloidal-field strength $B_p$, and an equivalent limit on the maximum allowable plasma current $I_p$.

Detailed stability theory for high-temperature, toroidally-confined plasmas begins by assuming an ideal, that is, perfectly conducting, fluid. Stability against flute-like (ballooning) modes on the large-major-radius side of a tokamak plasma at a high value of beta (ratio of plasma pressure to magnetic field pressure) is found to be favored by high plasma current (low q-value), but stability against kink-like modes that distort the entire plasma column requires that the safety factor q not be too small. The limiting beta-value depends on a compromise that optimizes the radial q-profile, and also on the detailed shaping of the minor plasma cross-section. Vertically elongated, D-shaped cross-sections allow larger current $I_p$ at fixed q-value and are favorable for high beta. The theoretical limiting beta-value (in percent) for configurations with various elongations is given by the simple "Troyon" expression 3.5 $I_p(MA)/a(m)B_t(T)$, the numerical factor 3.5 being known as the "Troyon coefficient."

The introduction of a small but finite amount of plasma resistivity into magnetohydrodynamics (MHD) theory has a remarkably strong destabilizing effect: it can give rise to various modes that grow on a time scale that lengthens only weakly with decreasing resistivity. In present-day tokamak experiments, these resistive modes constitute the dominant instability problem. Indeed, a tokamak with a strongly non-optimal q-profile may encounter gross instability and termination of plasma confinement—termed a "disruption." While major disruptions can be avoided in normal tokamak operation, a low level of resistive-MHD activity generally remains present, including the so-called "sawtooth" oscillations, which serve to maintain the central q-value approximately unity. A more detailed account of the ideal and resistive stability of the tokamak may be found elsewhere (Rosenbluth and Rutherford, 1981).

In a magnetic configuration with closed, nested flux surfaces, the irreducible or "classical" plasma loss rate is due to scattering of particle orbits and is carried mainly by the plasma ions, which have the largest orbital excursions. For the tokamak configuration, which is symmetric about the major axis, particle orbits form closed toroidal surfaces that lie very close to the magnetic surfaces: the orbits of thermal ions in a tokamak reactor stray at most a few centimeters from their initial magnetic surfaces. By classical criteria, the plasma current level of about 3 MA that would be needed in order to confine the bulk of the 3.5-MeV alpha particles of the DT reaction in a tokamak reactor would be sufficient to meet the requirement for ignition. However, plasma transport across the magnetic field of a tokamak is found to exceed classical predictions. Ion heat transport has been found to be up to an order of magnitude larger than classical theory, and electron heat transport—which classically would be almost negligible—is typically found to be at least as large as ion heat transport. Since a validated theoretical explanation of the deviation from classical behavior is lacking, tokamak transport is generally described only from an empirical viewpoint. However, there is good theoretical understanding of a variety of microscopic modes of instability that are probably the underlying cause of the anomalous transport.

In neutral-beam heating of tokamak plasmas, energetic beams of neutral atoms are created by charge-exchange of ion beams. When such neutrals are injected into a tokamak plasma, they readily become trapped as energetic ions and proceed to thermalize slowly with the bulk plasma particles. The thermalization processes appear to be classical.

The response of tokamak plasmas to externally generated radio-frequency waves has been studied extensively, the initial objective being plasma heating. Good penetration and absorption of the RF power can be achieved in certain special frequency ranges: (i) ion cyclotron resonant heating (ICRH), typically 30 to 100 MHz; (ii) lower hybrid heating (LHH), 1-5 GHz; and (iii) electron cyclotron heating (ECH), 60 to 150 GHz. Radio-frequency waves can also be used to drive a toroidal current non-inductively in the tokamak, by wave-particle interactions that introduce relative momentum between the plasma electrons and ions. In electron current drive, the RF power must be sufficient to maintain a population of suprathermal electrons, with energy $E_{res}$, against the "frictional" forces arising from Coulomb collisions with bulk-plasma ions and electrons. The resulting theoretical current-drive efficiency is given by $I(MA)/P(MW) = 0.4\ E_{res}\ (100\ keV)/ n_e(10^{20} m^{-3})\ R(m)$. The efficiency decreases as the plasma density increases, but improves with increasing energy of the resonant electrons. Current drive using lower-hybrid waves (LHCD) has been particularly successful.

Nonhydrogenic impurity ions are undesirable in the tokamak plasma core, since they dilute the fusion fuel. In the case of very heavy ions, which are not sufficiently well stripped of electrons, there is the additional problem of heat loss from the core by line-radiation. Present tokamak experiments are able to exert effective impurity control using mechanical limiters of high-grade graphite to define the plasma edge. A more powerful alternative approach is to define the plasma edge by a magnetic separatrix—a feature of the magnetic field topology that tends to occur naturally in a tokamak with a strongly shaped minor cross-section. The objective is to divert the plasma outflow to a mechanical surface (the divertor-plate) that can be isolated from the main plasma by the pumping action of the plasma outflow itself.

## 2. Brief History of Tokamak Research Outside Japan

The basic idea of the tokamak was described in the early 1950s in the Soviet Union by I. E. Tamm and A. D. Sakharov 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 Atomic Energy Institute in Moscow. The tokamak configuration was independently described in the United States by L. Spitzer, also in the early 1950s, but the United States preferred to concentrate its experimental program on the related stellarator concept, in which plasma equilibrium can be provided without the potentially destabilizing toroidal plasma current. However, compared with its competitors, the experimental success of the tokamak, which began to be evident by the end of the 1960s, does not seem to have been due to any intrinsic superiority of the tokamak magnetic configuration, but rather as a consequence of the relative simplicity of the tokamak, which permitted a plasma of relatively large minor radius to be confined in a device of modest overall size and cost.

Initial results from the T-3 tokamak, reported by Artsimovich in 1965, provided the first indication of improvement in confinement 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, $n_e = 4 \times 10^{13}$ $cm^{-3}$, for pulse durations of about 50 milliseconds and with energy confinement times of about 7 milliseconds. Remaining experimental anomalies in the 1968 T-3 data, in particular the discrepancy between the electron temperature obtained from the diamagnetic signal and the much lower temperature obtained from the measured plasma resistivity, were finally resolved by means of the first measurements of $T_e(r)$ in a tokamak by Thomson scattering, carried out on T-3A in 1969 by a joint team from the Culham Laboratory and the Kurchatov Institute. The validity of the diamagnetic data on $T_e$ was confirmed, and the anomalous plasma resistivity was shown to be mainly due to the presence of impurity ions in the plasma.

As a result of the spectacular successes on T-3, a number of major tokamak devices were put into operation outside the Soviet Union during the early 1970s. The first of these was the ST tokamak at Princeton, which was similar to T-3 in general capabilities and which provided an early confirmation of the T-3 results, and later served to extend very greatly the range of tokamak diagnostics.

However, by far the most important area of progress in tokamak research was the successful demonstration of techniques for auxiliary, that is, non-ohmic, plasma heating. Particularly successful were the neutral-beam heating experiments on the ORMAK device at Oak Ridge and on the TFR-400 tokamak at Fontenay-aux-Roses, France, in which ion temperatures approaching 2.0 keV were ultimately reached. Neutral-beam heating followed by magnetic compression was successfully demonstrated on the ATC device at Princeton, which thereby reached electron temperatures of about 2 keV at densities of about $10^{14}$ $cm^{-3}$. Somewhat later, a very-high-field device, Alcator A, was brought into operation at MIT that extended the capability of pure ohmic heating by permitting gross stability at exceptionally high plasma current density; the correspondingly intense ohmic heating led, ultimately, to the achievement of record densities (about $10^{15}$ $cm^{-3}$) at electron and ion temperatures of about 1 keV.

After 1975, a number of larger tokamaks, designed to extend the achievable plasma parameters, were brought into operation. These included the T-10 at the Kurchatov Institute, PLT at Princeton, Doublet III at General Atomics (all with about the same confinement capability), and a modified device, TFR-600, at Fontenay-aux-Roses. In addition, two intermediate-size devices—ISX-B at Oak Ridge and T-11 at the Kurchatov Institute—explored very intense neutral-beam heating, resulting in record values of the plasma beta. The very-high-field approach was pursued in two new devices—the Alcator C at MIT and the FT device at Frascati, Italy. Ion cyclotron heating was successfully tested on several of the larger tokamaks, especially PLT and TFR-600, and high-power electron cyclotron heating became operational on T-10. Application of radio-frequency waves in the lower-hybrid frequency range was less successful for plasma heating, but was found on PLT and Alcator, as well as on some smaller tokamaks, to be capable of driving the toroidal current needed for confinement in tokamaks, without any assistance from a transformer-induced voltage. Finally, several tokamaks were brought into operation incorporating a magnetic divertor, in which the edge of the plasma is defined by means of a magnetic separatrix, beyond which lies a "scrape-off" region in which field lines lead into a separate divertor chamber. Both the ASDEX (Axisymmetric Divertor Experiment) device at Garching, Germany, and the PDX (Poloidal Divertor Experiment) at Princeton employed a toroidally-symmetric poloidal divertor.

The plasma parameters achieved in these larger (now called moderate-size) tokamaks included ion temperatures up to 7 keV (PLT), electron temperatures up to 6 keV (T-10), products of density and confinement time up to $8 \times 10^{13}$ $cm^{-3}s$ (Alcator C), and beta-values up to five percent (Doublet III and PBX, the latter a reconfiguration of PDX). However, the confinement in ohmically-heated plasmas in Alcator C did not attain the levels that had been projected on the basis of scalings derived from the smaller Alcator-A device, and all tokamaks discovered that the application of high-power auxiliary, that is, non-ohmic, heating invariably led to a deterioration of confinement. Relative to this degraded (L-mode) level of confinement, the use of a poloidal divertor was found in ASDEX to result in enhanced confinement (the H-mode), and this result was confirmed in other tokamaks with plasmas that could be similarly bounded by a magnetic separatrix. The favorable H-mode was found to occur only above a certain threshold in auxiliary power, and its access was much easier in deuterium than in hydrogen plasmas.

In the early 1980s, the first members of the present generation of large tokamaks, TFTR (1982) and JET (1983), became operational. In addition, the Doublet III device was reconfigured to allow a larger, strongly-shaped plasma (DIII-D). The increased confinement capability resulting from the larger plasmas in these devices has extended greatly the confinement times and temperatures that have been achieved in tokamaks. The favorable effect of a poloidal magnetic divertor on confinement has been found to extend to large tokamaks, and new improved-confinement modes have been discovered. The DIII-D has exceeded previous record beta-values. Both neutral-beam and ion-cyclotron heating appear to be about equally effective for heating plasmas in large tokamaks, although the H-mode has proved somewhat elusive with ion-cyclotron heating alone. Pellet injection into large tokamaks has been successful in raising the plasma density and in producing the largest values of the Lawson parameter, that is, the product of density and confinement time. The large tokamaks JET and TFTR have both approached break-even level plasma conditions in deuterium plasmas, that is, conditions at which a deuterium-tritium plasma with the same parameters would produce almost as much fusion power as the auxiliary power used to heat and maintain the plasma.

More complete accounts of the early history of tokamak research may be found elsewhere (Rutherford, 1980; Furth, 1981; Stacey, 1984).

### 3. Early Japanese Tokamaks

Tokamak experiments at JAERI date from 1972 when JFT-2, the first tokamak in Japan, went into operation almost concurrently with ORMAK (United States), TFR (France), and Pulsator (Germany) (M. Tanaka, 1985). The JFT-2 was a circular-cross-section tokamak with a major radius of 0.9 m and a maximum plasma current of 170 kA. The early experimental program on JFT-2 was devoted to energy and particle confinement, plasma heating by lower-hybrid waves, and the development of plasma diagnostics and discharge-control techniques. By technological advances in the conditioning of the RF waveguides, JFT-2 was the first tokamak to demonstrate lower-hybrid heating and to achieve a large drop in the ohmic voltage upon application of lower-hybrid current drive. In later experiments with about 2 MW of neutral-beam heating, the JFT-2 was able to attain plasma beta-values in the range 2.5 to 3.0 percent—near-record values at that time. The JFT-2 was shut down in 1982 to make way for the JFT-2M device.

A somewhat smaller tokamak, the JFT-2a/DIVA, operated at JAERI in parallel with JFT-2 during the period from 1974 to 1979. The JFT-2a/DIVA was the first tokamak equipped with a poloidal magnetic divertor (magnetic limiter), and it used this capability to perform a number of experiments on impurity control and on the characteristics of the diverted "scrape-off" plasma. The JFT-2a/DIVA also achieved record-low plasma q-values, as low as 1.3—aided by effective impurity control and by the stabilizing effect of a conducting wall.

The much larger JFT-2M tokamak began operation in 1983, equipped with a high-power (4.5 MW) ion-cyclotron heating system. Early experiments concentrated on combining neutral-beam and ion-cyclotron heating to reach high beta-values, and definitive contributions were made to the design of RF antennas.

The subsequent program on JFT-2M, which has a D-shaped plasma cross-section, a poloidal divertor and a maximum plasma current of 500 kA, is described in Section E of this chapter.

The JIPP-T-II device ($R$ = 0.9 m, $a$ = 0.17 m) was operated at IPP-Nagoya from 1976 to 1981, first as a tokamak (1976 to 1979) and subsequently as a stellarator (1979 to 1981) (Fujita and Matsuoka, 1985). In the tokamak mode, the device was used to study optimized discharge scenarios for suppression of kink-like instabilities and associated disruptions. Comparative studies of neutral-beam heating in stellarator and tokamak plasmas gave generally similar results, with the heating efficiency only slightly better in the tokamak case. However, from 1981 to 1983, the JIPP-T-II device was converted to the JIPP-T-IIU tokamak to provide a somewhat larger plasma ($a$ = 0.24 m) and better diagnostic access for tokamak studies in connection with the proposed Nagoya R-Machine (see Section III.E). The emphasis in the early program on JIPP-T-IIU was on RF heating.

Radio frequency heating and current drive were studied on the small WT-1 and WT-2 tokamaks at Kyoto University, beginning in the late 1970s. By 1981, a tokamak current had been sustained in WT-2 by lower-hybrid waves alone and, by 1983, a tokamak discharge had been initiated without any transformer assist, by injecting lower-hybrid waves into a microwave, that is, electron-cyclotron-produced, plasma (S. Tanaka, 1985).

### 4. JAERI-Doublet III Collaboration

A five-year collaboration between JAERI and General Atomics (GA) was initiated in 1979 and focused on the GA tokamak Doublet III. The Doublet III collaboration was by far the largest single element in a broader agreement to undertake cooperative energy research, executed in 1979 by representatives of the governments of the United States and Japan. Under the terms of the Doublet III collaboration, JAERI provided approximately $70 million over the five-year period, and these funds were used to extend the operating run-time significantly and to support a major upgrade of the initial Doublet III device, including a new 2-GJ motor generator, two additional neutral-beam injectors, and several items of power equipment. JAERI also made several additions to the complement of diagnostics on Doublet III. In return, JAERI was allowed to send an experimental team to GA, and the JAERI team was allocated approximately one-half of the experimental run-time on Doublet III.

The benefits that JAERI hoped to gain from the collaboration included practical experience for the experimental team that would subsequently be running JT-60 and access to a tokamak with greater plasma-shaping and high-beta capabilities than JT-60. The activities of the JAERI team from the beginning of the collaboration focused on the study of D-shaped plasmas heated by high-power neutral injection. Later in the collaboration, after the discovery of the H-mode on ASDEX, the JAERI team concentrated its efforts on various types of divertor-like configurations in Doublet III. During the period of the collaboration, the Doublet III tokamak was still configured as a "doublet," however, tokamak discharges with currents up to about 1 MA could be produced in one of the two lobes of the doublet configuration.

The JAERI team at GA typically numbered about 15 to 18 physicists, mostly from JAERI itself but including a few from Hitachi and other industrial companies. Some stayed for the entire five-year period, while others did "tours of duty" of 6 to 12 months at a time. The JAERI team was headed by A. Kitzunezaki and M. Nagami.

In terms of the significance of the experimental results that were obtained by the JAERI team, the collaboration was a resounding success. Just before the IAEA (Baltimore) Conference in 1982, a beta-value of 4.6 percent was obtained in Doublet III—substantially higher than the previous record values of about 3.0 percent—and this important new result was published as a joint achievement (Nagami, for the JAERI team, and Overskei, for the GA team, 1983). At the IAEA (London) Conference in 1984, the JAERI team presented results on high-power neutral-beam heating of elongated plasmas in single-null poloidal-divertor configurations. (The diverted field lines in Doublet III could be channelled to the wall in the constricted "waist" between the two lobes of the doublet configuration.) The favorable ASDEX-like mode of confinement was reproduced, and record values were obtained for the product of plasma density, confinement time and ion temperature—the parameter that best measures progress toward fusion break-even (Kitzunezaki et al., 1985). A second paper by the JAERI Doublet III team at the IAEA (London) Conference in 1984 reported results on pellet injection into neutral-beam-heated limiter plasmas; a new type of enhanced-confinement mode was found, associated with reduced gas recycling at the plasma edge (Sengoku et al., 1985).

Despite these successes, the JAERI-GA collaboration was not an altogether satisfactory experience at the working level, especially for the GA physicists. Early in the collaboration, it was decided to assign entirely separate operating shifts to the JAERI and GA experimental teams. Typically, one team took the day-time shift, and the other the evening shift. Very soon, each team came to regard the data taken on its shift as proprietary and not to be divulged to the other team. Since the machine was generally run in the same operating mode and with the same machine parameters for both shifts, a highly competitive atmosphere developed, with each team trying to gain a slight edge over the other in terms of documentable plasma performance, and becoming deeply suspicious of the other's claims in this regard. The normal procedures for data validation and verification were probably not always followed during this period; certainly, a few of the most notable results were obtained from a single shot that could not be reproduced subsequently. At times, the two teams obtained different results with identical machine parameters and operating conditions, and these disagreements often surfaced only at outside meetings and conferences. In one instance, a special paper had to be written—about two years after the collaboration ended—attempting by further analysis to resolve differences in interpretations of some of the data (Abe et al., 1987). Although competition undoubtedly provided a strong and effective incentive to obtain the very best possible plasma performance from Doublet III, it would seem, in retrospect, that the overall value of the collaboration—and perhaps even the quality of the published results—would have been improved if the two teams had worked together as an integrated unit, accepting responsibility jointly for the analysis and interpretation of the data.

A number of other practical difficulties arose from the way in which the collaboration was implemented. With only a few exceptions, the JAERI team did not bring their own diagnostics physicists, but rather relied on GA to provide support in this area. This meant that the GA diagnosticians had to be organized as a service group, separate from the main GA physics team and with enough staff to support two experimental shifts. To provide the diagnostics support that was needed, GA was forced to expand their diagnostics group, and the additional costs for this were not fully recovered from JAERI. Since the same diagnostics physicist would often take data for both GA and JAERI teams, he was generally excluded from participating in the analysis of either team's results. Although the GA diagnosticians had been organized as a separate group even before the JAERI collaboration, most fusion laboratories have found it preferable to integrate diagnostics physicists into the main experimental team. After the JAERI collaboration ended, GA reorganized the Doublet III experimental effort in just this way.

The JAERI-GA collaboration effectively ended in 1984—a year before initial experimental operation of JT-60. Officially, the collaboration was extended until 1988, and has recently been extended again until 1992, but there are now rarely more than two Japanese physicists at GA (in 1989, one from JAERI and one from Hitachi) and there is no longer any significant level of JAERI financial support for the GA program.

## D. LARGE TOKAMAKS

### 1. Accomplishments and Capabilities

#### a. JT-60 Tokamak

The large tokamak JT-60 was constructed by JAERI to constitute the focus of the second phase of Japanese fusion development. The JT-60 project was initiated in 1975 and fabrication began in April, 1978 (Yoshikawa and Tomabechi, 1983), with initial plasma experiments taking place in April, 1985 (Yoshikawa et al., 1987). The JT-60 was constructed at a new site at Naka, approximately eight kilometers from the existing, larger JAERI facility at Tokai. The JAERI fusion program is funded through the Science and Technology Agency (STA).

The objectives of JT-60 and its role in the Japanese fusion research and development program were originally laid down in the "Second Phase Basic Program of Nuclear Fusion Research and Development" (AEC, Japan, 1975) and were reconfirmed in the "Long-Term Program for the Development and Utilization of Nuclear Energy" (AEC, Japan, 1982). The success of JT-60 in approaching break-even conditions in hydrogen plasmas is described in the more recent "Long-Term Program for the Development and Utilization of Nuclear Energy" (AEC, Japan, 1987), and this latest plan indicates that the next step will be to improve further the performance of tokamaks by upgrading the JT-60 device.

The objective of JT-60 was to provide an integrated evaluation of the plasma physics and associated heating and fusion technologies at break-even plasma conditions. In specifying the principal characteristics of the JT-60 in its design phase, emphasis was placed on those features that can be tested only when integrated in a single device, rather than on those that can be studied in complementary devices or parallel programs (Yoshikawa, 1985). The specifications for the device and for all of its principal auxiliary systems were determined early in the design phase.

As indicated in Table III.1, the machine parameters of JT-60 are generally similar to those of the large tokamaks JET (European Community) and TFTR (United States). An approximately circular cross-section was chosen for JT-60 (strongly shaped cross-sections being pursued in complementary, parallel programs on Doublet III and JFT-2M), and a single-null divertor (magnetic limiter) was placed on the horizontal midplane on the large-major-radius side of the torus. This single-null outer divertor—a unique feature of JT-60—was produced by three divertor coils placed inside the vacuum vessel. On the basis of theory, the placing of the divertor null on the large-major-radius side of the plasma could only be disadvantageous for plasma performance. The weakened poloidal field in the divertor region causes the field lines to dwell longer in the unfavorable curvature region, thereby reducing the depth of the stabilizing magnetic well and lowering the beta limit. The more conventional placement of the divertor null(s)—vertically above and/or below the plasma and slightly to the small-major-radius side—was known theoretically to have a favorable effect on plasma stability at high beta-value. However, the JT-60 design was clearly influenced less by theory than by considerations of engineering convenience—both in JT-60 itself and in a future reactor based on JT-60.

**Table III.1**
**DESIGN PARAMETERS OF JT-60 AND OTHER LARGE TOKAMAKS**

| | JT-60 | JET | TFTR |
|---|---|---|---|
| Major radius of plasma (m) | 3.0 | 3.0 | 2.5 |
| Minor radius of plasma (m) | 0.90 | 1.2 x 2.1 | 0.85 |
| Toroidal field on axis (T) | 4.5 | 3.5 | 5.2 |
| Maximum plasma current (MA) | 2.7 | 4.8 | 2.5 |
| Plasma cross-section | Circular | D-shaped | Circular |
| Limiter/divertor | Single-null outer divertor | Limiter (divertor possible) | Limiter |
| Working gases | H | H/D/T | H/D/T |

In the United States, where theoretical considerations play a larger role in the conceptual design of new machines, it is unlikely that the choice of divertor location in the JT-60 design could have survived scrutiny by the fusion community. Albeit for reasons unrelated to MHD stability, the JT-60 divertor coils were deactivated and the outer-null divertor configuration was replaced by a more conventional lower-null divertor, produced by a divertor coil placed vertically beneath the plasma in a machine modification that was implemented in 1987-1988.

Unlike JET and TFTR, which operate routinely with deuterium plasmas and are designed for eventual use of deuterium-tritium, the JT-60 is presently limited to hydrogen operation.

The JT-60 device is equipped with three separate high-power heating and current-drive systems, namely neutral-beam injection (NBI), ion-cyclotron resonant heating (ICRH), and lower-hybrid heating (LHH) and current drive (LHCD). The parameters of these heating and current-drive systems are given in Table III.2. The direction of neutral-beam injection is almost perpendicular to the main toroidal magnetic field, and the beams enter the plasma chamber from above and below the horizontal midplane, avoiding the outer-null divertor coils. The device and all of its auxiliary systems have a pulse-length capability of 10 seconds. The purpose of the high-power lower-hybrid system—unique among the world's three large tokamaks and representing by far the largest lower-hybrid system ever constructed—is to study long-pulse, non-inductively-driven tokamak plasmas.

**Table III.2**
**AUXILIARY HEATING AND CURRENT-DRIVE SYSTEMS ON JT-60**

| | NBI | ICRH | LHH/LHCD |
|---|---|---|---|
| Source power (MW) | | 6 | 24 |
| Power to torus (MW) | 20 | 5 | 15 |
| Power absorbed (MW) | 16-18 | 2.5 | 7.5 |
| Energy (keV) | 75 (H) | | |
| Frequency (GHz) | | 0.12 | 1.7 (LHH)<br>2.2 (LHCD) |
| Power sources | 28 ion sources | 8 tetrodes | 24 klystrons |
| Number of beamlines/ launchers | 14 | 1 | 2 (LHH)<br>1 (LHCD) |
| Pulse length (secs) | 10 | 10 | 10 |

The power required to operate JT-60 and its auxiliary systems is provided primarily by generators, although the utility line supplies some of the power for the toroidal-field coils. The parameters of the different generators are as follows: 215 MVA/4.0 GJ for the toroidal field coils, 500 MVA/1.3 GJ through individual thyristors for the poloidal field coils, and 400 MVA/2.65 GJ for the plasma heating systems. The machine is controlled by a centralized computer system. About forty different plasma diagnostics are operational, and these are described more fully in Section III.G.

The JT-60 was designed and built by Japanese industry, with Hitachi playing the major role. Although the tokamak machine itself was constructed by Hitachi, major subsystem contracts were given to other industries, for example to Mitsubishi for the toroidal-field power supplies and to Toshiba for the poloidal-field power supplies. A large-scale research and development program was carried out from 1975 to 1977, that is, up to three years prior to the start of construction. Extensive tests were performed on prototype and full-scale models of the toroidal-field coils, poloidal-field coils, vacuum-vessel segments, and the current-interrupter components for the poloidal-field-coil power supply. A prototype neutral-beam injector was manufactured and tested at full rating in March 1982, and prototype klystrons for the lower-hybrid system were tested in August 1983. This extensive pre-construction R&D program appears to have been highly beneficial in ensuring both early realization of the full design values of all machine parameters and timely achievement of full power ratings in the auxiliary heating and current-drive systems. The construction of JT-60 took exactly seven years, from start of fabrication in April 1978, to initial plasma operation in April 1985. The machine itself was completed in December 1984, and was then successfully tested at full design parameters before the first plasma shot. After an initial period of ohmic plasma operation in 1985, the neutral-beam (all 14 beamlines), ion-cyclotron (one launcher) and lower-hybrid (one of three launchers) auxiliary heating and current-drive systems were installed and became operational in July 1986. The power levels to the torus from the NBI, ICRH and LHH/LHCD systems reached 16 MW, 1.4 MW, and 1.2 MW, respectively, within three months of initial operation—a remarkable technological achievement.

The construction of JT-60 followed the normal Japanese pattern of large-scale industrial involvement at all stages of the project. However, JAERI retained full responsibility for the direction and execution of the construction project. Design studies at JAERI and a three-year period of design-specific R&D activities preceded the large-scale involvement by industry. Consequently, JAERI was able to provide the design concept and basic parameters, with industry performing the systems engineering and subsystem design and construction. On JT-60, because of the size of the project, there were individual contracts between JAERI and industrial vendors for each major subsystem, rather than for the total system, so that JAERI retained a greater degree of overall responsibility than would normally be the case with a smaller project. However, Hitachi was selected as "coordinating company" on JT-60, involving coordination between JAERI and other contractors, and among the various contractors, but stopping short of total management responsibility. As a result, JAERI continued to review designs, direct R&D activities, and let contracts to other vendors throughout the design and construction project. However, Hitachi's role included the adjustment of technical interfaces and construction schedule among contractors, safety and environmental considerations, and the arrangement of facilities at the site. Essentially all of the JT-60 construction contracts were awarded competitively, usually with at least two or three qualifying bids. Most contracts were on a fixed-price basis, even for development items, although an extended period of design study, often accompanied by industrial in-house and JAERI R&D, usually preceded the pricing of the final production contract (Postma and Rosenthal, 1983).

Organizationally, when fusion research was transferred from Tokai to the new site at Naka, the previous Fusion Research Center at the Tokai Research Establishment simply became the new Naka Fusion Research Establishment. Originally, the Fusion Research Center at Tokai had been directed by S. Mori but, before the move to Naka, Mori had become a vice president of JAERI and had been succeeded at Tokai by Y. Iso. The first Director General of the Naka Fusion Research Establishment was K. Tomabechi. Upon mandatory retirement (at age 58) from this administrative position, Tomabechi was replaced by M. Yoshikawa, who had previously been Director of the Department of Large Tokamak Research at Naka and who, more than any other single individual, is associated scientifically with the JT-60 project. Very recently, Yoshikawa has been promoted to the position as Vice President of JAERI previously held by S. Mori, moving to the JAERI headquarters office in Tokyo, and he has been replaced as Director General at Naka by M. Tanaka, who additionally continues to hold his former position as Director of the Department of Thermonuclear Research. There are four Departments at Naka reporting to the Director General: the Department of Large Tokamak Research, which is responsible for all experimental research on JT-60 and is currently directed by S. Tamura, who also heads the FER team; the Department of the JT-60 Facility, which is responsible for the operation of JT-60 and is currently directed by T. Iijima; the Department of Thermonuclear Fusion Research, which is responsible for theoretical research, plasma heating, certain technical support activities and the residual fusion program at Tokai, including JFT-2M, and continues to be directed by M. Tanaka; and a Department of Administrative Services. A key individual in fusion planning for the central JAERI administration is A. Kitzunezaki, Manager of the Office of the Fusion Program. Within the Department of Large Tokamak Research, there is a Large Tokamak Program Division, headed by H. Kishimoto; a Diagnostics Division, headed by A. Funahashi; two Large Tokamak Experimental Divisions, both headed by Y. Shimomura; and a Fusion Reactor Systems Laboratory, headed by N. Fujisawa. Within the Large Tokamak Experimental Division, the Experimental Group is headed by M. Nagami, who has primary responsibility for detailed planning of the JT-60 program, and who also coordinates the activities of the experimental team leaders.

During periods of experimental operations, JT-60 runs two experimental shifts per day, 9:00 a.m. to 10:00 p.m., Monday through Friday (Bell, 1987; Goldston, 1987). Alternate Saturdays are also workdays, but are used for analysis and discussion of the data, rather than for additional experiments. The third shift and weekends are used for maintenance. There are three separate experimental teams of about 10 to 12 physicists each. The teams rotate weekly from first-shift duty, to second-shift duty, to an off-duty week for data analysis and preparation for the next run-week. The teams are not differentiated by experimental tasks or goals, but rather carry out whatever experimental program has been scheduled for their duty-week; the evening-shift team tends to take the lead in planning the week's activities, and prepares a written summary of the day's results for distribution to the full team by the next morning. Weekly physics meetings are held, at which the present week's results are summarized and the next week's plans are presented, in each case by the leader of the respective evening-shift team.

The machine operations organization is divided into two teams, each containing about 12 to 15 engineers and 25 to 30 technicians (O'Neill, 1988). These two teams alternate between first- and second-shift duty. There are very few direct JAERI staff on duty during the third shift or on weekends, since all operations of vacuum, cryogenic and water systems that require 24-hour, 7-day coverage are performed primarily by industrial vendors. Contracts with original equipment manufacturers, renewed each year, provide for all needed maintenance and operational support. In general, vendors remain actively involved with their equipment for the life of the project. For the engineering design and analysis related to JT-60, the direct JAERI capabilities are also commonly augmented by industrial personnel.

Operating procedures on JT-60 are relatively labor-intensive and contribute to a rather modest number of shots per experimental run-day (Bell, 1987; Goldston, 1987). The maximum repetition rate of the machine itself is determined by the inertial cooling of the vacuum vessel and limiter/divertor-plates. At an auxiliary power level of 20 MW, the repetition rate could be as high as one pulse every 20 minutes—and higher with ohmic heating only. In practice, however, the number of pulses achieved in a typical 10-hour experimental run is generally in the range 10 to 20. Other large tokamaks achieve a repetition rate that is two to three times better than this. On the other hand, the conditioning techniques employed before an experimental run begins are at least as efficient as those on other large tokamaks: after a machine opening, there is an initial 100-hour period of conditioning using glow and pulse discharge-cleaning; each weekend, there are 10 hours of Taylor discharge cleaning. The vessel can also be baked to 300°C.

Procedures during an experimental shift involve a rigorous sequence of formal sign-offs. The lead physicist determines the conditions for each shot and enters these on special forms using hand-drawn sketches of wave-forms. These forms are carried by secretarial staff to operational engineers and computer-interface personnel, who create the required wave-forms in the computer that provides real-time control of the machine. Although the countdown after this data has been entered can be as short as five minutes, the time involved in communicating the relatively frequent changes in conditions and in programming them into the computer limits the achievable shot rate. During the shot itself, an elaborate display in the control room registers the operating parameters of all subsystems. The basic experimental data that has been obtained is available within about five minutes after the shot, including plot displays on terminals in the control room. Nonetheless, extensive logs are filled out manually after each shot for distribution to the following day's experimental team. An additional impediment to greater operational efficiency has been the decision to place most diagnostic controls and displays in a separate room, nearer the machine itself but sufficiently far from the main control room that shot conditions must be communicated to the diagnosticians either by a closed-circuit television picture of a board on which parameters are manually entered by operators, or by facsimile transmission of the data-forms. Correspondingly, detailed diagnostic data are not automatically displayed in the main control room. In addition, some diagnostics are controlled by stand-alone computers, which do not communicate directly with the central control computer. Overall, coordination between the physicist directing the experimental run and the physicists operating the diagnostics appears to be less effective than in situations where there is a single control room and a common computer system.

The initial results from JT-60 were presented in one summary paper (Yoshikawa, for the JT-60 Team, 1987) and three companion papers at the IAEA (Kyoto) Conference in 1986. The outer single-null divertor had been successful in exhausting almost all of the particle outflux and about 70 percent of the plasma power. Impurity radiation from the central core of the plasma was reduced markedly (to less than 10 percent of the auxiliary-heating power) by the action of the divertor, and values of $Z_{eff}$ (the effective ionic charge) as low as 1.5 were commonly achieved. About one third of the power exhausted by the divertor was radiated in the divertor region and about two thirds were measured (by thermocouple) to go to the divertor plate, which at that time was made of molybdenum with a 20-micron titanium-carbide coating. As in all other auxiliary-heated tokamaks, energy confinement was observed to deteriorate with the application of high-power neutral-beam injection (Nagami, for the JT-60 Team, 1987); in JT-60, the characteristic confinement time decreased from its ohmic value of 0.3 to 0.5 seconds to about 0.1 seconds with absorbed beam power of about 14 MW. The stored plasma energy exhibited an "offset linear" dependence on absorbed power, with only weak dependences on field strength, current and plasma density. The more favorable H-mode of energy confinement, first observed with divertor operation on the ASDEX tokamak at Garching, could not be realized on JT-60, despite the effectiveness of the outer-null divertor in fulfill-ing its particle- and power-exhaust functions. Attempts to achieve the H-mode by increasing the separatrix-limiter distance, by changing the working gas from hydrogen to helium (deuterium operation being precluded at the Naka site), and by fueling the plasma through the divertor chamber to increase the density of plasma in the diverted layer were all unsuccessful, although brief periods with H-mode-like characteristics were sometimes seen. The sawteeth and MHD-like fluctuations in ohmic and beam-heated plasmas in JT-60 were generally similar to those observed in other large tokamaks (Takeuchi, for the JT-60 Team, 1987). Extremely promising results were obtained, however, by combining high-power neutral-beam heating with lower-hybrid current drive—a unique capability of JT-60 among the world's large tokamaks. Using a single LHCD launcher (phased for current drive) with power to the torus of only 1.2 MW, plasma currents of up to 1.5 MA could be driven entirely non-inductively for 2-sec pulses. (Imai, for the JT-60 Team, 1987.) The figure-of-merit for current-drive efficiency, $nRI_{rf}/P_{rf}$ reached about 2.8 x $10^{19}$ A $m^{-2}W^{-1}$ in cases with neutral-beam heating—a factor-of-two improvement over previous results. At the time of the Kyoto conference, however, the analyses of inductive effects resulting from changes in the current profile and of possible direct neutral-beam contributions to current drive were incomplete.

In early 1987, the progress of JT-60 received extensive coverage in the Japanese press, and some of the media comments were quite hostile. The issue was whether the device had been successful in reaching break-even plasma conditions—its original objective. Success in this regard was apparently seen as vital to the longer-term future of fusion development in Japan. However, by September 1987, the experimental results had improved to the point where break-even conditions could be said to have been realized—provided the results were adjusted by the improvement factor in going from hydrogen to deuterium plasmas that had been observed in other tokamaks. The target "break-even region" had been defined in the original JT-60 objectives as corresponding to ion temperatures in the range 4.3 to 8.6 keV and products of density and energy confinement time in the range 2 to 6 x $10^{19}$ $m^{-3}$ sec. The best JT-60 experimental datapoint (hydrogen plasma) had an ion temperature of 3.7 keV and a density-confinement-time product of 1.8 x $10^{19}$ $m^{-3}$ sec. However, the confinement time (and hence also the temperature, at fixed density and heating power) had been found in all tokamaks capable of deuterium operation to vary with the squareroot of the isotopic mass, that is, increasing by a factor of 1.4 in going from hydrogen to deuterium. Adjusted by this correction factor, the JT-60 data had clearly entered the target region, and this favorable interpretation was widely publicized (JAERI, 1988).

A number of machine improvements had been made in early 1987, in particular to install graphite tiles over much of the inconel vacuum vessel and to replace the TiC-coated molybdenum divertor plates by graphite-tile divertor plates. Meanwhile, the machine parameters and the neutral-beam power level had exceeded their original design values. A more extensive machine modification was undertaken, beginning in October 1987, with the objective of providing a configuration more likely to yield the favorable H-mode of confinement. Specifically, the outer-null divertor coils were deactivated, and a new divertor coil was installed outside the vacuum vessel to produce the more conventional lower-single-null configuration. The maximum plasma current and the plasma volume were somewhat reduced in the new divertor configuration. A three-shot pellet injector operating at injection speeds of 1.5 km/sec with pellet diameters of 2.7 to 3.8 mm was also installed during this period. The shutdown to install the new divertor coil lasted only seven months—a remarkable feat brought about by meticulous planning and a round-the-clock, seven-days-a-week work schedule by the industrial team led by Hitachi. The evolution of the JT-60 machine and auxiliary-systems parameters is summarized in Table III.3.

The results from the modified JT-60 were presented in one summary paper (Kishimoto, for the JT-60 Team, 1988) and three companion papers at the IAEA (Nice) Conference in 1988. In relation to the break-even objective, the best-located point on the Lawson diagram remained the same, that is, a central ion temperature of 3.7 keV and a density-confinement-time product of $1.8 \times 10^{19}$ $m^{-3}$ sec, which had been achieved in September 1987, in a limiter plasma with a current of 3.2 MA. A clear indication of the full H-mode-enhanced confinement regime was still absent, although the lower-null divertor configuration showed a modest improvement in confinement, especially at high heating power (Tsuji, for the JT-60 Team, 1988). The improvement was associated with increased particle recycling and a lowering of the edge-plasma temperature and heat flux to the divertor-plate by radiative cooling of the edge plasma. Normal H-mode-like transitions occurred in divertor plasmas, and sometimes also in limiter plasmas, but the improvement in confinement was never substantial. The stored plasma energy continued to exhibit an offset-linear dependence on absorbed power—roughly the same in limiter, outer-null and lower-null divertor configurations. The lower-null divertor was as effective as the outer-null divertor for particle and power exhaust. However, the graphite tiles in limiter discharges were almost as effective as either divertor configuration in reducing radiation and impurity levels. Experiments with second-harmonic (hydrogen) ion-cyclotron heating at the 3-MW level in combination with high-power neutral-beam injection (also hydrogen) produced strong acceleration of the beam ions with favorable overall energy confinement (Fujii, for the JT-60 Team, 1988). Lower-hybrid heating of pellet-fueled, peaked-density-profile plasmas produced effective ion heating at relatively high plasma density, but with incremental energy confinement times similar to those achieved with neutral-beam heating (Ushigusa, for the JT-60 Team, 1988). By increasing the LHCD power to about 3 MW, the non-inductively driven current was raised to about 2 MA for a 3 second pulse; the figure-of-merit for current-drive efficiency remained in the range 2.6 to 2.9 x $10^{19}$ $Am^{-2}$ $W^{-1}$, depending on whether neutral-beam injection was also applied, and it exhibited the theoretically-predicted scalings with electron temperature and impurity level. The MHD-like fluctuations observed in JT-60 were found to be generally similar to those on other large tokamaks (Ninomiya, for the JT-60 Team, 1988). In ohmic discharges, a locked mode prevented operation at q-values much below 3. With neutral-beam injection, q-values as low as 2.2 were achieved, but bursts of MHD activity were often seen at frequencies corresponding to the precessional drift of trapped beam ions; given the near-perpendicular direction of the JT-60 injectors, MHD-like modes of this type would be expected to occur, even at relatively modest values of the plasma beta.

Since the IAEA (Nice) Conference in 1988, the JT-60 team has reported increased efficiency of lower-hybrid current drive by replacing one of the three launchers with a multi-junction waveguide, which produces a narrower spectrum of lower-hybrid waves.

**Table III.3**
**EVOLUTION OF JT-60 MACHINE AND AUXILIARY-SYSTEM PARAMETERS**

| | Design (1985) | Achieved (1987) | Modified (1988) |
|---|---|---|---|
| Toroidal field on axis (T) | 4.5 | 4.8 | 4.8 |
| Minor radius of plasma (m) | 0.9 | 0.9 | 0.68 x 0.85 |
| Divertor null location | outer | outer | lower |
| Plasma current, limiter (MA) | 2.7 | 3.2 | 3.5 |
| Plasma current, divertor (MA) | 2.1 | 2.7 | 2.2 |
| First wall | TiC-coated inconel | Graphite tiles | Graphite tiles |
| Divertor plate | TiC-coated molybdenum | Graphite tiles | Graphite tiles |
| Fueling | Gas | Gas | Pellet injector |
| Power to torus (MW): | | | |
| NBI | 20 | 25 | 25 |
| LHH/LHCD | 15 | 11 | 11 |
| ICRH | 5 | 3 | 3 |
| Heating pulse length (sec) | 10 | 3 | 6 |

Despite the lack of a substantial enhancement over the unfavorable L-mode of tokamak confinement, the overall results of JT-60 compare quite well with those of the other large tokamaks, JET and TFTR. Comparative plasma parameters are given in Table III.4. The principal limitation on JT-60's performance appears to have been the inability to operate in deuterium, which has resulted in superior confinement and easier H-mode access in other tokamaks. The restriction on deuterium operation arose from a longstanding commitment both to the Atomic Energy Commission and to the local authorities at Naka not to introduce deuterium into JT-60, because neutron shielding and facilities for handling activated components would be required. This restriction is apparently to be lifted for the upgraded JT-60 device discussed in the next section.

**Table III.4**
**COMPARATIVE BEST PLASMA PARAMETERS ACHIEVED IN JT-60 AND OTHER LARGE TOKAMAKS**
(Data from the same shot)

| | JT-60 (1987) | JET (1988) | JET (1988) | TFTR (1988) |
|---|---|---|---|---|
| Ion temperature (keV) | 3.7 | 7 | 20 | 28 |
| Electron temperature (keV) | 3.0 | 10 | 11 | 8.5 |
| Stored plasma energy (MJ) | 3.1 | 5 | 6 | 3.7 |
| Lawson parameter: product of central electron density and energy confinement time ($m^{-3}s$) | $1.8 \times 10^{19}$ | $4 \times 10^{19}$ | $8 \times 10^{18}$ | $1.5 \times 10^{19}$ |
| Product of Lawson parameter and central ion temperature ($m^{-3}s$ keV) | $7 \times 10^{19}$ | $3 \times 10^{20}$ | $2 \times 10^{20}$ | $4 \times 10^{20}$ |

Operating costs of JT-60 are relatively high by US standards, as indicated in Table III.5, but it must be remembered that industry plays a major ongoing role in the operation and maintenance of the JT-60 device and in the fabrication of most diagnostics. The FY89 operating budget also includes costs of the JT-60 upgrade.

b. JT-60 Upgrade

The idea of a major upgrade of the present JT-60 device was conceived in 1987 and became part of the most recent "Long-Term Program for the Development and Utilization of Nuclear Energy" (AEC, Japan, 1987). Approval for construction was received in early 1988, triggered by the successful results from JT-60 in late 1987, but apparently accompanied by the recognition that the more ambitious Fusion Experimental Reactor (FER) would necessarily be delayed.

**Table III.5**
**OPERATING COSTS OF THE LARGE TOKAMAKS**

| | JT-60* | JET** | TFTR |
|---|---|---|---|
| FY 1988 | $131 M (¥17.1 B) + $10 M† | $123 M (ECU 117 M) | $71.5 M |
| FY 1989 | $124 M (¥16.1 B) + $10 M† | $121 M (ECU 115 M) | $67.5M |

* JT-60 costs converted at the rate $1 = ¥130
** JET costs converted at the rate $1 = 0.95 ECU
† Direct JAERI personnel costs

Source: Meade, 1989

The objective of the upgraded device (JT-60U) is to achieve a doubling of the plasma current and plasma volume by means of a new vacuum vessel that almost completely fills the toroidal-field-coil bore (Kishimoto, for the JT-60 Team, 1988). The poloidal-field coils are also completely replaced, and the plasma cross-section becomes elongated by a factor of about 1.4. A lower single-null divertor will be employed. Approval is now said to have been granted for deuterium operation in the upgraded device. Neutron shielding for the machine and for the building are included in the upgrade plan. With the change to deuterium, the energy and power of the neutral-beam injectors are expected to increase significantly, but the injector orientation is unchanged. Improvements will also be implemented in the RF heating and current-drive systems, with particular emphasis on long-pulse lower-hybrid current drive. The remaining two lower-hybrid launchers will be replaced by multi-junction waveguides, but an earlier plan to increase the frequency to 3.7 GHz has apparently been abandoned. The present divertor coils on the outer mid-plane will be removed, allowing horizontal access for the RF launchers, especially the LHCD waveguides which will be horizontally moveable to provide good coupling to both circular and elongated plasmas. The design parameters of the JT-60U and its auxiliary systems are listed in Table III.6. In preparation for the new divertor plates, several carbon-carbon composites are already being tested in the present JT-60 machine.

The upgrade is to be implemented in a thirteen-month period beginning in December 1989—again, a remarkable feat by US standards. The costs of the Table III.6 upgrade are absorbed in an approximately-flat total JT-60 budget (see Table III.5). M. Kikuchi is in charge of the construction project. A four-year (1991 to 1994) experimental program has been outlined for the upgraded device, of which the principal elements are listed in Table III.7. Of particular interest is the inclusion in the plan of a second stage of current-drive experiments, utilizing either negative ion beams or ion-cyclotron fast waves to achieve efficient current drive at higher plasma densities.

c. Fusion Experimental Reactor

The "Long-Term Program for the Development and Utilization of Nuclear Energy" (AEC, Japan, 1982) laid out a long-range plan for fusion research in Japan and focused fusion-reactor design studies on a single device with comprehensive objectives, to be completed in the late 1990s (Tomabechi et al., 1983). Until about 1980, fusion-reactor design studies at JAERI had pursued a strategy for fusion development that required two sequential reactor-like devices: the first would have the goal of achieving plasma ignition but would involve only limited tests of reactor technology, while the second would seek to provide an integrated test of all relevant fusion-reactor technologies. Starting in 1980, the new approach involving only a single reactor facility—but possibly with several distinct stages of operation—had gained favor and had led to a test-reactor concept with comprehensive objectives, specifically: (i) plasma self ignition in deuterium-tritium; (ii) a burn pulse of at least 100 seconds; (iii) demonstration of essential fusion technologies, such as plasma heating and control, superconducting magnets, tritium systems and remote maintenance; and (iv) systems integration. The reactor would also provide tests of materials and tritium breeding technologies, and it would attempt to achieve a high level of availability and reliability. The new reactor concept, named the Fusion Experimental Reactor (FER), would serve as a focus for the entire JAERI fusion effort for at least the next decade.

**Table III.6**
**DESIGN PARAMETERS OF JT-60U AND ITS AUXILIARY SYSTEMS**

| | JT-60 (Achieved) | JT-60U (Design) |
|---|---|---|
| Major radius of plasma (m) | 3.0 | 3.4 |
| Minor radius of plasma (m) | 0.90 | 1.0 x 1.5 |
| Toroidal field on axis (T) | 4.8 | 4.2 |
| Maximum plasma current (MA) | 2.7 (div)<br>3.2 (lim) | 6.0 (div)<br>7.0 (lim) |
| Divertor type | Outer null<br>Lower null | Lower null |
| Power to torus (MW): | | |
| NBI | 25 (H) | 40 (D) |
| LHH/LHCD | 11 | 15 |
| ICRH | 3 | 10 |
| Neutral-beam energy | 75 (H) | 120 (D) |
| Limiter/divertor-plate | Graphite tiles | Carbon-carbon composites |
| Working gas | H | H/D |

Although the FER's objectives in technology demonstration and testing could have been accomplished using a driven, sub-ignited mode of plasma operation, the additional cost of providing ignition-level plasma performance was judged to be worthwhile. The energy flux of neutrons at the first wall was specified to be a relatively moderate 1.0 $MW/m^2$. However, an essential requirement was to achieve a tritium breeding ratio of at least unity—presumably to avoid a dependence on foreign sources for the substantial quantities of tritium that would be needed in the high-availability stage of operation. The plasma was to be D-shaped with a double-null divertor, and both neutral-beam and RF heating options were to be kept open. A start of construction as early as 1988-1989 was foreseen. The objectives and design concept of FER were generally similar to those of the IAEA International Tokamak Reactor, INTOR, which had been formulated in 1979-1980.

**Table III.7**
**EXPERIMENTAL PROGRAM PLAN FOR JT-60U**

| | 1991 | 1992 | 1993 | 1994 |
|---|---|---|---|---|
| Divertor | Lower-null divertor experiments at 6 MA | | | |
| Limiter | Limiter experiments at 7 MA | | | |
| Heating | NBI: 40 MW<br>LHH: 15 MW<br>ICRH: 10 MW | | | |
| Current drive | LHCD: 15 MW | | Negative ion beams<br>Fast wave ICRH<br>High plasma density | |
| Other | C/C composite divertor armor<br>Local n = 2 windings for disruption control | | | |

By the time of the IAEA (London) Conference in 1984, the FER design concept had begun to include advanced features, especially in the area of non-inductive current drive. Specifically, two new modes of plasma operation were under evaluation (Tone et al., 1985): the first, for which the plasma parameters were essentially the same as in the pulsed-ignition mode, employed lower-hybrid current drive (LHCD) to produce quasi-steady-state operation, involving inductively-driven burn pulses interspersed with periods of low-density plasma operation during which the ohmic transformer is recharged inductively from a plasma current driven by LHCD; the second, for which the plasma density must be lowered slightly, employed advanced current drive techniques, such as fast-wave or compressional-Alfvén-wave current drive, to achieve a true steady-state burn pulse with a Q-value (ratio of fusion power to input power) of at least 10. The benefits of the quasi-steady-state mode of operation were longer burn pulse, thereby reducing thermal and mechanical fatigue, and a further reduction in cyclic stresses arising from maintaining the plasma current almost constant throughout the entire cycle. The steady-state mode of operation had the additional benefit of allowing a substantial reduction in overall machine size, by elimination of the ohmic transformer altogether. Other advanced features had been incorporated into the design, such as a "high-recycling divertor," in which the temperature of the scrape-off plasma at the divertor is below the sputtering threshold for refractory metals such as tungsten, thereby providing about a one-year lifetime for the divertor-plate.

At the IAEA (Kyoto) Conference in 1986, a design variant was presented in which 500-keV negative-ion-based neutral beams, rather than RF, were employed for heating and current drive (S. Yamamoto et al., 1987). Again, both quasi-steady-state (transformer re-charge) and true steady-state modes of plasma operation were discussed. In the quasi-steady-state mode, the beams are used for current ramp-up (after ECH-assisted start-up), for transformer recharge (with near-tangential injection, the beam shine-through being only 20 percent even at low plasma density) and for heating. In the steady-state mode, the Q-value is only about 5, because of the lower current-drive efficiency relative to the "advanced" RF techniques assumed previously. A 1,000-MWe power reactor based on this FER variant was also described, employing 300-MW, 1-MeV negative-ion beams to drive a plasma producing 3,000 MW of fusion power (but requiring a Troyon beta-coefficient of about 5).

By the time of the IAEA (Nice) Conference in 1988, the FER design had bifurcated into two versions corresponding to different physics expectations (Sugihara et al., 1988). The first (optimistic) version assumes a favorable H-mode confinement scaling, a Troyon coefficient of 3.5, and effective non-inductive current ramp-up to provide about half of the voltseconds and thereby reduce the size of the transformer. There is no "margin" to provide assurance of ignition performance. The second (conservative) version seeks to reduce physics risks by increasing the ignition margin and by providing fully-inductive current-ramp capability. Even so, ignition is not quite achieved with the unenhanced L-mode confinement, unless the beta limit can be raised somewhat and the q-limit lowered. However, high-Q operation is realized in the L-mode with standard beta and q limits. A parallel thrust within the FER design effort has been to develop engineering approaches that provide the flexibility both to adapt to changing physics and to accommodate upgraded and extended operating modes. The design has remained totally flexible in regard to heating and current-drive options; in particular, tangential access suitable for negative-ion neutral beams remains an essential requirement. However, the original requirement for a full tritium-breeding blanket has been dropped; it is now considered sufficient to conduct small-scale tritium breeding and recovery tests in blanket modules.

The evolution of the FER design concept is illustrated by the parameter sets given in Table III.8. The present, nominal FER schedule is as follows: Concept Study, 1988; Conceptual Design, 1989-1990; Detailed Design, 1991-1992; Construction, 1993-2000.

The FER design team is composed of a small core-group of JAERI staff, augmented by a large industrial team drawn from many different companies. The FER team now has the additional responsibility for providing the Japanese effort on ITER, which appears to be consuming an increasing fraction of the total effort.

d. ITER Participation

At the Geneva Summit Meeting in November 1985, a proposal was made by the Soviet Union to build a next-generation tokamak experiment on a collaborative basis among the world's four major fusion blocs. 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 between diplomatic and technical representatives of the four prospective participants resulted in the establishment, under the auspices of the IAEA, of the ITER Conceptual Design Activity. During 1987, the ITER Quadripartite Initiative Committee formulated the Terms of Reference under which the ITER Activity would take place. The programmatic objectives of ITER, as stated in the Terms of Reference, are as follows:

> The overall objective of ITER is to demonstrate the scientific and technological feasibility of fusion power. The ITER will accomplish this by demonstrating controlled ignition and extended burn of a deuterium and tritium plasma with steady state as an ultimate objective, by demonstrating technologies essential to a reactor in an integrated system, and by performing integrated testing of the high-heat-flux and nuclear components required to utilize fusion power for practical purposes. The ITER, in accomplishing these objectives, will provide the database in physics and technology necessary for the design and construction of a demonstration fusion power plant.

**Table III.8**

**EVOLUTION OF THE FUSION EXPERIMENTAL REACTOR (FER) DESIGN CONCEPT**

| | 1984 Pulse Ignited | 1984 Quasi-Steady | 1984 Steady State | 1986 Quasi-Steady | 1986 Steady State | 1988 Optimistic Physics | 1988 Conservative Physics |
|---|---|---|---|---|---|---|---|
| Divertor | Double null | Double null | Double null | Double null | Double null | Single null | Double null |
| Major radius (m) | 5.5 | 5.5 | 4.0 | 5.2 | 5.2 | 4.4 | 5.1 |
| Plasma current (MA) | 5.3 | 5.3 | 6.4 | 5.9 | 5.9 | 8.7 | 15.8 |
| Toroidal field (T) | 5.7 | 5.7 | 4.5 | 5.3 | 5.3 | 4.9 | 4.7 |
| Mean temperature (keV) | 10 | 10 | 13 | 10 | 20 | -- | -- |
| Density ($10^{20}m^{-3}$) | 1.4 | 1.4* | 0.9 | 1.1* | 0.7 | -- | -- |
| Fusion power (MW) | 440 | 440 | 250 | 300 | 200 | 410 | 730 |
| Burn pulse (s) | 100 | 2,000 | ss | 2,000 | ss | 800 | 100 |
| Current drive/ramp | Ohmic | LHCD | Advanced | NB (Neg. ion) | NB (Neg. ion) | Ramp (NB or RF) | Ohmic |
| CD power (MW) | 15† | 18 | 40† | 40 | TBD | | |
| Beam energy (keV) | | | | 500 | 500 | TBD | |

* During burn pulse
† During transformer recharge

The ITER Activity is under the overall guidance of the ITER Council, composed of governmental representatives. The ITER Council is advised by the International Scientific and Technical Advisory Committee. The technical work itself is directed by the ITER Management Committee, composed of a managing director from each of the four participants. The managing directors are assigned full-time to the ITER Activity. Each of the participants provides a design team of approximately 30 to 50 physicists and engineers, most of whom are assigned only part-time to ITER, but about 10 of whom form part of the core group that is resident at Garching, West Germany, during periods of joint design work. The Conceptual Design Activity began in 1988 with a total of about five months of joint design work at Garching, and this pattern will be repeated in 1989 and 1990. The Conceptual Design Report is due by December 1990; there is presently no commitment from any participant to extend the ITER Activity beyond 1990, but it seems likely that the Activity will indeed continue in some form. Presently, each participant spends the equivalent of $16-18 million annually on the ITER Activity—split about equally between design and R&D. The proposed R&D contributions are submitted by each participant to the ITER Management Committee, which formulates an approved list of proposals for consideration by the ITER Council.

Japan has played a prominent role in ITER from the beginning. K. Tomabechi was selected to be Chairman of the ITER Management Committee—an appointment that coincided with his retirement as Director General of the Naka Fusion Research Establishment. Within the ITER structure, Japan supplies the head of one of the four Project Units, namely, H. Iida (Systems Analysis), and the heads of two of the eight Design Units, namely Y. Shimomura (Poloidal Field) and T. Honda (Maintenance). The Japanese have maintained a strong presence at Garching during all of the periods of joint work and have assigned several senior JAERI physicists to the ITER Activity, presumably at significant cost to their domestic programs, especially JT-60. The contributions of Y. Shimomura to ITER have been particularly influential—especially the idea of a sufficiently flexible PF design to allow "staged operation" involving different plasma configurations and sizes within the same vacuum vessel. Other Japanese physicists assigned to the ITER core-group are N. Fujisawa, M. Sugihara, and T. Tsunematsu.

Japan has also proposed ITER Technology R&D Tasks in the following major areas: ceramic breeders, low-Z and high-Z materials for plasma facing components, manufacturing technology for first-wall structures, manufacturing technology for bonded metal structures for divertor plates, toroidal- and poloidal-field magnets and magnet cryogenics, pellet injectors for plasma fueling, high-speed ceramic turbo-pumps, negative-ion beams, and in-vessel remote maintenance.

The Japanese members of the ITER Scientific and Technical Advisory Committee are N. Inoue (Tokyo University), T. Sekiguchi (Yokahama National University), and M. Tanaka (Naka, JAERI).

## 2. Outlook

From the viewpoint of furthering the scientific understanding of confinement in tokamaks, 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. Was it only the inability to operate in deuterium, or was there also some deficiency in the type of divertor or the manner of its operation? 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. However, the conventional H-mode scalings predict that the confinement time in JT-60 could be limited to about 0.5 to 0.6 seconds. An additional possible problem in JT-60U might be the relatively large value of the toroidal-field ripple (2.5 percent at the plasma edge), brought about by the requirement to increase the plasma volume within the existing TF-coil set. Even in the first stage of operation, the upgraded device and improved launchers will maintain JT-60's position at the forefront of research in lower-hybrid current drive. 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 probability (but not certainty) 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 seems 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, if and when such a project were to be authorized by the Japanese government.

## E. MODERATE-SIZE TOKAMAKS

### 1. Accomplishments and Capabilities

#### a. JFT-2M

The JFT-2M is a moderate-size tokamak located at JAERI's Tokai Research Establishment. The role of JFT-2M in the Japanese program is the improvement of tokamak performance by such means as strong plasma shaping to achieve high beta-value, enhanced modes of confinement (especially the H-mode), and

RF current drive. Thus, the JFT-2M device carries out exploratory experiments that require the flexibility afforded by a moderate-size facility, and it also provides for more detailed examination of scientific issues raised by the large tokamaks, especially JT-60. The JFT-2M is viewed in Japan as contributing both to the developmental program for the next-generation fusion facility and to the improvement of the economic and commercial attractiveness of fusion power. By far the most notable achievement of JFT-2M has been the successful realization of the principal features of the favorable H-mode of confinement in a plasma bounded by a material limiter, rather than by a magnetic divertor. This important result has been aggressively publicized in semi-popular technical journals (Funahashi, 1987), as well as in the scientific literature (Sengoku et al., 1987; Matsumoto et al., 1987), with the apparent aim of assuring the survival of the JFT-2M program—a matter that might have been at issue now that the bulk of JAERI's fusion activities have moved from Tokai to the new site at Naka.

Although still located at Tokai, the JFT-2M is administratively a part of the Department of Thermonuclear Fusion Research at the Naka Fusion Research Establishment. The JFT-2M experimental team is headed by H. Maeda, and a key physicist is N. Suzuki.

Compared with JT-60, experimental operations on JFT-2M have less management structure, and the research is conducted in an atmosphere of greater informality (Goldston, 1987). There is generally lively debate within the physics team regarding the interpretation and significance of results that have been obtained, as well as about future plans. There is a weekly physics planning meeting, involving the entire physics team, at which N. Suzuki presents an overview of the previous week's run. This is followed by a discussion of the next week's plan which, in final form, is constructed on a blackboard during the meeting itself. Despite the informality, the JFT-2M effort clearly benefits from strong and effective leadership by Maeda and Suzuki.

The principal parameters of JFT-2M and its auxiliary systems are given in Table III.9. A broad range of auxiliary heating and current-drive capabilities are operational on JFT-2M, and the experimental program in recent years has been correspondingly diverse. At the IAEA (London) Conference in 1984, the JFT-2M team reported on high-power ion-cyclotron heating (ICRH) experiments, using the two-ion hybrid heating regime (with mixtures of hydrogen and deuterium), in which the average plasma beta-value was raised to 1.2 percent at a toroidal field strength of 1.15 T with only 1.6 MW of RF power (Mori et al., 1985). The significance of this result was the successful reduction of impurity build-up by controlling the spectrum of the launched waves.

**Table III.9**

**PRINCIPAL PARAMETERS OF JFT-2M AND ITS AUXILIARY SYSTEMS**

| | |
|---|---|
| Plasma major radius (m) | 1.3 |
| Plasma cross-section | D-shaped |
| Plasma minor radius (m) | 0.35 x 0.53 (limiter)<br>0.26 x 0.44 (divertor) |
| Toroidal field strength (T) | 1.5 (power limited) |
| Plasma current (MA) | 0.55 (maximum)<br>0.28 (typical) |
| Limiter | Graphite tiles |
| Divertor | Open design<br>Single null<br>Graphite tiles |
| Working gas | Hydrogen or deuterium |
| Heating and current drive: | |
| • NBI energy (keV)<br>- Power (MW)<br>- Direction | 40 (H)<br>1.6 (absorbed)<br>Tangential, balanced |
| • ICRH frequency (MHz)<br>- Power (MW) | 15.2<br>4.5 (source), 1.6 (to torus) |
| • ECRH frequency (GHz)<br>- Power (MW) | 60<br>0.4 (source), 0.24 (to torus) |
| • LHH/LHCD frequency (GHz)<br>- power (MW) | 0.75<br>0.6 (source), 0.2 (to date) |

At the IAEA (Kyoto) Conference in 1986, the JFT-2M team reported the first achievement of H-mode confinement with ion-cyclotron (rather than neutral-beam) heating and with a material limiter (rather than a magnetic divertor) (Odajima et al., 1987). First, the JFT-2M team had reproduced the original ASDEX-like H-mode with hydrogen neutral-beam injection into a deuterium plasma; the threshold power for the H-mode transition was found to be quite low—typically only 0.2 MW. In limiter plasmas, the threshold power increased to about 0.5 MW, but H-mode-like transitions were still observed, although the resulting increase in confinement was not so pronounced. The results with ion cyclotron heating (in hydrogen/deuterium mixtures) were very similar to those with neutral injection, except for a greater tendency for impurity accumulation. In the divertor-plasma experiments, the H-mode confinement time was a factor 1.3 to 1.7 times higher than the L-mode value. A second JFT-2M paper at the IAEA (Kyoto) Conference in 1986 reported on electron cyclotron heating of plasmas in which a significant population of energetic electrons has first been produced by LHCD (T. Yamamoto et al., 1987). Second harmonic X-mode ECH was found to couple successfully at downshifted frequency: the LHCD-accelerated electrons whose parallel velocities satisfy the relativistic cyclotron resonance condition were selectively heated by the ECH. However, the efficiency of the LHCD was not improved. Subsequently, the JFT-2M team also reported the successful realization of the H-mode when about 100 kW of ECH were added to a subthreshold level (150 kW) of neutral-beam power (Hoshino et al., 1988).

At the IAEA (Nice) Conference in 1988, the JFT-2M team reported further studies of the H-mode (Suzuki et al., 1988). In neutral-beam heated divertor discharges, the H-mode could be sustained for pulse-lengths up to 300 msec, aided by reductions in impurity influx from installation of graphite over much of the vacuum vessel. Detailed confinement studies had led the JFT-2M team to the view that the "incremental confinement time" (increase in stored energy divided by increase in heating power) is the same in L- and H-modes, and that the H-mode enhancement arises from a larger initial energy content due to the formation of elevated "pedestals" on the density and temperature profiles. The "limiter H-mode" produced a significant increase in confinement only in elongated cross-section plasmas. A recently-installed 1.4 km/sec 4-shot pellet injector produced a further 30 percent improvement in confinement of neutral-beam-heated plasmas. An improved L-mode of confinement was also observed, generally occurring after a transition from the H-mode back to the L-mode regime.

b. JIPP-T-IIU

The JIPP-T-IIU is a moderate-size tokamak located at IPP-Nagoya. It was constructed as a modification of the earlier JIPP-T-II tokamak, and it became operational in 1983. The emphasis of the JIPP-T-IIU program has been on RF heating and current drive and on the characterization and control of various types of tokamak plasma instabilities.

The JIPP-T-IIU device is small enough to be operated with a strong research orientation and with a minimum of managerial structure. The JIPP-T-IIU team is headed by Y. Hamada. Other senior physicists are A. Mohri, K. Matsuoka, and T. Watari, who directs the RF work.

The principal parameters of JIPP-T-IIU and its auxiliary systems are given in Table III.10. The experimental program in recent years has been quite diverse. At the IAEA (London) Conference in 1984, the JIPP-T-IIU team presented results on lower-hybrid current start-up and ion cyclotron heating (Toi et al., 1985). The start-up experiments used 50 kW of LHCD power to produce a 20 kA tokamak current at low plasma density without inductive assist. In the ICRH experiments, about 800 kW of power had been coupled successfully in the hydrogen-minority/deuterium-plasma mode from high-field-side antennas, and the impurity influx was controlled by wall-carbonization and by employing a ramped-current, puffed-gas plasma scenario. In addition, experiments on ion-Bernstein-wave heating (IBWH) with a low-field-side antenna had achieved heating efficiencies comparable with those in the minority-ion ICRH experiments.

At the IAEA (Kyoto) Conference in 1986, JIPP-T-IIU reported further results on high-power-density ion-cyclotron heating and also some initial results on fast-wave current drive (FWCD) at frequencies in the lower-hybrid range, specifically 800 MHz (Watari et al., 1987). The current-drive efficiency at low density was about the same as with slow-wave LHCD, and it was not possible to exceed the usual slow-wave density limit. In another paper at the Kyoto Conference, the JIPP-T-IIU team reported on disruption control experiments using modular multipole coils (Yamazaki et al., 1987). In these innovative experiments, local modular multipole coils with dominant m/n = 3/2 field components—initially intended for ergodic magnetic limiter experiments—were used to delay the onset of major plasma disruptions.

**Table III.10**
**PRINCIPAL PARAMETERS OF JIPP-T-IIU AND ITS AUXILIARY SYSTEMS**

| | |
|---|---|
| Plasma major radius (m) | 0.92 |
| Plasma cross-section | Circular |
| Plasma minor radius (m) | 0.24 |
| Toroidal field strength (T) | 3.0 (maximum) |
| Plasma current (kA) | 300 (maximum)<br>150 (typical) |
| Limiter | Graphite |
| Working gas | Hydrogen or deuterium |
| Heating and current drive: | |
| • ICRH frequency (MHz)<br>- Power (MW) | 40<br>20 (source), 0.8 (to torus) |
| • LHCD frequency (GHz)<br>- Power (MW) | 0.8<br>0.1 |
| • NB energy (keV)<br>- power (MW) | 30<br>1.5 |

At the IAEA (Nice) Conference in 1988, the JIPP-T-IIU team presented results on fine-scale density fluctuations and their relation to cross-field transport (Kawahata et al., 1988). An HCN laser scattering system was used to measure density fluctuations in ohmic and auxiliary-heated plasmas. As the density of ohmic plasmas is raised, density fluctuations that propagate in the ion diamagnetic direction appear, and their amplitude is even more pronounced in neutral-beam-heated and ion-cyclotron-heated plasmas. The fluctuations are interpreted as being due to the ion temperature gradient mode of drift-wave microinstabilities. A second paper from JIPP-T-IIU at the Nice Conference reported the results of a collaboration with General Atomics on a resonant helical divertor experiment, in which a particle scoop (pump limiter) is placed in the magnetic island created by an applied m/n = 3/1 magnetic perturbation (Evans et al., 1988).

c. TRIAM-1M

The TRIAM-1M is a moderate-size superconducting tokamak at Kyushu University. It is the world's first tokamak to come into operation using the $Nb_3Sn$ superconductor.

The TRIAM-1M project is headed by S. Itoh. Compared with other experimental tokamak groups in Japan, the Kyushu group is regarded as very strong in engineering but somewhat weak on the physics side.

The principal parameters of TRIAM-1M are given in Table III.11 and are compared with those of the Soviet superconducting tokamak T-7 (completed in 1979, but operated only intermittently). The TRIAM-1M magnet was successfully tested mechanically at full field rating. Initial plasma operation was in June 1986. At the IAEA (Kyoto) Conference in 1986, the TRIAM-1M team reported on inductively-driven plasmas with currents in the range 100 to 150 kA, on-axis toroidal fields in the range 4 to 5 T, mean densities of about $7 \times 10^{19}$ $m^{-3}$, electron temperatures of about 500 eV, and pulse durations up to 70 msec (Itoh et al., 1987). The principal limitation on performance at this stage was the capacity of the poloidal-field power supplies. By the time of the IAEA (Nice) Conference in 1988, a lower-hybrid current-drive system had been installed, with which, following inductive start-up, a plasma current of 25 kA had been sustained for 190 seconds—certainly a world record for a tokamak discharge (Itoh et al., 1988). Since the Nice Conference, the TRIAM-1M team has raised the LHCD power to 200 kW and has achieved a corresponding increase in the driven current at somewhat higher plasma density.

**Table III.11**
**COMPARATIVE PARAMETERS OF TRIAM 1M AND T-7**

| | TRIAM-1M | T-7 |
|---|---|---|
| Plasma major radius (m) | 0.83 | 1.2 |
| Plasma cross-section | D-shaped | Circular |
| Plasma minor radius (m) | 0.12 x 0.18 | 0.35 |
| Toroidal field at coil (T) | 11 (design)<br>7 (achieved) | 5 (design)<br>3 (achieved) |
| Toroidal field at plasma (T) | 8 (design)<br>5 (achieved) | 3 (design)<br>2 (achieved) |
| TF-coil conductor | $Nb_3Sn$ | NbTi |
| Plasma current (MA) | 0.5 (maximum)<br>0.15 (achieved) | 0.24 to 0.4 (max) |
| Current drive: | | |
| • LHCD power (MW)<br>- Frequency (GHz) | 0.2 (to date)<br>2.45 | 0.6 (design)<br>0.9 |

2. Outlook

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 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 second 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 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 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-60 Upgrade project, the view seems to be growing that JFT-2M may, in fact, remain at Tokai.

Although the main thrust of the Ministry of Education, Science, and Culture's (MOE) future program of fusion research will be on the heliotron/ torsatron concept, it has apparently been decided that the JIPP-T-IIU tokamak 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.

In the early 1980s, the IPP-Nagoya, developed an ambitious proposal for a new deuterium-tritium tokamak, called the R-Machine (Hamada et al., 1985). This device was to have been constructed entirely of aluminum alloy to reduce neutron activation and to allow hands-on maintenance after about 1,000 D-T shots. The major radius was to be 2.1 m, the toroidal field 3 T, and the plasma current up to 3 MA. Assuming that the aluminum vacuum vessel would serve as a conducting shell to eliminate kink instabilities, very high plasma beta values were projected which, if realized, would provide Q-values in D-T in the range

0.1 to 0.3. A number of alpha-particle diagnostics were designed for testing on this device. The R-Machine engendered considerable controversy within the Japanese fusion community and received mixed reviews abroad—mainly on account of the lack of interest in D-T physics at such low Q-values and of the perceived unsuitability of a D-T emphasis for the MOE program. The proposal was abandoned in 1985 and was replaced by the LHD heliotron/torsatron as the main future thrust of the MOE program.

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 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.

## F. SMALL TOKAMAKS

### 1. Accomplishments and Capabilities

Although several very small tokamaks may still be used for teaching purposes in Japanese universities, there are now only two small tokamaks in operation in Japan, the WT-3 and the TNT-A, that produce research results of interest to the wider fusion community. The parameters of these devices and of two other small tokamaks no longer in operation are listed in Table III.12.

The WT-2 device at Kyoto University was the first tokamak in the world to demonstrate a fully non-inductive mode of tokamak operation—termed the RF tokamak (S. Tanaka et al., 1985). In the WT-2 experiments, a microwave discharge was formed by ECH, and the subsequent application of LHCD was successful in producing and sustaining a toroidal current of about 10 kA (corresponding to a tokamak q-value of about 9). The current-drive efficiency was smaller than the theoretical value, probably because the resonant electron energy (15 keV) far exceeded the electron temperature (70 eV). A somewhat larger device, the WT-3, came into operation in 1986 and was able to extend the RF tokamak concept to currents in the 50 kA range (S. Tanaka et al., 1987). By applying electron cyclotron heating to a unidirectional energetic-electron tail, current ramp-up and current drive by ECH alone was demonstrated at the 30-kA level in WT-3 (S. Tanaka et al., 1988). However, the current-drive efficiency was found to be somewhat smaller than that obtained on the same device with LHCD, and much smaller than the theoretical value. Experiments on WT-3 on the control of various modes of MHD instability using LHCD to broaden the current profile were successful in suppressing the sawtooth oscillation and in modifying the behavior of the disruption precursor oscillations.

**Table III.12**
**PARAMETERS OF SMALL TOKAMAKS IN JAPAN**

| | WT-2 | WT-3 | TNT-A | TORIUT-4,5 |
|---|---|---|---|---|
| Location | Kyoto University | Kyoto University | Tokyo University (Physics) | Tokyo University (Engineering) |
| Major radius (cm) | 40 | 65 | 40 | 30-38 |
| Minor radius (cm) | 9 | 22 | 9 x 13 | 11-13 |
| Toroidal field (kG) | 15 | 17 | 4.2 | 5.0 |
| Plasma current (kA) | 30 | 100 | 20 | 20-30 |
| Special features | Al shell<br>ECH (120 kW)<br>LHCD (100 kW) | ECH (200 kW)<br>LHCD (350 kW)<br>ICRH (500 kW) | D-shaped | Thin shell |
| Program emphasis | RF start-up<br>current drive | RF start-up<br>current drive<br>MHD control | MHD studies<br>ICRH/IBWH | Very low q<br>Transition to RFP |
| Status | Replaced by WT-3 | Operating | Operating | Replaced by REPUTE RFP |

The TNT-A device at Tokyo University is a non-circular cross-section tokamak that has studied mainly MHD plasma control and magnetic fluctuations

(Miyamota and Toyama, 1985). The TORIUT-4 and TORIUT-5 devices are thin-shell tokamaks that have been used to study the very-low-q tokamak regime and the transition to the reversed-field-pinch configuration (Inoue, 1985).

2. Outlook

The 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 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 instead as an ultra-low-q tokamak.

As research vehicles, 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 two years) on JIPP-T-IIU at Nagoya.

## G. DIAGNOSTICS

### 1. Accomplishments and Capabilities

a. Diagnostics on JT-60

An impressively complete basic set of diagnostics became fully operational on JT-60 within a year after initial operation of the machine—in time to contribute significantly to the results presented at the IAEA (Kyoto) Conference in 1986 (Yoshikawa, for the JT-60 Team, 1987). The plasma stored energy used in the confinement studies presented at Kyoto was evaluated not only from magnetic measurements, but also from a six-point Thomson scattering profile of the electron temperature and a spectroscopically-determined central ion temperature. The central electron temperature was also measured by electron cyclotron emission. Particle confinement was studied using multi-chord H-alpha measurements in the periphery of the main plasma and in the divertor chamber. Power flow to the divertor was studied using a multi-channel bolometer array and thermocouples at the divertor plates. Extensive studies of the impurity content of the plasma were based on a grazing-incidence spectrometer to identify the impurities present, together with soft X-ray detectors and the scattering of a helium diagnostic beam for quantative measurements of the densities of high-Z (titanium) and low-Z (carbon and oxygen) impurities, respectively. Studies of magnetic fluctuations were based on soft X-ray and external magnetic-loop measurements.

In the period from 1987 to 1988, the reliability of the JT-60 diagnostics was improved further, and individual instruments were used in a fairly sophisticated manner to shed light on particular features of the JT-60 discharges, for example:

- the electron-cyclotron-emission system was used to study the energetic electron population produced by lower-hybrid current drive;
- the helium diagnostic beam was used to measure the central ion temperature for comparison with the more conventional Doppler-broadening spectroscopic method;
- the charge-exchange analyzers were used to study the energetic ion tails produced by adding ion-cyclotron heating in resonance with beam-injected ions;
- the vacuum-ultraviolet and X-ray crystal spectrometers were used to study impurity transport;
- the soft X-ray fluctuation detectors were used to study sawteeth and other MHD modes in ohmic and beam-heated (rotating) plasmas; and
- the magnetic loops and edge-region H-alpha emission detectors were used to study the locked modes that lead to plasma disruptions in JT-60.

Several of JT-60's diagnostics needed to be relocated to accommodate the lower-null divertor modification that was implemented in 1987-1988. Two new diagnostics were also installed during the 1987-1988 shutdown: a photo-diode array system to measure H-alpha light from pellet-fueled discharges, and an upgraded charge-exchange-spectroscopy system to measure simultaneously the ion temperature at eight different radii. The JT-60 diagnostic set, as it existed at the time of the IAEA (Nice) Conference in late 1988, is summarized in Table III.13. The Diagnostics Development Division at JT-60 is under the direction of A. Funahashi.

With few exceptions, the diagnostics on JT-60 are similar to those on other large tokamaks such as JET and TFTR. Indeed, in many cases, the diagnostic specifications for JT-60 were developed as a direct result of visits by JAERI physicists to TFTR under the US-Japanese and International Energy Agency Large Tokamak Agreements. Certain instruments—for example, the charge-exchange analyzer—are very similar to those on TFTR.

Nonetheless, the instruments themselves are generally of excellent quality, presumably due to the strong emphasis on accuracy and reliability in the industrial manufacturing process. Overall, the diagnostics costs for JT-60 are estimated to have been about twice those for TFTR. However, the diagnostic data produced thus far on JT-60 does not obviously surpass in quality that produced on JET and TFTR—perhaps due in part to the relative inexperience of the JT-60 diagnostics physicists.

The JT-60 diagnostics were almost all built by industry. There are about 40 individual diagnostics, and these were grouped into eight major subsystems for procurement purposes (Yokomizo et al., 1987). The groupings were roughly as indicated in Table III.13, except that the edge-plasma and divertor-plasma diagnostics were combined into one subsystem, and there were two additional subsystems, namely data processing and diagnostics support. Generally, each group of diagnostics was procured from industry as a unified subsystem, integrated in regard to subsystem design, fabrication, installation and commissioning. The

**Table III.13**
**DIAGNOSTICS ON JT-60**

| Plasma Parameter | Diagnostic Type | Diagnostic Characteristics |
|---|---|---|
| Electron density | Far-infrared interferometer<br>2-mm interferometer | 3 channels, $CH_3OH$ laser<br>1 Channel |
| Electron temperature | Fourier-transform spectrometer<br>Thomson scattering system | Electron cyclotron emission<br>Multi-phase ruby laser<br>Six channels |
| Ion temperature | Charge-exchange analyzer<br>Active beam scattering system<br>Charge-exchange recombination spectrometer<br>Neutron counter | Energies 0.1-110 keV<br>Mass energy analyzer<br>200 keV, He, 7° scattering with active beam |
| Impurities | Vacuum-ultra-violet spectrometer<br>Doppler spectrometer<br>Crystal spectrometer<br>Visible spectrometers (2)<br>Grazing-incidence spectrometer | 0.2-500 Angstroms holographic grating<br>5-9000 Angstroms<br>0.6-2.7 Angstroms<br>2000 -7000 Angstroms spectrograph, photomultipler, rotating mirror<br>10-1300 Angstroms |
| Radiation flux | Soft X-ray pulse-height analyzer<br>PIN diode array<br>Bolometer array<br>Hard X-ray detectors | 1 channel<br>17 channels<br>16 channels |
| Edge plasma | Visible TV<br>Magnetic probes, thermocouples<br>H-alpha diode array | 3 channels<br>61 channels<br>8 channels |
| Divertor plasma | Far-infrared interferometer<br>Visible spectrometer<br>Vacuum-ultraviolet spectrometer<br>H-alpha diode array<br>Bolometer array<br>Thermocouple array<br>Infrared and visible TV | 2 channels, $CH_3OH$ laser<br>2000-7000 Angstroms<br>2-1200 Angstroms holographic grating<br>4 channels<br>On divertor plate<br>2 channels |

diagnostic specifications were written by (relatively junior) JAERI physicists during the early phase of JT-60 construction, and major contracts were then given to industry to develop and build the actual instruments. For example, a very large contract (approximately $10 million) was given to Hammamatsu to develop optical systems for use in spectroscopic instruments. Other larger contracts were given to Nikon for the spectrometers, to Toshiba for charge-exchange analyzers, and to NEC for both Thomson scattering and electron-cyclotron-emission systems. The large data acquisition and processing system was developed by Fujitsu, while the main tokamak control systems were developed by Hitachi. In all cases, the industrial companies assigned sizeable engineering teams to these development contracts, far outnumbering the JAERI physicists with whom they worked. These teams have generally retained responsibility for the maintenance and, where necessary, upgrading of their instruments.

One of the few JT-60 diagnostics that is unique is the so-called "active beam scattering system." This is a 200-keV helium beam that is used for ion-temperature measurements, either by measuring the Doppler-broadened near-forward-scattered beam or by measuring the Doppler broadening of lines of impurities that have recombined by charge-exchange on the helium beam (charge-exchange-recombination spectroscopy). This instrument has not worked very reliably, and most quoted ion temperatures have been based on more conventional spectroscopic data.

None of JT-60's diagnostics are presently shielded for deuterium operation. The space in the diagnostics basement under the machine is considered somewhat inadequate to accommodate fully-shielded diagnostics. Presumably, this problem will be addressed as part of the JT-60 Upgrade project.

The diagnostic capabilities of the smaller JAERI tokamak, JFT-2M, are generally similar to those of comparably-sized devices in the United States. The resources available to JFT-2M do not allow a major role for industry in diagnostic development.

b. Diagnostic Development

In contrast to the industry-dominated diagnostic development for JT-60, the diagnostics for the MOE's toroidal program are generally developed in the MOE laboratories and universities themselves. The largest single activity of this kind is in the Fusion and Plasma Diagnostics Center, headed by J. Fujita, at IPP-Nagoya.

The roles of Fujita's group at Nagoya are threefold: (i) to develop and construct diagnostics for the Nagoya devices themselves, such as the present JIPP-T-IIU tokamak and the future LHD torsatron; (ii) to develop and construct diagnostics to be employed in various programs of international collaboration; and (iii) to conduct a research and development program on future diagnostics, especially those that could be used to study alpha-particle effects in DT-burning tokamaks. Fujita also led the Special Research Project in Nuclear Fusion to survey available data on radiation hardening of diagnostic components and to produce necessary data through in-situ experiments. Sumita's group at Osaka University were significant users of the RTNS-II neutron source at Lawrence Livermore National Laboratory as part of this program. The Nagoya group was not involved at all in the JT-60 diagnostics development program. However, there have recently been some collaborations between Nagoya and JAERI on JFT-2M diagnostics.

A number of quite sophisticated instruments have been developed at Nagoya and operated successfully on JIPP-T-IIU, including a six-channel HCN-laser interferometer that has been used for density measurements in high-density pellet-fueled plasmas and for measurements of the plasma current profile by Faraday rotation, a high-resolution X-ray crystal spectrometer for ion temperature and rotation measurements, and a high-time-resolution charge-exchange-recombination spectrometer for ion-temperature profiles in neutral-beam and RF-heated plasmas.

In addition to these diagnostics, which have become relatively standard on present-day tokamaks, Fujita's group has specialized in the development of neutral-beam probe spectroscopy, which can be used to measure the local values of a variety of plasma parameters. These instruments use a neutral lithium beam, at energies from thermal up to about 30 keV, produced by a variety of techniques. A Japanese team led by Nagoya has successfully used neutral-lithium-beam probe spectroscopy (thermal pencil beam) to measure the density fluctuations with a resolution of a few millimeters in the scrape-off layer of the TEXTOR tokamak at Jülich, West Germany. An agreement has also been reached on a collaborative effort to use neutral lithium-beam probe spectrocopy (5-eV sheet beam formed by laser blow-off) to measure the two-dimensional electron density profile in the ergodic edge-plasma region of the Tore Supra tokamak at Cadarache, France.

Prompted by the design effort on the R-Machine at Nagoya in the early 1980s (see Section III.E.2), a research and development program on alpha-particle diagnostics was initiated in Fujita's group, and this effort has continued to the present time, although there is no immediate prospect for its application to a D-T-burning tokamak in Japan. The principal diagnostic under study is an energetic neutral lithium (or perhaps helium) beam probe, on which the alpha-particles will recombine by charge-exchange processes. The technique would be capable of measuring the alpha-particle density and velocity distribution. The energy needed for the lithium beam is sufficiently high (about 2 MeV) that the beam must be formed by neutralization of a negative-ion beam. Current work is focused on the development of appropriate negative-ion sources; a beam current of about 10 mA is needed. (A study is also underway at JT-60 on a 2-MeV lithium beam probe as an alpha-particle diagnostic; since there are certainly no plans for D-T use on JT-60, it is unclear where this effort would find its initial application.) A second approach to alpha-particle diagnostics under study at Nagoya uses a high-speed low-Z pellet to create a cloud of neutrals on which the alpha-particles will recombine to $He^+$, from which the Doppler-broadened spectroscopic signal will provide information on the alpha-particle velocity distribution. Pellet speeds in the range $10^4$ to $10^5$ m/sec are needed for this technique.

There is a smaller diagnostics development group under K. Muraoka at Kyushu University, specializing in laser diagnostics, but the primary interest here has been on mirror and stellarator applications, rather than on tokamaks.

### 2. Outlook

The principal research activities of the Japanese tokamak program for the next few years will be centered on the JT-60U device with high-power neutral-beam heating and lower-hybrid current drive. For the basic evaluation of JT-60U's experimental data, the existing diagnostic capability will undoubtedly prove sufficient. In addition, several of JT-60's more sophisticated diagnostics have been brought to the point where relatively routine measurements of difficult quantities such as the ion temperatures profile are possible. Nonetheless, a significant amount of work will be needed to harden the existing diagnostic set for operation in deuterium.

An area of diagnostics that JT-60 has largely ignored is the measurement of the fine-scale density fluctuations that are believed to be the underlying cause of anomalous cross-field transport in tokamaks. Although this fundamental research topic has not previously been seen as part of the mission of large tokamaks such as JT-60, it should be noted that the TFTR program is presently being redirected into studies of this type. Although smaller tokamaks are in many ways more suitable for these studies, only the large tokamaks can produce the plasma parameters that are exactly prototypical of reactor regimes.

Longer term, the keen Japanese interest in the development of alpha-particle diagnostics, especially at Nagoya but now also at JAERI, bodes well for the quality of the physics that can be done whenever a DT-burning tokamak becomes available to Japanese researchers. The lithium-beam-probe spectroscopic technique—originally conceived in the United States, but under fairly intense study in Japan—appears to be one of the most promising approaches to the measurement of alpha-particle densities and velocity distributions in a tokamak plasma. Assuming that diagnostic development and construction for a future DT-burning device such as FER will follow the industry-dominated pattern set by JT-60, the Japanese program has the technical resources to provide a superior and highly-reliable diagnostic capability for future fusion development.

## CHAPTER III: TOKAMAK CONFINEMENT
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# CHAPTER IV
# 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 Ministry of Education, Science and Culture (MOE) at a level much lower than that for tokamak research and development at the Japan Atomic Energy Research Institute (JAERI) funded by the Science and Technology Agency (STA). The confinement approaches being studied, in order of decreasing effort, are stellarators or helical systems, tandem mirrors, reversed field pinches (RFPs), and compact tori, that is, spheromaks and field reversed configurations (FRCs).

The small university research groups are limited in size by the number of available faculty positions and related support positions. This is especially true in the relatively small theory area. However, their funding, separate from salaries, allows purchase of turnkey machines that are usually well-engineered but very conservatively designed from Hitachi, Mitsubishi, or Toshiba. They also rely on these companies for all phases of an experiment: R&D, concept development; detailed design, construction, commissioning, repairs, and upgrading both of the device and its auxiliary equipment (including plasma heating, controls, and diagnostics). This process works well (Heliotron E, CHS, TPE-1RM-15) when there is good coordination between the experimental group and the company, but there have been some failures (initial GAMMA-10 configuration, REPUTE-1) when good communication was lacking. This 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, the Japanese are much better at adapting 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 and computations on magnetohydrodynamics (MHD) and transport. There are, of course, some notable exceptions in a few areas. 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 to the alternate confinement groups 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 that 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, configuration codes) that are well exercised. Although computer acquisition of experimental data is well established, routine on-line integrated analysis of data is not well developed.

A major change is taking place in the alternate confinement programs in Japan. One approach, the stellarator (or helical system) has been selected for a large next step. More than half of the alternate concepts funding in Japan will be devoted to one project, the Large Helical Device (LHD), which is to be built at a new MOE-operated (not university-operated) laboratory at Toki. 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 Institute of Plasma Physics (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 LHD and to the MOE decision that the activities on the other types of plasma confinement system (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 LHD. After a seven year hiatus in stellarator research, IPP-Nagoya has built the low-aspect-ratio CHS (Compact Helical System) torsatron, a unique facility. These groups are presently among the best in the world. However, there will be a decline in 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 LHD in 1995, Japan will dominate the world stellarator program. Their theory effort is 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 mirror area, the GAMMA-10 experiment at Tsukuba University is now the only tandem mirror in the world studying concept improvement. 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 area, the TPE-1RM-15 facility at the Electro-Technical Laboratory (ETL) in Tsukuba is an excellent facility that has made contributions to the understanding of confinement scaling in RFPs. It has obtained the highest current density and electron temperature in RFPs. The REPUTE-1 RFP at Tokyo University has not performed satisfactorily as an RFP because of inherent field errors and 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 ZT-H (United States) devices in the 1990s.

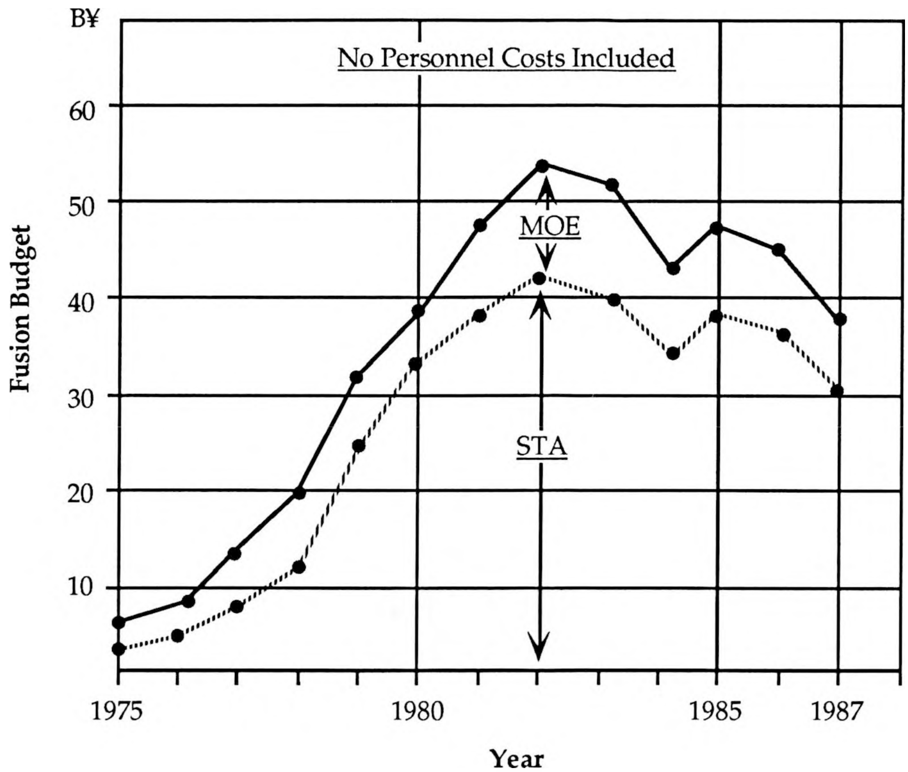
In the compact torus area (field reversed configurations and spheromaks), Japanese facilities are relatively modest, although some significant contributions have been made in this area. A major contribution has been the experimental and theoretical work on stabilization of the $n$ = 2 rotational instability. 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.

## B. INTRODUCTION

### 1. Alternate Confinement Efforts in Japan

Study of alternate confinement approaches in Japan is carried out in universities funded by the Ministry of Education, Science and Culture (also referred to as MOE or by its Japanese name Monbusho), whereas tokamak research is largely the responsibility of JAERI funded by the STA (Yamanaka, 1987). There is also a small alternate concept effort at ETL funded by the Ministry of International Trade and Industry (MITI), just as there is a small tokamak effort funded by MOE at Kyushu University (TRIAM-1M) and at IPP-Nagoya (JIPP T-IIU). Some of the limitations on development of alternate confinement approaches in Japan follow from this division of resources. These agencies are largely independent with some coordination of priorities and funding at the governmental level.

As the worldwide effort on tokamaks grew, so did the Japanese effort and with it the budget of JAERI. By contrast, the funding for university fusion research (Sekiguchi, 1988) grew relatively little (see Figure IV.1). This is partly due to the traditional limitations of Japanese university research. The number of technical staff at each university is limited by the number of available faculty positions, hence the small number of scientists attached to each experiment and the heavy reliance on industry for support of experiments. The fact that a number of competent companies can fulfill this need is essential to the success of experimental fusion research in Japanese universities. However, a comparable resource is not available from outside sources in the theory area, with the result that the theory effort on alternate confinement approaches is much smaller than it is in the United States or Europe.




The fusion budgets for MOE and STA do not include personnel and administration costs and the MOE budgets also do not include building construction costs. Because of the exclusions and the factor of two variation in the yen to dollar conversion over this period, these budgets are not easily converted to corresponding US budgets.

**Figure IV.1**
**Growth of Budgets for Fusion Research in Japan in Billion Yen (B¥)**

Another factor to consider has been the relative independence of university research in Japan. Following World War II, the constitutional right of the universities to be independent of governmental interference was exercised and university professors were free to choose their staff and area of research. Staff salaries were independent of project operating funds. However, approval and funding of a construction project was determined by the national government. After completion of construction, operating funds were assigned for 10 years, with a gradual reduction of funding after that. In addition, after termination of a project, a small fraction of the operating funds continued for seven years to ease that termination, another source of flexibility for universities. This practice is being discontinued.

This has been the historical context for alternate confinement research in Japan that has influenced its development over the past six years that are covered in this report. However, as will be discussed in Section IV.B.2, this context is changing.

a. Alternate Confinement Approaches

Alternate confinement research in Japan covers the study of all confinement approaches other than tokamaks. However, here we exclude the research on inertial confinement fusion: the high-power Lekko $CO_2$ and Gekko glass lasers and the high-power Reiden IV light ion beam at the Osaka University Institute of Laser Engineering and the particle beam research at the Technical University of Nagaoka. This research is described adequately elsewhere (Yamanaka, 1987; Yamanaka, 1985) and is not part of the magnetic confinement fusion program covered in this assessment.

A general classification of the different magnetic confinement schemes (Sekiguchi, 1987) based on the relative strengths and geometry of the toroidal (or axial) and poloidal magnetic fields is illustrated in Figure IV.2. The principal magnetic confinement concepts being studied in Japan are the stellarator, the tokamak, the RFP, the compact torus (spheromaks and FRCs), and the tandem mirror. Among these devices, the tokamak (discussed in Chapter III) is dominant overall, and the stellarator is dominant among the alternate (non-tokamak) concepts in Japan.

The stellarator, tokamak, and RFP are toroidal confinement devices with toroidally nested, closed flux surfaces that differ in how the toroidal $(B_t)$ and poloidal $(B_p)$ fields are created. In the tokamak, the stronger toroidal field is created using external coils, and the weaker poloidal field is created by an internal plasma current. In a stellarator, both fields are created by currents in external windings and there is no net plasma current. In an RFP, there is a weak external toroidal field and a large plasma current with the result that the toroidal and poloidal fields are comparable in size. These three devices are the most developed and have obtained the best plasma performance.

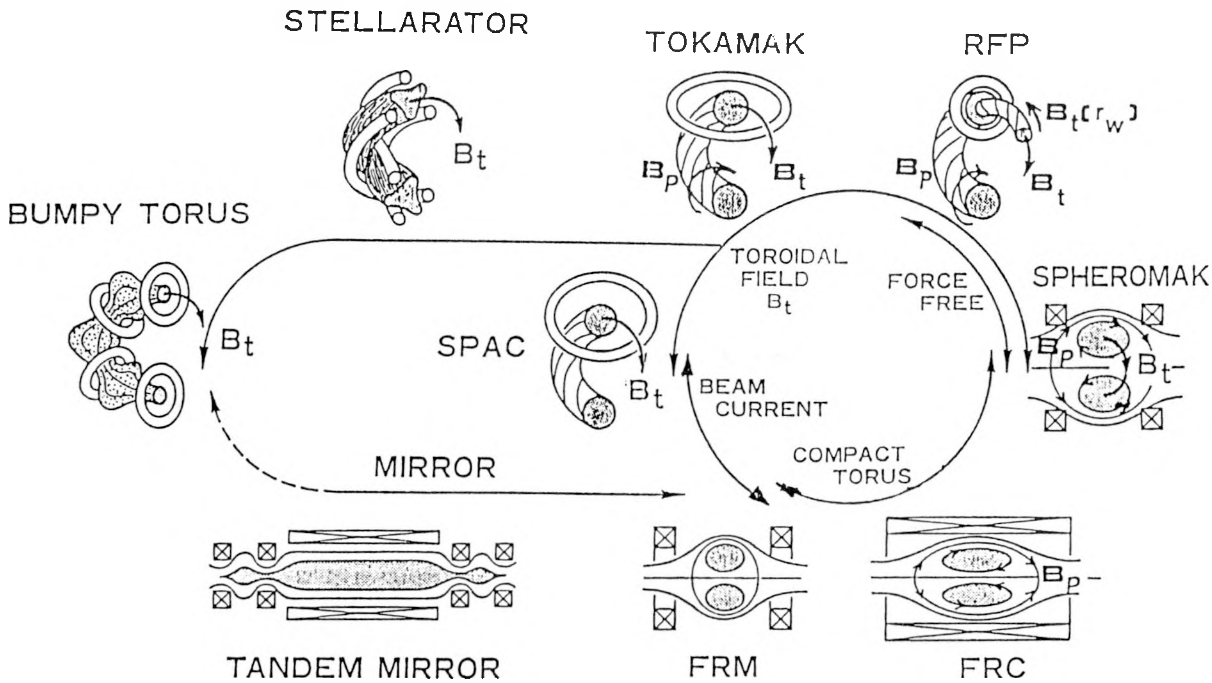



**Figure IV.2**
**Generic Classification of Magnetic Confinement Concepts by Relative Strength and Geometry of Toroidal and Poloidal Fields**

The spheromak, field reversed configuration (FRC), and tandem mirror rely upon a magnetic mirror field. The tandem mirror relies upon end plugs (minimum-B mirror regions) and thermal barriers (electrostatic potential) to reduce the end loss. Although simpler mirror configurations had been studied during this period in Japan, the tandem mirror has become the dominant mirror geometry worldwide. The spheromak and FRC (referred to as compact tori) are topologically similar but differ in their elongation; the spheromak with $B_t \sim B_p$ is oblate and the FRC with $B_t = 0$ is prolate.

This chapter will discuss stellarators, mirrors, reversed field pinches, and compact tori. Listings of the main device and plasma parameters for these experiments are given in the reference *World Survey of Activities in Controlled Fusion Research.* An excellent source of more detailed recent information is the biennial *Proceedings of the International Conference on Plasma Physics and Controlled Nuclear Fusion Research* published by the International Atomic Energy Agency (IAEA). Comparative summaries of the world research on alternate confinement approaches are given in the summaries of these conferences (Pease, 1985; Sekiguchi, 1987; Sheffield, 1989).

The Field Reversed Mirror (FRM) is not pursued in Japan and work on the relativistic electron ring devices SPAC (Mohri, 1985) and Bumpy Torus (Fujiwara and Ikegami, 1985) at IPP-Nagoya has stopped in order to transfer people to the stellarator programs, CHS and LHD. The relativistic electron ring programs will not be discussed here in detail. The SPAC series of experiments (1973-1987) studied the potential for injection of relativistic electron beams into toroidal devices. The latest in the series, SPAC-VII (Narihara et al., 1987), injected a 1.3 MeV, 30 kA, 1 μs electron beam into a 0.08-$m^3$ magnetic trap with $B$ = 0.1 to 0.2 T. The Nagoya Bumpy Torus devices (1977-1986) NBT-1 ($R_0$ = 1.6 m, $a$ = 0.1 m, $B_0$ = 0.3 T) and NBT-1M ($R_0$ = 1.4 m, $a$ = 0.1 m, $B_0$ = 1 T) used electron cyclotron heating to create stabilizing hot-electron poloidal rings in a set of toroidally-linked magnetic mirrors, such as that used in the US ELMO Bumpy Torus (EBT) experiment. NBT-1M (Ikegami et al., 1987) achieved beta values up to five percent, $n_e \approx 10^{19}$ $m^{-3}$, and $T_i \approx$ 100 eV (with ion cyclotron heating), but the transport was anomalously high.

The term stellarator is widely used to describe the broad class of magnetic confinement devices whose helical (toroidal plus poloidal) magnetic fields are created by currents in external windings (no net plasma current required). The stellarator (Spitzer, 1958) class includes classical stellarators (with toroidal field coils and opposite currents in adjacent helical windings), torsatrons or heliotrons (without toroidal field coils and unidirectional currents in half as many helical windings), and helical-axis devices (asperators, heliacs, helias). The different terms reflect both the variety of coil configurations used to create the magnetic confinement geometry and the history of the development of the concept.

The stellarator variant in widest use today is the torsatron (called a heliotron at the Kyoto University Plasma Physics Laboratory). This concept was invented about the same time by Koji Uo of Kyoto PPL, who called it a heliotron (Uo, 1971), and by a group at Fontenay-aux-Roses (France), who called it the torsatron (Gourdon et al., 1969). The term torsatron came to be widely accepted (and is used in the United States) because of the wider familiarity with the Fontenay-aux-Roses work and the fact that Koji Uo had also used the name heliotron to describe linear (open ended) devices with undirectional helical windings (Uo, 1961) and toroidal devices with an alternating ring-cusp geometry (Heliotrons B and C). Professor Uo should be more widely recognized as the co-inventor of this confinement concept. As a compromise, the term helical system or stellarator/heliotron is now used in Japan (and elsewhere in interactions with the Kyoto PPL) for stellarators.

b. Principal Efforts

The main centers for alternate confinement research in Japan are listed in Table IV.1, along with the principal research efforts during the 1980s and the key persons. Some of the experimental efforts have since been terminated. The largest of these centers (by a factor of 2) was the Institute for Plasma Physics at Nagoya University, which traditionally had been the center for alternate concept research in Japan. IPP-Nagoya has always had a variety of experimental approaches, whereas the other research centers have tended to focus on one approach. For example, in 1985, there were five different experiments (the JIPP T-IIU tokamak, the NBT bumpy torus, the RFC-XX-M cusp mirror experiment, the STP-3 (M) pinch, and the SPAC-VII relativistic electron ring experiment) at IPP-Nagoya, in addition to design studies for the CHS torsatron and a crescent-shaped ATX tokamak experiment. The previous director of IPP-Nagoya, Professor Kakihana, tried to focus the Nagoya activities on one project, a low-Q D-T tokamak called the R-Project, to be built at a new site (Toki) near Nagoya. However, the R-Project was not approved, the Toki site was appropriated for a new MOE fusion laboratory with most of the staff to come from IPP-Nagoya, and IPP-Nagoya was closed in May 1989. While some staff for the new MOE laboratory will also come from the other university laboratories, most of the other research centers listed in Table IV.1 will continue their work, albeit at a reduced level.

## Table IV.1
## ALTERNATE CONFINEMENT ACTIVITIES IN JAPAN

| Institution | Activities | Main Experiments | Key Person |
|---|---|---|---|
| Institute of Plasma Physics, Nagoya University | Stellarator<br>Mirror<br>RFP<br>REB Ring<br>Bumpy Torus | CHS<br>*RFC-XX-M<br>*STP-3 (M)<br>*SPAC-VII<br>*NBT-1M | K. Matsuoka<br>T. Sato<br>K. Sato<br>A. Mohri<br>M. Fujiwara |
| Plasma Physics Laboratory, Kyoto University | Stellarator | Heliotron DR | S. Morimoto |
| Plasma Research Center, Tsukuba University | Mirror<br>Mirror | GAMMA-10<br>*GAMMA 6 | S Miyoshi<br>S. Miyoshi |
| Electro-Technical Laboratory, Tsukuba | RFP<br>RFP | TPE-1RM-15<br>*TPER-1R (M) | K. Ogawa<br>K. Ogawa |
| Osaka University | FRC<br>FRC<br>Spheromak | PIACE-II<br>OCT series<br>CTCC-II | T. Ishimura, S. Goto<br>T. Ishimura, S. Goto<br>K. Watanabe |
| University of Tokyo | RFP | REPUTE-1 | N. Inoue,<br>K. Miyamoto |
| Nihon University, Tokyo | RFP<br>RFP<br>FRC | Noncircular RFP<br>ATRAS<br>NUCTE-II, III | K. Yokoyama<br>K. Saito<br>Y. Nogi |
| Hiroshima University, Institute for Fusion Theory | Theory | -- | K. Nishikawa |

* Experiment terminated

## 2. Redirection of Alternate Confinement Research

### a. Decision Process and Result

Up through 1983, the MOE funding for fusion had been steadily growing each year (Sekiguchi, 1988; Lyon, 1985). In 1983, it reached ¥12.5 billion, but dropped to ¥6.9 billion in 1984 and ¥7.7 billion in 1985 (due mainly to the decrease in construction funding from ¥8.9 billion in 1983 to ¥2.5 billion in 1984 and ¥2.6 billion in 1985). Because the total MOE budget was foreseen to be approximately constant, researchers in other areas funded by MOE (high-energy physics, space sciences, and biotechnology) were not supportive of the desire by the university plasma physics community to return to the 1983 level. This pressure led to a requirement by MOE in October 1984 that the entire plasma physics community agree on a single approach for a large next step in order for funding to continue and that this new large experiment would be built at a new MOE (not university) laboratory at Toki. The 1985 review of the Japanese alternate concept program was based on the reports of four working groups: advanced tokamaks, helical systems (stellarators), open systems (mirrors), and inertial confinement (lasers and particle beams). These groups were to select within their area a concept for a next-step experiment and then an oversight committee would propose one for approval (Lyon, 1985).

The stakes were high. Of an assumed MOE budget of ¥100 billion over a 10-year period, half or more would be for the new device (plus additional money for the site and facilities), and the remainder would be for the continuation of the other experiments and for new, small-scale experiments. The MOE-funded TRISTAN accelerator facility at Tsukuba had cost about ¥80 billion, so this budget seemed reasonable.

In February 1986, the Committee on Nuclear Fusion Scientific Research of MOE recommended that: (i) it is appropriate for the university sector to select the helical-plasma system for further machine upgrading as a complement to the JAERI's major tokamak approach; (ii) the activities on the other types of plasma confinement system (tandem-mirror, laser and particle-beam inertial confinement, and RFP) should be maintained as far as possible, for future possible innovative developments; and (iii) if necessary, a new institute, which will be under the direct control of the MOE and be tentatively called The Institute of Nuclear Fusion Science and Technology, will be established on the basis of the present IPP, Nagoya University, the Heliotron Research Center, Kyoto University, and staffs in other Japanese universities (Sekiguchi, 1988).

b. The New MOE Laboratory and the Large Helical Device

The recommendations of the MOE panel were accepted by the Japanese government and are now being implemented. A tract of land (47 hectares or 116 acres) has been purchased at Toki (one hour north of IPP-Nagoya) and is being leveled for the new MOE National Institute for Fusion Science. This new laboratory will be operated directly by MOE, and not by Nagoya University, even though the site was originally planned for IPP-Nagoya's D-T tokamak, the R-project, which was not approved. The first buildings are scheduled for completion on the new site in 1990, and the rest of the site should be complete by 1993 when all the staff should have moved to the new site.

The new institute will have a major impact on alternate confinement research in Japan, because it is meant to be the center for Japanese university fusion research and will have the world's largest stellarator as its focus. IPP-Nagoya ceased to exist in May 1989 and almost all of its members have become part of the new MOE laboratory. The few that remain at Nagoya University will no longer be associated with fusion research. One-half of the Kyoto University PPL group will join the new institute and the Heliotron E experiment (after a few more years of operation in support of the Large Helical Device [LHD] and with much reduced resources) will be used for training students. The present Hiroshima University Institute for Fusion Theory group will be moved to the new site as well. The 87 Japanese fusion scientists will be drawn from IPP-Nagoya (73), Kyoto PPL (9), and Hiroshima University Institute for Fusion Theory (4). In addition, up to one-third of the staff may be guests (from other laboratories in Japan and abroad).

The director of the new institute is Atsuo Iiyoshi, presently head of Kyoto PPL and head of the LHD planning office for the last few years. He was chosen for his expertise even though he is 5 to 10 years younger than the age traditionally reserved for such a post, and considerably younger than a number of others from IPP-Nagoya.

The experiment chosen for the new institute is presently called the Large Helical Device (previously called LHS from an earlier name, the Large Helical System). There is, as yet, no official name for the experiment. A sketch of the main experimental building for the LHD is shown in Figure IV.3. The LHD room itself is 50 meters by 100 meters and has walls and a ceiling of 2-meters-thick concrete for D-D operation. The site costs (land, site preparation, buildings, utilities, and power supplies) and the personnel costs (staff and administration) are not included in the estimated ¥62 billion (~ $463 million at the May 1989 exchange rate of 135 ¥/$) cost of the device, its plasma heating, and diagnostics (Iiyoshi, 1989). Budget pressures to reduce the cost of the LHD may reduce this by 10 to 20 percent. The total project cost is probably more than $750 million. Thus LHD is roughly comparable to the US TFTR in scope. Official approval of the first year's budget has been obtained, but the total LHD cost must be reviewed in a year for final budget approval. The schedule calls for detailed design during 1989 and 1990, start of construction in 1991, and start of operation in 1995 (Motojima, 1989). The sheer scope of the LHD project and the resources it will require will dominate the alternate confinement research effort in Japan. It will certainly be the premier stellarator in the world.

### 3. Industrial Involvement

Alternate confinement research in Japan depends heavily upon industrial participation in all phases of an experiment: R&D, concept development, detailed design, construction, commissioning, repairs, and upgrading both of the device and of its auxiliary equipment (plasma heating, controls, and diagnostics). This strong reliance on industry for anything other than a tabletop experiment is due to the relatively small number of technical staff at the universities limited by the number of faculty positions and the corresponding number of technical support positions. Because of the lack of expertise and engineering support in the universities, industry provides turn-key facilities and is called in to do all repairs and upgrading. This is how the relatively small Heliotron group at Kyoto PPL was able to obtain and maintain what (until ATF) had been the world's largest stellarator, and the much smaller CHS group at IPP-Nagoya was able to obtain in one year a front-line stellarator experiment, all without an engineering staff. For example, in the case of CHS, detailed blueprints for its major components were available from the potential suppliers (Hitachi, Mitsubishi, and Toshiba—the dominant companies in fusion device fabrication in Japan) more than four months before the government approved the project and construction had started several months before the official funding was available.

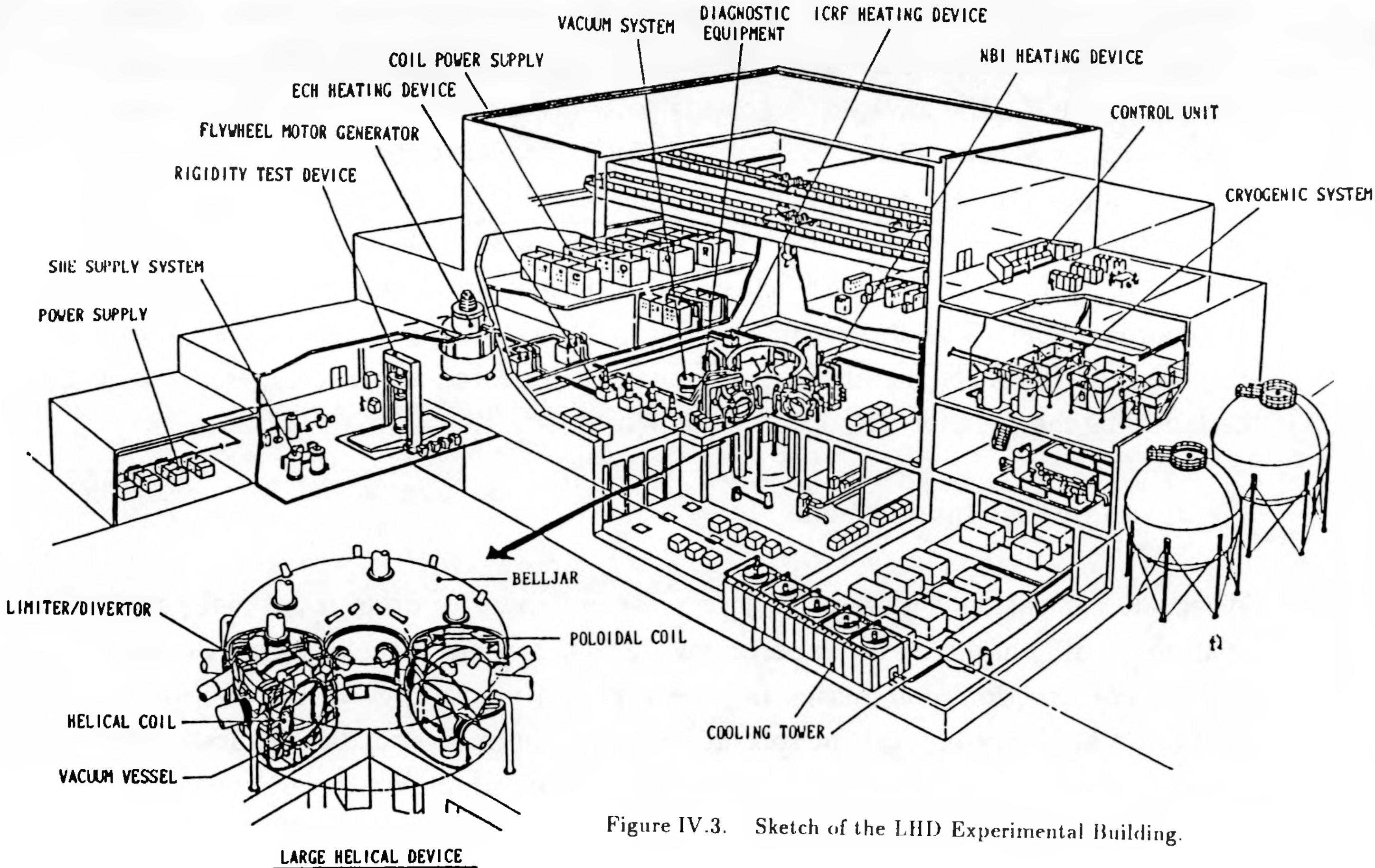


Figure IV.3. Sketch of the LHD Experimental Building.

**Figure IV.3**
**Sketch of the LHD Experimental Building**

The benefits to the university groups go beyond that described above because the experiments are partially subsidized by industry. Hitachi absorbed some of the cost of the CHS torsatron at IPP-Nagoya, and Mitsubishi gave the Heliotron DR torsatron to Kyoto PPL free of charge upon a request from the previous director, Koji Uo. The three companies also have small working experiments themselves to better understand the construction and operation of these devices, and scientists from these companies also work on the larger university experiments. These companies also share the work. If one company is awarded the contract for construction of an experiment, it will subcontract some of the work to the other two. The purpose of this approach is to better position the companies for the large fusion projects (JT-60, LHD, and possible FER or ITER work).

A negative aspect to the above industry-laboratory interaction is that the companies take a very conservative engineering approach because their design must, as a matter of honor, meet the performance specifications and be on schedule. The drawback with this approach is less performance than might be obtained with more aggressive engineering. Another drawback is that there is no on-site capability to make changes and improvements in a device, so the evolutionary upgrading and improving of an experiment that occur in the United States are more difficult and less frequent in Japan.

This laboratory-industry interaction works well when there is close coordination between the experimental group and the industry and has led to some excellent turnkey facilities, notably the Heliotron E at Kyoto PPL, the CHS torsatron at IPP-Nagoya, and the TPE-1RM-15 RFP at ETL. However, there have been some notable failures when good communication did not exist. The original construction of the GAMMA-10 tandem mirror facility at Tsukuba University had the end fans aligned, rather than being orthogonal. The REPUTE-1 RFP at Tokyo University was designed with large access ports that spoiled the toroidal symmetry and created large field errors due to eddy currents in the thin vacuum shell. It never worked well as an RFP and is now being used for ultra-low-q tokamak studies.

### 4. International Collaboration

International collaboration, primarily through the personnel exchanges occurring under the US-Japanese Cooperation in Fusion Agreement, is very important to alternate confinement research in Japan, because it brings experienced people, and sometimes equipment, to Japanese university experiments that have relatively small staffs. The theoretical exchanges are also of value to Japan because of the much larger and broader US theory program in alternate concept studies. Table IV.2 gives the number of person-weeks in the US-Japanese exchanges in the alternate concepts areas in recent years. The total averages to about four person-years each year. Here theory, which amounts to about 20 percent of the exchanges, also includes studies of next-generation experiments and reactors. The decline in the tandem mirror area (and earlier in the bumpy torus area) is due to the phasing out of these programs in the United States during this period. Multinational collaboration (for example, IEA Implementing Agreements on Stellarators and RFPs) is reserved increasingly for workshops.

## C. STELLARATORS

### 1. Accomplishments and Capabilities

Four groups have been active in stellarator research in Japan: Kyoto University Plasma Physics Laboratory (or Heliotron Laboratory), Nagoya University Institute of Plasma Physics, Tohoku University at Sendai, and Tokyo University. The stellarator experiments presently operating at these institutions are listed in Table IV.3. The stellarator researchers and their areas of expertise are listed in Table IV.4. The dominant group has been the Heliotron group at Kyoto PPL. This group is the largest and has the greatest capability in the experimental area (device size, heating power, diagnostics, staff) as well as a small, but strong, theory group. The IPP-Nagoya group has made important contributions in the past on classical stellarators, dropped this line for a while, and has returned with a significant low-aspect-ratio torsatron experiment in preparation for the IPP-Nagoya group's work on LHD. The other two groups are relatively small.

**Table IV.2**
**US-JAPANESE EXCHANGES IN ALTERNATE CONCEPTS**
(Number of Person-Weeks)

| Area | FY 1989 | | FY 1988 | | FY 1987 | | FY 1986 | |
|---|---|---|---|---|---|---|---|---|
| | Exp. | Th. | Exp. | Th. | Exp. | Th. | Exp. | Th. |
| Stellarator | | | | | | | | |
| To Japan | 35 | 17 | 17 | 12 | 6 | 36 | 40 | 15 |
| To United States | 34 | - | 14 | 32 | 21 | - | 9 | 4 |
| Tandem Mirror | | | | | | | | |
| To Japan | 4 | - | 14 | - | 36 | 6 | 80 | - |
| To United States | 8 | - | 16 | - | 5 | - | 65 | - |
| RFP | | | | | | | | |
| To Japan | 22 | - | 12 | 3 | 6 | - | 2 | 5 |
| To United States | 32 | - | 13 | 13 | 22 | 4 | 26 | 13 |
| Compact Torus | | | | | | | | |
| To Japan | 4 | 11 | 12 | 9 | 14 | 3 | 20 | 15 |
| To United States | 30 | 12 | 25 | - | 26 | - | 26 | 19 |

a. The Heliotron Experiments

There has been a long series of Heliotron experiments at Kyoto PPL, dating back to 1959 (Uo, 1985). The first helical heliotron (torsatron) at Kyoto PPL was Heliotron D (1970) with major radius $R$ = 1.09 m, minor radius $a$ = 0.1 m, and magnetic field $B_0$ = 0.5 T. The earlier heliotrons used an alternating ring-cusp geometry and were called poloidal heliotrons. Heliotron D was followed by Heliotron DM (1975) with $R$ = 0.45 m, $a$ = 0.044 m, and $B_0$ = 1 T. The two heliotrons operating during the 1980s are Heliotron E (1980) and Heliotron DR (1981). The device parameters are given in Table IV.3. The relatively small Heliotron DR has been used for studies of different types of ion cyclotron heating (ICH) antennas and for high-power-density electron cyclotron heating (ECH) in plasmas with densities above cutoff (Motojima, 1988). Overdense currentless ECH plasmas were heated effectively at the electron cyclotron frequency as well as at the second and third harmonic. Heating was also possible at the fourth and fifth harmonics of $\omega_{ce}$ with a small amount of additional Ohmic heating (< 1 kW). The plasma stored energy was limited to $\langle\beta\rangle$ = 0.5 percent in all cases.

**Table IV.3**
**STELLARATOR EXPERIMENTS IN JAPAN**

| Institution | Device (Operation Dates) | Type (Field Periods) | Major, Minor Radius (m) | Magnetic Field (T) | Pulse Length (s) | Heating Power, Type (MW) |
|---|---|---|---|---|---|---|
| Plasma Physics Laboratory, Kyoto University | Heliotron E (1980 - ) | Torsatron (19) | 2.2, 0.2 | 2.0 | 0.5 | 4.0, NBI<br>1.0, ECH<br>3.0, ICH |
| | Heliotron DR (1981 - ) | Torsatron (15) | 0.9, 0.07 | 1.0 | | |
| Institute of Plasma Physics, Nagoya University | CHS (1988 - ) | Torsatron (8) | 1.0, 0.2 | 1.5 | 2 | 3-4, NBI<br>0.2, ECH<br>0.5, ICH |
| Tohoku University, Sendai | Asperator-NP4 | Helical axis | 1.53, 0.1 | 0.5 | | |
| | Asperator-H (1988- ) | Heliac | 0.42, 0.07 | 0.35 | | |
| Tokyo University | SHATLET-M | Modulator torsatron | 0.035 | 0.3 | | |

Until ATF (Oak Ridge National Laboratory [ORNL]) and Wendelstein VII-AS (Garching, West Germany) started operation in 1988, Heliotron E was the world's largest stellarator experiment. It has achieved some of the highest-performance plasma parameters obtained in stellarators and has significant plasma heating (7 MW) and diagnostic capability. Heliotron E has obtained $T_i$ = 1.6 keV with 3.5 MW neutral beam injection (NBI) at $\bar{n}_e = 2.6 \times 10^{19}$ m$^{-3}$, $\langle\beta\rangle$ = 2 percent with 1.8 MW NBI at $\bar{n}_e = 9 \times 10^{19}$ m$^{-3}$, and $\bar{n}\tau_E = 5 \times 10^{18}$ m$^{-3}$ with 1.8 MW NBI at $n_e$ = $1.4 \times 10^{20}$ m$^{-3}$. The good performance of Heliotron E was an important factor in the choice of a torsatron configuration for the Advanced Toroidal Facility (ATF) at Oak Ridge. Its earlier program was more concerned with improving param-

## Table IV.4
## STELLARATOR RESEARCHERS IN JAPAN

**IPP-Nagoya (CHS Group)**

Tsuneo Amano—Transport theory
Masami Fujiwara—CHS design
Minoru Hosokawa—ECH
Katsumi Ida—Spectroscopy
Harukazu Iguchi—VUV, HIBP
Takako Kato—Spectroscopy
Shin Kubo—ECH
Kuniaki Masai—Spectroscopy
Keisuke Matsuoka—CHS head
Shigeru Morita—X-rays
Kiyohiko Nishimura—CHS design
Shoichi Okamura—Configuration
Tatsuo Shoji—ICH
Shuugo Tanahashi—CHS design
Hiroshi Yamada—Diagnostics
Kozo Yamazaki—CHS design

**Kyoto University PPL (Heliotron Group)**

Koji Uo - Director (-1988)
Atsuo Iiyoshi—Director (1988-89)
Kiyoshi Hanatani—Orbit theory
Kimitake Itoh—Transport theory
Hiroshi Kaneko
Katsumi Kondo
Tohru Mizuuchi—Plasma-wall
Shigeyuki Morimoto—Heliotron-DR
Osamu Motojima—Heliotron-E head
Takashi Mutoh—ICH
Yuji Nakamura—MHD theory
Tokuhiro Obiki—NBI, divertors
Hiroyuki Okada—HIBP
Fumimichi Sano—NBI
Motoyasu Sato—ECH
Shigeru Sudo—Thomson scattering
Yasuhiko Takeiri—NBI
Masahiro Wakatani—MHD theory
Hideki Zushi—Charge exchange

**LHD Planning Group**

Atsuo Iiyoshi—Head
Masami Fujiwara—Assoc. Head
Junji Fujita—Diagnostics
Osamu Motojima—Torus, SC coils
Takashi Mutoh—RF heating
Tokuhiro Obiki—Divertor
S. Ohshima—MOE
N. Ohyabu—Divertor
Teruyuki Sato—Heating
Y. Takeiri—Transport
M. Takeo—Superconducting coils
Jiro Todoroki—MHD theory
Masahiro Wakatani—Transport theory
Kozo Yamazaki—Diagnostics

**Tohoku University (Asperator Group)**

S. Kitajima
M. Takayama
N. Takeuchi
H. Watanabe

**Tokyo University (SHATLET Group)**

Y. Iida
M. Katsurai
S. Kogoshi
H. Seki
H. Ohsaki
H. Okuyama

eters than with physics understanding, but in recent years more attention has been given to careful physics studies with the result that important work has been done in a number of areas: scaling of confinement time and maximum density with device parameters; comparison of electron and ion heat diffusivities with neoclassical values; plasma heating with ECH, ICRF, and NBI; reversal of radial electric field at low density; study of helical divertors; comparison with theoretical beta limits; identification of MHD behavior; and understanding of orbit confinement (Uo et al., 1987; Obiki et al., 1989).

b. The IPP-Nagoya Experiments

Stellarator studies have been conducted at IPP-Nagoya since 1970 (Fujita and Matsuoka, 1985). JIPP-Ia (1970 to 1973) was an $l = 3$ stellarator with $R = 0.5$ m and $B_0 = 0.4$ T. It was modified to become JIPP-Ib (1973 to 1976), a stellarator with both $l = 2$ and $l = 3$ helical windings. The first series of stellarator experiments at IPP-Nagoya ended with JIPP T-II which could be operated either as a classical stellarator or as a high-aspect-ratio tokamak. JIPP T-II had $R = 0.91$ m, $a = 0.17$ m, $B_0 = 3$ T, $l = 2$ helical windings, toroidal field coils, and an ohmic heating transformer. It operated first as a tokamak (1976-1983) and then as a stellarator (1979-1981). As a stellarator, its main contributions were studies of confinement scaling in ohmically heated plasmas (Fujita et al., 1981). In tokamak-stellarator hybrid operation, major disruptions could be suppressed for $\tau > 0.14$ and the stellarator field had a stabilizing effect on the positional instability. Comparisons were made between tokamak performance and stellarator performance with different types of plasma heating (neutral beam, lower hybrid, electron cyclotron, and ion cyclotron); the heating efficiencies were approximately the same in both modes of operation. However, JIPP T-II was far from optimum in either of these configurations. Its main limitations as a stellarator were a low rotational transform ($\tau = 1/q = 0.1$-$0.3$) without plasma current and reliance on plasma current (which deteriorates stellarator confinement) for higher $\tau$. Its main limitations as a tokamak were its high aspect ratio, small plasma radius, low plasma current, and limited access. It was modified in 1983 for more effective tokamak operation (JIPP T-IIU).

After a stellarator was selected for the next large step in the Japanese alternate confinement program, IPP-Nagoya initiated a new stellarator experiment, CHS (Compact Helical System), a low-aspect-ratio torsatron with the same magnetic configuration as ATF but of a type known as a Compact Torsatron (Carreras et al., 1988). CHS has the same average plasma radius (0.2 m) as Heliotron-E, but much smaller major radius (1 m versus 2.2 m). CHS has a relatively small but energetic staff and limited resources, but it has already performed well (Matsuoka et al., 1989). It began operation in July 1988 and has studied currentless plasma production with 28 GHz ECH and various types of ICH (slow wave, whistler, ion Bernstein wave). Typical plasma parameters with 120 kW ECH at $B$ = 1 T are $n_e$ = 2-6 x $10^{18}$ $m^{-3}$, $T_e$ = 0.3-0.9 keV, and $T_i \leq$ 0.1 keV. ICRF plasma production gives plasma parameters $n_e$ = 5-6 x $10^{18}$ $m^{-3}$, $T_e$ = 0.2-0.3 keV, and $T_i$ = 0.2-0.3 keV. Although the main purpose of CHS is preparation of the IPP-Nagoya staff for a major role on LHD, it will also make a significant contribution to stellarator research because of its uniqueness (low-aspect-ratio torsatron).

### c. Asperator Group, Tohoku University

This small group has studied circular-cross-section, helical-axis stellarators (which they call asperators) for many years. The latest of these were the small (0.02 $m^3$ plasma volume) Asperator-NP3 with 16 field periods and the larger (0.43 $m^3$ plasma volume) Asperator-NP4 with 8 field periods. With the recent worldwide interest (the Australian SHEILA and H-1, and the Spanish TJ-II) in flexible heliacs (3 or 4 field periods, bean-shaped cross section plasmas, large excursion of the helical axis), the Sendai group has constructed Asperator-H (Watanabe et al., 1989) which is a scaled-down version of the TJ-II device ($R$ = 0.42 m versus $R$ = 1.5 m) with 4 field periods and a 0.046 $m^3$ plasma volume but without the $l$ = 1 winding which gives it flexibility. It began operation in 1988.

### d. Tokyo University

This group is more interested in studies of laser-produced plasmas than in the magnetic configuration used to contain them. This group has tried a variety of magnetic confinement geometries in the past; the stellarator is the latest. The particular stellarator variant used is the Oak Ridge Symmotron (modular torsatron) concept. The SHATLET-M (Ohsaki et al., 1989) experiment is of interest because no group had tested this stellarator variant before. High values of beta ([β] = 3 to 5 percent with $n_e \approx 10^{19}$ m$^{-3}$ and $T_i \approx 100$ eV) were obtained in this experiment (Seki et al., 1989).

e. Theory and Computation

There are relatively few stellarator theorists in Japan, but their work is competitive with that done in the United States and Europe. The principal contributors are Masahiro Wakatani (MHD and transport), Kiyoshi Hanatani (energetic particle orbits), Kimitake Itoh (transport), and Yuji Nakamura (MHD) from Kyoto PPL; and Jiro Todoroki (MHD), Tsuneo Amano (transport), and Tetsuo Kamimura (particle simulation) from IPP-Nagoya. The work of Wakatani and his students and of Kamimura is of leading quality. The work has been heavily directed toward design and optimization of the Large Helical Device (LHD) and interpretation of Heliotron-E results (Todoroki et al., 1989). They have effectively extended their capabilities in this work through extensive use of US codes in the MHD and transport areas to supplement their own codes, and through collaborations with US theorists at ORNL, PPPL, and NYU.

**2. Outlook**

Because of the enormous resources (funding, but more importantly experienced technical staff) required for the LHD project, there will be, paradoxically, a decline in the productivity of the Japanese stellarator program through the design and construction phase of the LHD project (through 1995). Already some of the best people from the Heliotron group have left to join the LHD group and the Heliotron operating budget has been reduced. There will also be an increasing participation in the US ATF experiment because of its close similarity to LHD. Part of the staffing need can be met from abroad; three to four guest professorships are being created at the new Toki Institute, housing for foreigners is being built, and eventually up to one-third of the final staff may be from other laboratories in Japan and from outside Japan.

Heliotron-E is a well-documented experiment with the best plasma performance and significant heating and diagnostic capability. It will take time for ATF and Wendelstein VII-AS to reach the same maturity of operation. Therefore, Heliotron-E could continue to make leading contributions. However, it is planned for Heliotron-E to operate at a reduced level for another two to three years and then be used as a Kyoto University teaching facility. The main task for Heliotron-E for the next few years will be to gain information needed in the design of LHD, particularly in the areas of divertor design and access to second stability.

CHS will also operate for another two to three years. It began operation in July 1988, so it has a full program to complete on auxiliary heating of low-aspect-ratio torsatrons. Its main relevance to the LHD project will be to develop more experience in the IPP-Nagoya staff and to test ideas for use on LHD because the CHS magnetic configuration is also similar to that of LHD. CHS will be dismantled in about three years and it may be reassembled later at the Toki site.

The other reason for the relative decline of productivity in the Japanese stellarator program in the next five years is the sudden upswing in activity elsewhere. Two larger devices (ATF in the United States and Wendelstein VII-AS in West Germany) came into operation in 1988, and three more (Uragan-2M in the Soviet Union, H-1 in Australia, and TJ-II in Spain) will begin operation in the next few years. However, when LHD starts operation in 1995, Japan will certainly dominate the world stellarator program. The theory effort should also become stronger in a few years with the consolidation of the theory effort at Toki.

A sketch of the Large Helical Device (Motojima et al., 1989) is shown in Figure IV.4. The device parameters for LHD are compared with those of the present largest Japanese (Heliotron-E) and world (ATF) stellarator experiments in Table IV.5. LHD is patterned closely after the ATF device but will be a factor of 2 larger in linear dimensions and field and will have much higher heating power (20 MW) and improved confinement. With its superconducting coils, it will be capable of steady-state operation at full field, limited only by the steady-state heating power available (currently 4 MW).

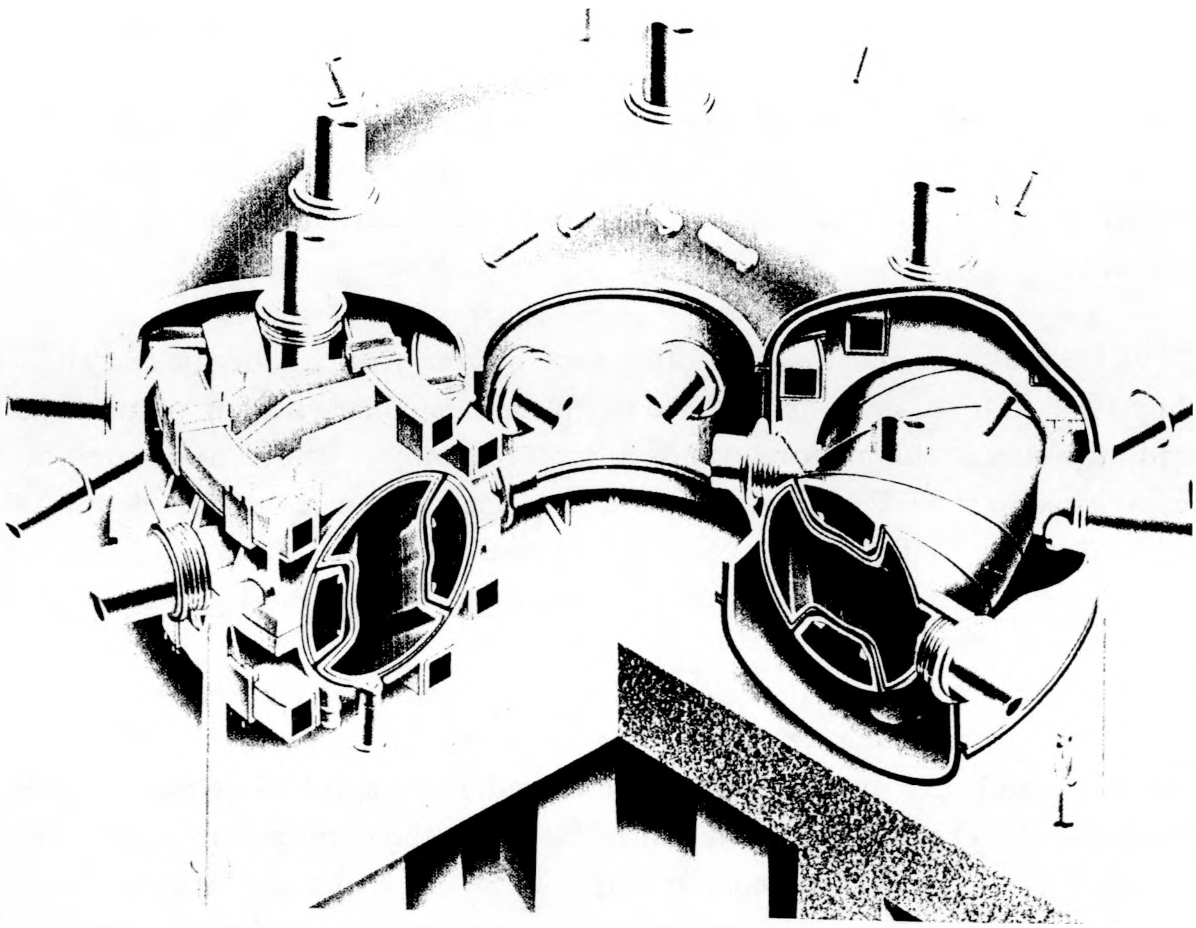


**Figure IV.4**
**Sketch of the Large Helical Device**

The target plasma parameters (Design Group, 1988; Iiyoshi, 1988) for LHD are: (1) $\bar{T}_i$ = 3-4 keV, $\bar{n}$ = $10^{20}$ m$^{-3}$, $\tau_E$ = 0.1-0.3 s at $B$ = 4 T in the high $n\tau T$ mode; (2) $T_i(0)$ = 10 keV, $\bar{n}$ = 2 x $10^{19}$ m$^{-3}$ at $B$ = 4 T in the high $T_i$ mode; and (3) $\langle\beta\rangle \geq 5$ percent at $B$ = 1-2 T in the high beta mode.

**Table IV.5**
**COMPARISON OF LARGE HELICAL DEVICE TO OTHER STELLARATORS**

| Parameter | LHD | Heliotron-E | ATF |
|---|---|---|---|
| Plasma Size | | | |
| Major radius (m) | 4.0 | 2.2 | 2.1 |
| Average minor radius (m) | 0.5-0.6 | 0.2 | 0.27 |
| Plasma aspect ratio | 7-8 | 11 | 7.8 |
| Plasma volume ($m^3$) | 20-30 | 1.7 | 3 |
| Magnetic Field, Coils | | | |
| Field on axis (T) | 4 | 2 | 2 |
| Field duration (s) | $\infty$ | ~ 1 | 5 |
| No. of field periods | 10 | 19 | 12 |
| Center transform | $\gtrsim$ 0.5 | 0.5 | 0.35 |
| Edge transform | ~ 1.0 | 2.5 | 0.95 |
| Coil mirror radius (m) | 0.96 | | 0.48 |
| Helical coil current (MA turns) | 8 | | 1.75 |
| Conductor | NbTi | Cu | Cu |
| Plasma Heating | | | |
| Total power (MW) | 20 | 8 | 2.7 |
| Duration (s) | 5-10 | 0.2 | 0.3-30 |
| ECH (GHz, MW) | 110, 10 | 52, 1 | 52, 0.4 |
| NBI (kV, MW) | 250, 20 | 25, 4 | 40, 2 |
| ICH (MHz, MW) | 30-120, 9 | ~ 27, 3 | 5-20, 0.3 |

## D. MIRROR PROGRAM

### 1. Accomplishments and Capabilities

There is only one substantial mirror effort in Japan (at Tsukuba University), and only one elsewhere (in the Soviet Union) since the United States halted its large mirror program. The IPP-Nagoya RFC-XX-M mirror program on RF ponderomotive plugging of the end regions was terminated in 1988. The HIEI program at Kyoto University (in Kyoto, not at the Plasma Physics Laboratory in Uji) focusing on ICRF stabilization studies is a relatively small effort. Table IV.6 gives the central cell parameters and heating power for the principal Japanese mirror experiments in the 1980s and the Japanese mirror researchers during this period are listed in Table IV.7. The RFC-XX-M group has since joined the JIPP T-IIU group and the LHD stellarator project.

**Table IV.6**
**MIRROR EXPERIMENTS IN JAPAN**

| Institution | Device (Operation Dates) | Center Cell: Radius, Length (m) | Center Cell: Plasma Volume ($m^3$) | Center Cell: Magnetic Field (T) | Center Cell: Mirror Ratio | Heating Power, Type (MW) |
|---|---|---|---|---|---|---|
| Tsukuba University | GAMMA-10 (1983- ) | 0.2, 5.6 | 0.59 | 0.64 | 4.8 | 10, NBI<br>0.8, ECH<br>1, ICH |
| | GAMMA-6 (1978-1982) | 0.28, 2.4 | | 0.15 | 6.4 | |
| Institute of Plasma Physics, Nagoya University | RFC-XX-M (1983-1988) | 0.1, 1.5 | 0.1 | 0.35 | 2.8 | 4.2, ICH |
| Kyoto University | HIEI | 0.045, 1.20 | | 1.1 | | ICH |

a. Tsukuba University Program

The tandem mirror program at Tsukuba University Plasma Research Center (Miyoshi, 1985) started in 1978 with operation of GAMMA-6, the first device based on the original tandem mirror concept. The configuration was that of a long central mirror region with a Yin-Yang mirror set at each end to plug the end loss. It had an overall length of 7 m, a radius of 0.21 m, and a plasma volume of 0.03 $m^3$. The plasma parameters achieved were: $n_e \approx 2 \times 10^{19}$ $m^{-3}$ (end plug),

$n_e \approx 10^{19}$ $m^{-3}$ (central cell), $T_i \approx 40$ eV, and $T_e \approx 18$ eV. Its principal achievements were demonstration of an NBI-supported tandem mirror potential configuration, which supported the concept of creating a thermal barrier on the basis of a sloshing-ion distribution (Tamai et al., 1984), and validation of the Pastukhov confinement scaling law for the tandem mirror (Miyoshi et al., 1981).

**Table IV.7**
**MIRROR RESEARCHERS IN JAPAN**

| | |
|---|---|
| **IPP-Nagoya (RFC-XX-M, terminated)** | |
| Teruyuki Sato (Leader) | Ryuhei Kumazawa |
| Keizo Adati | Kiyohiko Nishimura |
| Takashi Aoki | Shoichi Okamura |
| **Kyoto University (HIEI)** | |
| R. Itatani (Leader) | H. Takeno |
| S. Inoue | Y. Yasaka |
| **Tsukuba University (GAMMA-10)** | |
| Syoichi Miyoshi (Leader) | Makoto Ichimura |
| Akiyoshi Itakura | Masaaki Inutake |
| Atushi Mase | Naohiro Yamaguchi |
| Denji Tsubouchi | Takaya Kawabe (Theory) |
| H. Hojo | Teruji Cho |
| Isao Katanuma (Theory) | Teruo Saito |
| Kameo Ishii | Y. Nakashima |
| Katsuro Sawada | Yasuhito Kiwamoto |
| Kiyoshi Katsu | |
| **Other Institutions** | |
| M. Fukao (Kyoto University) | Akio Komori (Kyushu University) |
| Yoshinobu Kawai (Kyushu University) | |

The newer (1983) GAMMA-10 experiment is larger (an overall length of 27 m, a radius of 0.5 m, and a plasma volume of 1.7 $m^3$) and has a more complicated coil configuration: a 6-m central solenoid, flanked on each end by a 4.8-m long anchor cell region with six nonplanar coils and a 2.5-m long end plug thermal barrier cell region with five planar coils. One of the distinguishing features of GAMMA-10 is the effectively axisymmetrized magnetic-field configuration, designed to reduce possible neoclassical radial transport caused by cumulative radial drifts due to the geodesic curvature of the magnetic field lines. The quadrupole mirror anchor regions that cancel the geodesic curvature are on the inside of the thermal barrier region rather than on the outside (as in the MIT TARA tandem mirror experiment). Dr. Richard S. Post of MIT played a major role in assisting in the design of this experiment.

An electron-repelling thermal barrier potential dip and an ion-confining plug potential hill are created by a combination of sloshing ion and hot and warm electron populations at each end of the axisymmetric mirror cell using neutral beam injection and electron cyclotron heating. The confining potential is approximately proportional to the thermal barrier potential depth (Cho et al., 1987) as predicted by ECRH theory; a value of 1.2 kV was obtained for a barrier depth of 0.9 kV. The Pastukhov confinement scaling holds on each magnetic flux surface. Radial transport is inferred to be smaller than axial transport for strong plugging conditions. The best central cell parameters obtained with 200 kW ICRF in the central cell are $n_e = 3.5 \times 10^{18}$ m$^{-3}$, $T_{i}\perp = 1.8$ keV, $T_i|| = 0.2$ keV, and $n_e\tau|| = 2 \times 10^{18}$ m$^{-3}$ s (Cho et al., 1989).

b. The RFC-XX-M Program

RFC-XX-M was the fourth in a series of experiments at IPP-Nagoya on RF plugging of end losses with ICH (T. Sato, 1985a). The earlier experiments had cusp fields. RFC-XX-M had a simple mirror field in the central section with an RF-plugged spindle cusp field (plug section) at each end (separated by 3 meters). The purpose was to study confinement at a few percent beta in an axisymmetric linear device. Central plasma parameters are $n_e = 2.4 \times 10^{18}$ m$^{-3}$, $T_i = 100$ eV, and $T_e = 140$ eV. Measurements of the enhanced RF electric field at the RF plug section and the RF plug potential agree with that expected for an $n = 1$ ion Bernstein mode (K. Adati, et al., 1989). The plasma potential in the central region rises to confine electrons (equalizing the ion and electron losses) in good agreement with the generalized Pastukhov formula. No strong nonambipolar loss occurs because of the axisymmetry. Earlier experiments (T. Sato et al., 1987) gave an empirical sealing for the RF plug potential up to 1 kV and a negative potential for ICRF power only. MHD modes in the central cell were stabilized with a plasma pressure in the small-volume end cusps much lower than that in the central cell.

c. The Kyoto University HIEI Program

There have been two different mirror experiments using ponderomotive stabilization but with the same name (HIEI) at Kyoto University. The earlier device (Itatani et al., 1987) was a simple axisymmetric mirror with dynamic stabilization and RF plugging. MHD-stable plasmas with $T_i > 100$ eV were produced and sustained by selecting the azimuthal mode ($m = \pm 2$ and $m = \pm 1$) of the applied ICRF. Stabilization is from the RF ponderomotive force due to the radial gradient of the RF field. The new experiment (Yasaka et al., 1989) is an axisymmetric three-cell tandem mirror (overall length of 4.6 m) with a 1-m long central cell that features ponderomotive stabilization and whistler wave heating of minority species plasmas. It began operation in 1988.

d. Theory and Computation

An active area of study by Takaya Kawabe at Tsukuba University is the potential use of a tandem mirror as a fusion neutron source. His scheme features ponderomotive stabilization and requires a large RF field and large circulating currents. Industry is also involved in these studies.

**2. Outlook**

The Tsukuba University GAMMA-10 effort is in a unique position. This group has the only tandem mirror in the world studying concept development. Furthermore, this effort has good people, good diagnostics, and a good machine. It is clearly the best group to provide information on how well the tandem mirror concept works. There are plans for some improvements (addition of 1 MW of ICRF to increase $T_i$, 0.6 MW of ECH to increase $T_e$, and cryogenic panels for pumping to reduce charge-exchange losses) and for continued operation for the next few years. However, the long-term future of the Japanese mirror program is uncertain. Although the Tsukuba group has a good experiment and a sound program, it may be affected by the resource demands for the LHD project and the weak worldwide mirror program (no significant experiments remain in the United States or Europe).

## E. REVERSED FIELD PINCH PROGRAM

### 1. Accomplishments and Capabilities

There are two major RFP efforts in Japan (Inoue, 1987), the 15-member TPE-1RM-15 group at the Electro-Technical Laboratory in Tsukuba funded by MITI, and the nine-member REPUTE-1 group at Tokyo University. N. Inoue heads the team from the Nuclear Engineering Department at Tokyo University, and Kenro Miyamoto, previously a stellarator researcher at IPP-Nagoya, heads the team from the Physics Department. The STP-3(M) effort at IPP-Nagoya has been stopped for the LHD project, and the Nihon University effort is a small one. The RFP experiments in Japan in the 1980s are listed in Table IV.8 and the RFP researchers are listed in Table IV.9.

#### a. Electro-Technical Laboratory Program

The TPE (Toroidal Pinch Experiment) program (Ogawa, 1985) was initiated in 1971 as a fast toroidal screw pinch and modified in 1975 as an RFP with fast field control. The TPE-1 experiment (1975-1977) had $R = 0.4$ m, $a = 0.05$ m, $I_p \approx 50$ kA, $n_e \sim 10^{21}$ m$^{-3}$, $T_e \approx 20$ eV, and lifetime $\tau = 0.02$ ms. Its successor TPE-1R (1977 to 1979) had $R = 0.5$ m, $a = 0.1$ m, $I_p \approx 150$ kA, $n_e \sim 10^{21}$ m$^{-3}$, $T_e \approx 30$ eV, and $\tau = 0.1$ ms. TPE-1R(M) was built in 1980 with a metal liner (the earlier experiments used glass insulating discharge tubes) for study of an RFP plasma in a slow control mode. It had higher temperature ($T_e \approx 600$ eV) and lower density ($n_e = 5 \times 10^{19}$ m$^{-3}$) and had $T_i \gtrsim T_e$ with $T_{i0}$ proportional to $I_p$, as were $n_{e0}$ and $T_{e0}$. Scaling laws for the plasma resistance ($R_p \propto I_p^{-3/2}$), input power ($P_{in} \propto I_p^{1/2}$), and the energy and particle confinement times ($\tau\ I_p^{3/2}$) were also established.

**Table IV.8**
**REVERSED FIELD PINCH EXPERIMENTS IN JAPAN**

| Institution | Device (Operation Dates) | Major, Minor Radius (m) | Plasma Current (MA) | Pulse Length (ms) |
|---|---|---|---|---|
| Electro-Technical Laboratory, Tsukuba | TPE-1RM-15 (1986- ) | 0.70, 0.135 | 0.2 | ≤ 8 |
| | TPE-1R(M) (1980-1985) | 0.50, 0.09 | 0.13 | 1.2 |
| Tokyo University | REPUTE-1 (1984- ) | 0.82, 0.20 | 0.2 | 1-2 |
| Institute of Plasma Physics, Nagoya University | STP-3(M) (1984- ) | 0.50, 0.083 | 0.15 | 1.6 |
| Nihon University, Tokyo | ATRAS | 0.50, 0.09 | 0.1 | 0.1-0.5 |
| | Noncircular RFP | 0.14, 0.10 x 0.38 | 0.06 | 0.2 |

The larger TPE-1RM-15 (Ogawa, 1987; Shimada et al., 1989) started operation in 1986 and has obtained $I_p$ = 180 kA, $n_e$ = 2-3 x $10^{19}$ $m^{-3}$, $T_e \approx$ 800 eV, and $t_{pulse}$ = 7-8 ms. Its main features are minimization of error fields (from coils, current feeds, holes in the shell, support structures) and equilibrium control by a DC vertical field with pulsed cancellation inside the shell to assist in plasma production. Typical plasma parameters are $I_p$ = 160 kA, $T_e$ = 0.7 keV, $T_i < T_e$, $n_{e0}$ = 2 x $10^{19}$ $m^{-3}$, $\beta_p$ = 10 percent, $\tau_E$ = 0.2 ms, and $Z_{eff}$ = 5. $T_e$, $n_{eo}$, and $\tau_E$ scale almost linearly with $I_p$. The finding that $T_i$ is typically a factor of 2 less than $T_e$ differs from other RFP experiments where $T_i \gtrsim T_e$. It has obtained the highest current density and electron temperature in RFPs and this remains the focus of their program.

Table IV.9
RFP RESEARCHERS IN JAPAN

| | |
|---|---|
| **ETL, Tsukuba (TPE-1RM-15 Group)** | |
| K. Ogawa (Leader) | Y. Maejima |
| Y. Hirano | T. Shimada |
| I. Hirota | Y. Yagi |
| **Nagoya University IPP (STP-3(M) Group)** | |
| Koichi Sato (Leader) | H. Arimoto |
| Tsuneo Amano (Theory) | S. Yamada |
| **Nihon University** | |
| Katunori Saito | Yukio Osanai |
| Shoichi Shiina | Kazuo Yokoyama |
| **Tokyo University (REPUTE-1 Group)** | |
| N. Inoue (Leader) | Shunjiro Shinohara |
| Kenro Miyamoto (Leader) | Hiroshi Toyama |
| J. Morikawa | K. Yamagishi |
| Yoshiro Nagayama | Z. Yoshida |
| H. Nihei | |

b. Tokyo University (REPUTE-1) Program

The REPUTE-1 RFP (Miyamoto and Inoue, 1985) was designed with a thin shell (1-ms skin time) for vertical field penetration. The maximum discharge duration is 2.5 ms. Optimum performance parameters are $\bar{n}_e \sim 10^{20}$ m$^{-3}$ and electron temperature $T_e \sim 80$ eV (assuming $Z_{eff} = 1$) at $I_p = 200$ kA. Recent RFP studies (Inoue et al., 1989) have shown that the sawtooth oscillations observed in the soft X-ray signals are consistent with the results of MHD stability analysis and simulation.

Unfortunately, REPUTE-1 has never worked satisfactorily as an RFP. The device, built by Hitachi, had a stainless steel liner with large access ports. However, the transient currents flowing in the liner (needed for equilibrium and stability) caused large field errors and prevented use of a crowbar to extend the pulse length. Welding over the ports to make it more axisymmetric made little improvement, underlining the need to avoid field errors in RFPs. As a result, recent studies have shifted to ultra-low-q tokamak operation.

### c. IPP-Nagoya Program

The IPP-Nagoya RFP program started with STP-3(M) in 1983 (K. Sato, 1985). The earlier (1970-1983) STP (symmetric toroidal pinch) devices had been screw pinches and a fast RFP, STP-1(M). The main objective of STP-3(M) was higher current density operation; $I_p$ = 170 kA and $j$ = 7 MA $m^{-2}$ has been achieved. Use of a control system (Sato et al., 1989) for plasma position has doubled the electron temperature ($T_e$ = 0.8 keV) and discharge duration (6 ms) and halved the plasma resistance for the same value of plasma current (130 kA). The poloidal beta is about 0.2 and the confinement time has increased from 0.1 to 0.3 ms. A clear picture of the RFP dynamo action has been obtained together with the role of the $m = 0$ mode in an RFP plasma with large magnetic Reynolds number from experiment and numerical simulation.

### d. Nihon University Program

Nihon University is a private university with a small RFP program. The noncircular RFP was a tabletop device that had problems with arcing of a voltage gap that was exposed to the plasma. The larger ATRAS RFP was under construction at the time of writing in mid 1989.

### e. Theory

The experimental program on RFPs is considerably stronger than the theoretical program, which focuses on three-dimensional MHD computations (T. Sato and his group at Hiroshima University Institute for Fusion Theory; Sato et al., 1987). Kenro Miyamoto at the University of Tokyo is also contributing to development of RFP theory.

### 2. Outlook

The outlook for the Japanese RFP program is uncertain at this time because of the major commitment to the LHD project in the alternate confinement area. Experiments and some minor changes are planned for TPE-1RM-15 at ETL for the next few years and it would be one of a few operating RFPs in the world. Other factors are the severe illness of group leader K. Ogawa and the field error problems with REPUTE-1. Its future will depend on funding decisions by MITI. The STP-3(M) RFP work at IPP-Nagoya has been terminated and REPUTE-1 at Tokyo University has stopped RFP experiments and is focusing on ultra-low-q tokamak operation. Design studies (Inoue, 1987) had been done for larger RFP devices in Japan (TPE-RX with $R$ = 1.5 m, $a$ = 0.2 m, $I_p$ = 2 MA at ETL; REPUTE-II with $R$ = 1.5 m, $a$ = 0.3 m, $I_p$ = 2 MA at U. Tokyo; and STP-4 with $R$ = 1.2 m, $a$ = 0.2 m, $I_p$ = 1 MA at IPP-Nagoya), but these are not likely to be built. Future RFP research will be dominated by the large RFX (Italy) with $R$ = 2.0 m, $a$ = 0.5, $I_p$ = 2 MA, and ZT-H (United States) with $R$ = 2.4 m, $a$ = 0.4 m, $I_p$ = 1.7 MA.

## F. COMPACT TORUS PROGRAM

### 1. Accomplishments and Capabilities

The device parameters for the principal compact torus experiments in Japan are listed in Table IV.10. These are relatively small experiments. There are three main groups conducting compact torus research in Japan (Watanabe and Katsurai, 1987): (i) the FRC group (PIACE-II and the OCT series of experiments) previously under H. Ito (but now under T. Ishimura and S. Goto) at Osaka University; (ii) the FRC group (NUCTE-II, III) under Yasuyuki Nogi at Nihon University; and (iii) the spheromak group (CTCC-II) at Osaka University under Kenji Watanabe, who is approaching retirement. There is also a small spheromak effort (TS-3) at Tokyo University under Makoto Katsurai. The researchers active in compact torus studies are listed in Table IV.11. The largest of these groups is the Osaka group.

**Table IV.10**
**COMPACT TORUS EXPERIMENTS IN JAPAN**

| Institution | Device (Operation Dates) | Type | Radius, Length (m) | Field (T) | Bank Energy (kJ) | Current (kA) | Pulse Length (ms) |
|---|---|---|---|---|---|---|---|
| Osaka University | PIACE-II (1979- ) | FRC | 0.074, 1.0 | ≤ 1.5 | 150 | 500 | ≲ 0.07 |
| | OCT-S (1983- ) | FRC | 0.065, 1.5 | ≤ 0.3 | 50 | 600 | ≲ 0.15 |
| | CTCC-I | Sph. | 0.25 | 0.2 | -- | 90 | 1.3 |
| Nihon University Tokyo | NUCTE-III | FRC | 0.16, 1 | 1.2 | 60 | -- | 0.05 |
| Tokyo University | TS-3 | Sph. | 0.15 | 0.05-0.1 | | | |

The Japanese FRC work has had a significant impact on the development of the world FRC program. In earlier FRC studies, the plasma rotated and the centrifugal force led to an elliptical deformation and the plasma hitting the wall. S. Ohi from Osaka University stabilized this $n = 2$ rotational instability by adding a weak quadrupole field and the plasma lifetime doubled (Minato et al., 1983). The Nihon group, led by Yasuyuki Nogi, then showed that this mode could be stabilized with a smaller current in a helical quadrupole winding. The most recent studies have improved the experiment-theory agreement to within a factor of two (Ishimura et al., 1989). The effect of the axial current on confinement and on stabilization of the $n = 2$ rotational instability is being studied in the NUCTE-III experiment at Nihon University. Careful studies of different techniques for plasma formation have also been carried out.

Two types of spheromak studies are being pursued in Japan: the flux-conserver type of device (CTCC-II) at Osaka University and the external-field type (TS-3) at Tokyo University. The plasma parameters obtained in the CTCC-II spheromak are $n_e = 2 \times 10^{19}$ m$^{-3}$, $T_e = 30$ eV, and a plasma duration of 1.2 ms. An additional field has been applied to diminish the leakage of field lines through the entrance hole (Kato et al., 1989). The magnetic surfaces near the entrance hole are found to be perfectly closed but the stepwise instability that occurred in CTCC-I still occurs (Satomi et al., 1987). Various operational modes and merging of spheromaks are being studied by Makoto Katsurai and his students on TS-3. Studies are also being done of spheromaks as $D$-$^3He$ reactors by Hiromu Momota at IPP-Nagoya (Momota et al., 1987). In addition, T. Sato and collaborators at the Hiroshima University Institute for Fusion Theory have made progress on detailed three-dimensional MHD simulations of spheromaks.

**Table IV.11**
**COMPACT TORUS RESEARCHERS IN JAPAN**

**Nihon University**

| | |
|---|---|
| Yasuyuki Nogi (Leader) | Shin Shimamura |
| Yujio Osanai | Tsutomu Takahashi |

**Osaka University**

| FRCs | Spheromak |
|---|---|
| S. Goto (Leader) | Kenji Watanabe (Leader) |
| T. Ishimura (Leader) | M. Nagata |
| Y. Ito | N. Satomi |
| M. Kako | A. Ozaki |
| S. Ohi | M. Nishikawa |
| S. Okada | T. Uyama |
| S. Sugimoto | Y. Kato |
| Y. Ueda | Y. Honda |

**Tokyo University**

Makoto Katsurai

## 2. Outlook

The outlook for the Japanese compact torus program is uncertain because of the major commitment to the LHD project in the alternate confinement area. There are no definite plans for significant upgrades or new devices and the groups have decreased in size. There was a proposal for neutral beam injection into CTCC-II, but it was not approved. The three groups are in a position to study some interesting physics questions in the compact torus area but are sub-critical in size for studying the key physics issues needed (on larger devices) to advance the concept.

## CHAPTER IV: ALTERNATE CONFINEMENT APPROACHES
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# CHAPTER V
# PLASMA TECHNOLOGY

## A. OVERVIEW

Capability in developing plasma technologies is determined by specific skills within a particular research program and by the existence of a much broader external infrastructure. For example, a successful ion cyclotron heating effort requires specific knowledge and experience on how to design, fabricate, and operate effective radio frequency (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 JT-60—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), laboratory R&D programs have not been established. Even then, Japanese industry has been able to produce useful components which, however, are based on existing technology and have not advanced the state of the art.

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

Plasma technology development efforts have been closely tied to the support of major facilities. Thus, most of the work has been carried out by the Japan Atomic Energy Research Institute (JAERI) and that effort has been focused on JT-60 and the Fusion Experimental Reactor (FER). FER is Japan's domestic engineering test reactor project. The recent decline in budgets in plasma technology (as presented at the March 1989 US-Japan Fusion Technology Planning and Coordinating Committee) is likely 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/ITER and on the extent of Japan's participation. This could range from an independent, national FER to multilateral or bilateral participation in ITER.

Prospects for the development of those areas which are not presently competitive with the United States are dependent on the priority given them within the Japanese 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 Large Helical Device (LHD) experiment, then Toshiba has a good chance of becoming an alternative supplier to Varian.

## B. INTRODUCTION

Experimental advances in fusion plasma physics are often only possible after advances in the technologies for the components that heat and fuel the fusion plasma or for the magnets that confine the plasma. Vacuum technology and wall conditioning on the Soviet T-3, neutral beams on PLT at Princeton, gyrotrons on the Soviet T-10, and pellet fueling on Alcator C at the Massachusetts Institute of Technology are but a few examples. In some cases, advances in an area can motivate the initiation of a new line of facilities, as happened in the case of high-field magnet technology relative to the Alcator devices. Furthermore, requirements on fusion technology will only increase as facilities move closer to power-producing systems. Future components will have to perform in the difficult 14 MeV fusion neutron nuclear environment in addition to meeting the demanding economic and reliability requirements of power production.

Plasma technology development efforts in the Japanese program are closely tied to facilities. Thus, JAERI has had by far the largest effort as evidenced by JT-60 and the long-range development for their next-step facility (the FER). This balance will shift as the new Ministry of Education, Science and Culture (MOE) National Institute for Fusion Science at Toki begins work on development in support of LHD.

The plasma technologies assessed in this chapter include plasma heating technology (Section V.C), fueling technology (Section V.D), and magnet technology (Section V.E). A discussion of the role of Japanese industry in fusion development (Section V.F) is also included. The chapter concludes with a discussion of fusion-related atomic physics (Section V.G).

## C. PLASMA HEATING TECHNOLOGY

### 1. Neutral Beam Technology

Neutral beams have been used for plasma heating on nearly every major tokamak facility in the past 15 years. From early experiments in the mid-1970s on ORMAK (United States), ATC (United States), CLEO-tokamak (United Kingdom), T-6 (Soviet Union), and T-11 (Soviet Union), to the most recent results on TFTR, JET, and JT-60, neutral beam heating has been central to many of the major advances in tokamak parameters and understanding. A typical present-day beam-heating system consists of 6 to 12 ion sources, each producing 50 to 100 amperes of positive ions with energies in the range of 60 to 120 keV for pulses of 0.3 to 10 seconds. Total system power is in the range of 5 to 35 MW. Only recently, with the ion cyclotron heating (ICH) results on JET and the lower hybrid experiments on JT-60, has RF begun to play a major role in the big experiments.

Relative to other techniques, the plasma physics of beam heating and current drive is well understood, and excellent predictive capability exists. It is the only technique that can drive current in the center of high density, high temperature, reactor plasmas* and for which a physics database exists. However, the technol-

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* Lower hybrid waves tend to be damped before they reach the center of a reactor plasma.

ogy is difficult and the extrapolation to reactor applications has been widely questioned. The issues involve the increased beam parameters (energy, and therefore power) required in a reactor-scale plasma and the difficulty of attaining reasonable availability for a system that will have tens of ion sources and accelerator structures which are an integral part of the torus vacuum system. Beam energies in the range of 1 to 2 MeV are required for central current drive. Negative ion sources will have to be developed for reasonable efficiency in this energy range and advances in accelerator technology are needed to accelerate the needed 50 to 100 amperes of total beam current with a reasonable number of components. Very high reliability will be required to meet overall system availability requirements.

a. Accomplishments and Capabilities

Present capability is reflected by the operating parameters of the neutral beam systems on the large tokamaks. These data are summarized in Table V.1.

**Table V.1**
**NEUTRAL BEAM PARAMETERS FOR THE LARGE TOKAMAKS**

| Device | Beam Energy | Power | Species | Pulse Length* |
|---|---|---|---|---|
| JT-60 | 75 keV | 25 MW | H | 10 s |
| TFTR | 110 keV | 30.5 MW | D | 2 s |
| JET | 80 keV | 21 MW | D | 10 s |

* Design pulse lengths are reported since the experiments do not routinely use the maximum capability.

Source: H. Aikawa et al., 1988; M. G. Bell et al., 1988; The JET Team, 1988

These data indicate comparable capability in positive-ion-based neutral beam technology. What is not presented, and is intrinsically more difficult to justify, is the conclusion that the JT-60 beams came into operation more readily and are more reliable. This is likely due to the extensive off-line testing of the components (Ohara et al., 1984; Matsuda et al., 1982) and to the capability of Japanese industry to deliver quality components. This industrial capability was likely a significant factor in the ability of MOE institutions to obtain significant beam power; for example, the 4-MW Heliotron-E system (Uo et al., 1987) and the 120-keV, 75-ampere ion source (operation to 80 keV, 40 amperes was attained) that was delivered to the Institute for Plasma Physics (IPP)-Nagoya for the "R" project (Oka et al., 1984).

As discussed earlier, negative-ion-based neutral beams will be required in the future. Negative ion source development is under way in JAERI in support of the FER. A multi-apertured source has been operated at a current of 1.6 amperes with an extraction voltage of 31 kV (Watanabe et al., 1985). This source uses volume production of the negative ions. The US effort has focused on single aperture source concepts in the 100-milliampere range and is now exploring surface production source concepts.

b. Outlook

Positive ion based technology will be focused on in the planned upgrade of JT-60 which includes increasing the neutral beam energy to 120 keV and the power to 40 MW with deuterium operation (H. Aikawa, 1988). Progress in MeV-class beam system development depends on the schedule and role that Japan assumes with respect to an ITER-type facility. Decisions have been delayed on construction of a 5-ampere, 800-kV facility; a 100-mA, 500-kV system is now planned as an intermediate step. This will likely receive higher priority and increased funding when plans for ITER/FER are established.

## 2. Radio Frequency Technology

As indicated in the previous section, neutral beams were the earliest, most successful (even with the recent progress on JET using ICH), and most broadly used auxiliary heating method for tokamaks. Neutral beams retain their central role on TFTR and JT-60. Despite this success, there has been a long-standing 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 heating can provide. The technology issue is motivated by the need to use higher-energy, longer-pulse systems which have sufficient reliability and ease of maintenance to be compatible with the fusion reactor environment. Maintenance should be easier with RF because power sources can be located some distance away from the reactor core in a location where hands-on repairs are possible. Only the launcher and a small portion of the transmission system will require remote maintenance.

Plasmas have a number of characteristic frequencies that range from a few megahertz (for Alfvén-wave interactions) to hundreds of gigahertz (for electron cyclotron interactions). 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.) In each case, several different modes of heating or current drive are possible. For example, the fast- or slow-wave IC branch may be used with the possibility (although not necessarily for each branch) of heating at the fundamental or higher harmonics of the ion cyclotron frequency. The cyclotron interaction may be with a majority species (a principal plasma constituent) or with a deliberately added minority, often $He^3$, or with electrons. By controlling the spectrum of the waves and coupling to the electrons, current can, in theory, be driven with waves in the IC range. The relative status and characteristics of ICH, LHH, and ECH, in order of increasing frequency, are summarized in Table V.2. The physics required to successfully develop RF heating and current drive is indicated for completeness. 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. The extent of this diversity is evident in Table V.3, as will be discussed in the following sections.

Table V.2

CHARACTERIZATION OF RF HEATING TECHNIQUES

| | Physics | Source Technology | Coupling System In-Vessel Components |
|---|---|---|---|
| ICH | Good qualitative understanding emerging; quantitative models under development; current-drive possibilities have not been explored experimentally. | Straightforward extrapolation of shortwave broadcast tube technology; sources in the MW range at 10 to 120 MHz available. | Faraday shield required and small plasma antenna spacing desirable; erosion and impurity generation pose technical problems. |
| LHH | Nonlinear effects are important; basic phenomena are being identified, but significant effort remains to obtain quantitative models; significant current drive has been demonstrated, but heating is complex. | High-power klystrons are available at 1 MW in the 2-GHz range and 0.5 MW at 3.7 GHz; 0.5 to 1 MW level 8 GHz tubes under development. | Relatively simple waveguide launch; plasma-waveguide gap should be small for good coupling; at high power density, waveguide arcing near the plasma, as well as erosion and impurity generation, are major issues. |
| ECH | Good database for heating; linear absorption models are adequate but nonlinear effects may be important for high power free electron laser pulses; current drive not explored. | Long-pulse gyrotrons in the 100-GHz range are limited to 100 to 300 kW at present but have the potential for ~500 kW; free electron lasers are a long-term possibility. | Simple waveguide launcher. |

a. Ion Cyclotron

(1) Accomplishments and Capabilities

Ion cyclotron heating system performance is determined by transmitter characteristics and by launcher technology. The power and frequency ratings of the transmitter output tube are the most important parameters of the RF power source; however, its impact is mainly one of economics. A 2-MW tube will allow the fabrication of a less expensive power source than a 1-MW tube. However, these tubes are a relatively small part of the total cost and, as long as they are available commercially, the issue is one of national technological capability. The JT-60 ICH system is based on an Eimac (Varian) tube which can produce 750 kW in the 120 to 130-MHz range (Kimura et al., 1987). Eight tubes are used to produce a total of 6 MW. A higher-power version of this US tube is now undergoing testing in Japan as a US-Japanese collaboration and will be used for the planned JT-60 ICH upgrade.

**Table V.3**
**RADIO FREQUENCY HEATING SUMMARY**

| | Frequency | Pulse Length (Source) | Power | Power/ Source | Coupled | Date |
|---|---|---|---|---|---|---|
| **Ion Cyclotron** | | | | | | |
| TFTR (US) | 40-60, 47 MHz | 2s (+) | 4 MW, 6 MW | | 3.4 MW | 1988 |
| LHD* (Japan) | 60 MHz | 10 s | 10 MW (in plasma) | | | 1996 |
| CIT (US) | 95 MHz | 5s | 10 (+) MW (in plasma) | 1.5 MW | | 1997 |
| PLT (US) | 30 MHz | 1s | 5 MW | 1.7 MW | 4.25 MW | 1985 |
| JET (UK) | 25-55 MHz | 20 s | 32 MW (in plasma) | | 18 MW | 1988 |
| JT-60 (Japan) | 110 -130 MHz | 10 s | 6 MW | 0.75 MW | 3.1 MW | 1987 |
| Tore Supra (France) | 35-80 MHz | 30 s (+) | 12 MW | | | 1990 |
| **Lower Hybrid** | | | | | | |
| JET (UK) | 3.7 GHz | 10 s | 10 MW (in plasma) | | | 1990 |
| JT-60 (Japan) | 1.7-2.23 GHz | 10 s | 15 MW | 1 MW | 11 MW | 1988 |
| PLT (US) | 0.8 GHz | Up to 1 s | 1.2 MW | 0.2 MW | 0.3 MW | 1984 |
| | 2.45 GHz | | 1 MW | 0.33 MW | 1 MW | 1986 |
| Tore Supra (France) | 3.7 GHz | 30 s (+) | 8 MW (in plasma) | 0.5 MW | | 1990 |
| Alcator C (US) | 4.6 GHz | | 2 MW | | | |
| **Electron Cyclotron** | | | | | | |
| T-10 (USSR) | 83 GHz | 0.05-0.1 s | 2 MW | 0.2 MW (+) | 1.5 MW | 1986 |
| T-15 (USSR) | 83 GHz | 0.3 s | 4 MW | 0.2 MW (+) | | 1990 |
| DIII-D (US) | 60 GHz | 0.5 s (+) | 1.2 MW | 0.2 MW | 1 MW | 1988 |
| LHD* (Japan) | 56, 112 GHz | 10 s (+) | 5 MW (in plasma) | | | 1996 |
| MTX (Alcator C) (US) | 140, 280 GHz | Seconds | 2 MW | 2 MW | | 1990 |

* Preliminary assessment. Parameters will be determined in 1990.

The launcher is usually the limiting element in the amount of power that can be effectively coupled to the plasma, and power density is a useful figure of merit. The launching structure on the highest power experiment, JET, is mounted inside the vacuum vessel. The power density is approximately 200 $W/cm^2$. 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 total power has been limited to 3.1 MW on JT-60, this corresponds to a quite respectable 1.6 $kW/cm^2$ power density. Impurity production as opposed to RF breakdown is believed to be limiting operation at the design plasma heating power level of 5 MW.

(2) Outlook

The JT-60 upgrade plans 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 LH power, this level 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 dependence on US power tubes is not a limitation and could likely be eliminated within a few years if it were expedient.

b. Lower Hybrid

(1) Accomplishments and Capabilities

JT-60 is the only large tokamak with major emphasis on LH heating and current drive. This will remain the situation until LH experiments begin on JET in 1990. Although the superconducting TRIAM-1M experiment is not shown in the table, it is remarkable in its demonstration of several-minute-long pulses with the plasma current being sustained by LH waves.

There are both power source and launcher technology issues for LH. The JT-60 LH system is based on a 1-MW, 1.7 to 2.23 GHz klystron that was developed by Toshiba (Nagashima et al., 1983). The economy of larger tubes is not clear, because the power from any given tube must be divided several times to drive the multiple waveguide arrays that provide the needed spectrum control for LH current drive. The 24-MW (15 MW into the plasma) JT-60 system uses three launchers. Each launcher has 32 waveguides that are driven in groups of four by a single klystron. As with the neutral beams and ICH, extensive component testing was carried out before machine installation (Fujii et al., 1983); operation at 11 MW has been reported. Experimental results were presented, however, only through power levels of 2.5 MW (for current drive) and 6 MW (for heating) (Aikawa et al., 1988). The design power per waveguide, about 140 kW, is high compared to the 30 to 40 kW typically found in other experiments (Stevens, 1989). This may help explain the relatively low power levels which were achieved in practice.

Recently, one of the 4 x 8 arrays was replaced with a 4 x 24 array to obtain a narrower wave spectrum (Aoki et al., 1989). A power of 2.6 MW was launched from this improved grill, and the improved current drive efficiency, which was expected, was in fact observed.

(2) Outlook

All current drive scenarios for ITER rely on LH current drive over (roughly) the outer half of the plasma (ITER-1, 1988). This emphasis will help maintain and possibly increase the role of LH experiments within the JT-60 program. However, funds are limited and early plans to include a frequency change from the 1.7 to 2.23 GHz range to 3.7 GHz for the JT-60 upgrade have apparently not been implemented. Higher frequencies, in the 4 to 8 GHz range, are needed for ITER and tubes of reasonable size, 1 MW or greater, are not presently available, especially at the upper end of the frequency range. Development is now under way in Europe (Thomson CSF) and the United States (Varian) for a 0.5 to 1 MW, 8-GHz tube for the FTU tokamak experiment at Frascati. A comparable effort in Japan is not apparent; however, based on accomplishments at 2 GHz, such an effort is within the capability of Japanese industry, given a commitment of resources.

### c. Electron Cyclotron

#### (1) Accomplishments and Capabilities

Electron cyclotron heating has been widely used in Japan, including work on the Nagoya Bumpy Torus (28 GHz), Heliotron-E (53 GHz) and JFT-2M (60 GHz). Progress in Japan, as well as in the rest of the world, has been limited by the availability of high-power millimeter wavelength microwave tubes. Launchers are relatively simple and have not been a significant limitation. Despite some efforts on domestic tube development (Bigelow, 1987), Varian-supplied gyrotrons (five in the case of Heliotron-E) were used in the experiments cited above.

Increases in gyrotron power and frequency capability are becoming progressively more difficult. Thus, within the United States, free electron lasers (FELs) are viewed as a potential alternative to the gyrotron. Experiments are now under way on the Microwave Tokamak Experiment (MTX) at Livermore to explore the physics of the intense pulses produced by an induction linac FEL. This physics program is part of a US-Japan collaboration. High power FEL development in the United States is focused on Strategic Defense Initiative missions. The Japanese do not have a comparable effort. However, this technology is viewed as having significant impact in a range of research and industrial areas (K. Thomassen, 1989), and a number of FELs have recently been built (Sokolof, 1989).

#### (2) Outlook

As shown in Table V.3, LHD is the one Japanese confinement experiment for which significant ECH is planned. Given past willingness to rely on Varian, it is not clear to what extent domestic development of gyrotrons for LHD will be supported. The LHD schedule, which does not call for plasma operation until 1995, is consistent with the time needed for Japanese industry to become competitive. However, a substantial investment would be required. This has not been done in the past, but is a possibility for LHD given its size and visibility.

## D. FUELING TECHNOLOGY

Plasma confinement devices can be operated in either a batch or continuous fueling mode, depending both on the characteristics of the particular confinement system and on the chosen mode of operation. In the continuous mode, plasma particles must be replaced by new fuel as plasma is lost by diffusion and, in the case of a reactor, consumed by fusion reactions. Gas puffing, neutral beams, and pellet injection are the most commonly used fueling techniques for major confinement facilities. In general, gas fueling results in too much new plasma being created in the plasma edge, while neutral beams result in an unfavorable energy balance. Thus, pellet injection is the preferred technique for major near- and intermediate-term facilities. Enhanced plasma confinement modes have been observed in association with the peaked density profiles associated with pellet fueling. Pellet sizes in the 2 to 6 mm range with velocities of 0.5 to 2 km/s are typical.

In the longer term, the ability to centrally fuel reactor-scale plasmas is desired. It is uncertain if this can be done with pellet velocities which can be reasonably attained. This is especially true for the 20-keV mean temperatures required for efficient current drive. Initial evaluations suggest that some form of plasma gun fueling might be an effective fueling technique (Perkins et al., 1988); however, the physics basis for this approach has not been established. Thus, the focus of this discussion will be on the technology of solid hydrogen pellet injectors.

### 1. Accomplishments and Capabilities

Pellet injectors have been used in Japan in fueling experiments on JFT-2M, Heliotron-E, and, most recently, JT-60 (Noda et al., 1987; Aikawa et al., 1988; Uo et al., 1983). These injectors were designed and built by Japanese industry, Kobe and Mitsubishi, and are based on concepts developed at the Oak Ridge National Laboratory (ORNL). Performance parameters of the injectors are similar to those attained in the United States; velocities of 2.3 km/s are being reported for hydrogen pellets from the JT-60 injector.

No indication was found of development of higher velocity systems, such as the two-stage light gas gun work now under way in both the United States and Europe.

### 2. Outlook

High velocity pellet injection, or more broadly, central fueling, was not identified as a critical development issue in the ITER concept definition process. In part, this is likely due to the fueling technique not having any significant impact on the device conceptual design, and the "add on" nature of fueling components. This is in contrast, for example, to the neutral beam and magnet systems. As a result, a major thrust to develop advanced fueling systems 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 almost certainly build on US and/or European technology rather than embarking on an independent development effort. In the long term, an independent development program could be established, for example, in JAERI, and would likely be successful within a few years, if priority were given.

## E. MAGNET TECHNOLOGY

High-performance, reliable, economic magnet systems are central to the effective conduct of magnetic fusion research and to the successful development of fusion as a competitive power-production option. While the majority of present-day research facilities use resistive copper magnets, superconducting systems will eventually be required for all but the highest beta confinement systems. Both types of magnets are important. Even though future large tokamaks will almost certainly be superconducting, alternate concept and advanced tokamak research will continue to rely heavily on copper-based systems. Although less true for superconducting than for copper magnet designs, the capability to successfully build a state-of-the-art magnet system has far more to do with the ability to build large, complex components of any type, for example, airplanes or spacecraft, than with specialized magnet technology. Indeed, the magnet problems that are seen in the operation of various fusion facilities around the world are more often due to failures in conventional fabrication tasks, to poor workmanship, and to lack of attention to detail, than to failures in technology. Thus, it can be argued that successful magnet system design and fabrication require precisely the strengths of Japanese industry.

Superconductivity as a whole has been the subject of a separate assessment by Gomory et al. (1988), which should be consulted for a much broader and complete perspective. Only fusion-related work will be discussed in this section.

### 1. Conventional Copper Magnets

#### a. Accomplishments and Capabilities

The Heliotron-E and JT-60 conventional copper magnets are representative of those that Japanese industry has fabricated for fusion research. Heliotron-E is a stellarator with a 2T magnetic field and major radius of 2.2 meters. The helical coils were wound directly on the vacuum vessel. The location of the current center was controlled within a few millimeters in order to control field errors. The JT-60 coils operate at a maximum field of 9.8T at the conductor, roughly the same as TFTR, and are somewhat larger: the JT-60 coils have an inside diameter of 1.94 meters versus 1.4 meters for TFTR. Characteristically, extensive modeling and coil testing were performed (Ohkubo et al., 1980). No significant deviations from design specifications have been reported for either the Heliotron-E or the JT-60 magnets.

#### b. Outlook

Japanese industry has a history of producing reliable magnets which perform at design parameters. While there are no plans for any new major facilities that would use copper magnets, it is clear that they could meet any needs that might arise in the future.

### 2. High Power Density Magnets

All of the planned or presently existing magnetic confinement facilities use either conventional copper or superconducting magnets. There are no devices with magnet technology comparable to the Alcator line of devices and CIT in the United States, FTU in Italy, or T-14/TSF in the Soviet Union. Mitsubishi is building the magnets for Alcator C-Mod, but the technology and design were provided by the United States (Montgomery, 1989). Without a facility to drive development, it is unlikely that this line of magnet technology will be pursued in Japan.

### 3. Superconducting Magnets

#### a. Accomplishments and Capabilities

Indicative parameters are presented in Table V.4 for a number of fusion superconducting magnet systems. Two figures of merit are shown. The maximum magnetic field at the conductor is intrinsically related to the performance of superconductors; the product of current density and magnetic field is a measure of local stress, as well as representative of the trade-off between magnetic field and current density in a superconductor; and the product of all three is a measure of global forces. As with any figure of merit, these are only representative of more complex underlying issues and are best used to compare similar systems.

Even though TRIAM-1M, located at Kyushu University, is a relatively small tokamak, it is a high-field device that uses the relatively brittle $Nb_3Sn$ as compared to the more commonly used ductile NbTi. The device has operated routinely with no major problems, unlike the other superconducting tokamaks T-7, T-15, and Tore Supra. The Japanese LCT coil was the first to be completed of the six coils that made up the array and met or exceeded all specifications (Haubenreich et al., 1988). In both cases, quality workmanship and attention to detail were evident.

Present development work on tokamak toroidal magnets is focused on high-field conductor development. A new toroidal magnet test facility based on two LCT coils, including one US coil, with 12T high field inserts has been proposed, but not yet approved.

In addition to work on toroidal magnet development, an active program is under way to develop the high-field pulsed superconducting magnets needed for tokamak poloidal fields. The work is focused on the Demonstration Poloidal Coil Project where 1-meter bore, 7T pulsed coils will be tested using the JT-60 power supplies to provide the necessary pulse power. Tests on Japanese test coils will be conducted in 1989 and a US coil will be tested in 1990. Both tests are part of a US-Japanese collaboration.

**Table V.4**
**SUPERCONDUCTING MAGNET SYSTEM COMPARISONS**

| | $B_{max}$(T) | | a | $J^*$ | | | |
|---|---|---|---|---|---|---|---|
| | Design | Achieved | (m) | (kA/cm$^2$) | $J.B_{max}$* | $J.B_{max}a$* | Status |
| T-7 | 5.0 | 4.0 | 0.5 | 4.1 | 16.3 | 8.16 | Operates infrequently |
| TRIAM-1M | 11.0 | 11.0 | 0.6 | 4.5 | 49.5 | 29.7 | Operating |
| Tore Supra | 9.0 | 4.0 | 1.27 | 4.9 | 44.1 | 56.1 | Initial operation |
| T-15 | 6.4+ | | 1.25 | 2.75 | 17.6 | 22.0 | Initial operation |
| LCT (US-General Dynamics) | 8.0 | 9.0 | 1.75 | 2.5 | 20 | 35 | Coil tests only |
| LCT (Japan-Hitachi) | 8.0 | 9.1 | 1.75 | 2.7 | 21.6 | 37.8 | Coil tests only |

$B_{max}$ - maximum field at conductor
a - coil minor radius
$J$ - average current density in winding pack
* Maximum achieved where the facilities are completed or design parameters if system is not completed
\+ For Phase One of operation

The preceding development tasks are directed at tokamak engineering test reactor (FER/ITER) coils. The LHD is a (tentatively) 4-meter major radius, 0.5 meter minor radius, 4T (8T at the conductor) stellarator, which will be built at MOE's new National Institute for Fusion Science and will likely use superconducting magnets. The new institute and development of the LHD device were approved in the 1989 Japanese fusion budget, but device parameters and a budget will not be fixed until design optimization studies are completed in 1989. Physics considerations place a high premium on high current density magnets to maximize the useful plasma volume and a significant development program will be required to support the detailed design and fabrication.

b. Outlook

Fusion superconducting magnet development is consistent with both the 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.

## F. INDUSTRY

Japanese industry is an important component of the Japanese fusion program and must be considered in evaluating future prospects for fusion development. This is due to:

- The industrial "big three" of Japan (Hitachi, Toshiba, and Mitsubishi) have extraordinarily broad capabilities which range, for example, from microelectronics to heavy electrical equipment and to microwave tubes, and from superconducting wire production to large-scale magnet fabrication. This integrated capability, along with a strong emphasis on advanced technology, is a good match to fusion's needs.

- The development of advanced technology and its subsequent commercial exploitation is an important component of the rationale for the Japanese government's support of fusion development (AEC, 1987). In targeted areas, like superconductivity, R&D expenditures and the organization of the national laboratory-university-industry combine are well integrated and optimized for commercial ends. Even though comparable resources are expended in the United States on R&D in the field of superconductivity, the Japanese work is better organized to realize commercial returns (Gomory et al., 1988).

- Japanese fusion research institutions have small engineering staffs and limited internal fabrication capability. They must necessarily work closely with industry. There are well established working relationships with the major industries; these relationships are not limited by the same antitrust and competitive bidding policy which constrains such interactions in the United States.

This last point is illustrated in the following quotation from a paper given by S. Terasawa (1982) of Hitachi:

> If a company is selected as a main contractor of a project and other companies are participating as subcontractors, the responsibility of manufacturing and construction becomes clearer and the efficiency is improved. However, it is not appropriate to issue the order to a single company when the project is a national project completely supported by the government fund. Several companies offer bids and the share of the work is decided at the discretion of the customer and then a coordinating company is assigned. This method is a realistic solution and has been adopted in other national projects such as the advanced thermal reactor development project in Japan.

The strong position described above has reinforced an almost legendary commitment to quality, cost, and schedule. Meeting this commitment is made easier by prolonged conceptual design, followed by extensive prototyping. When manufacturing does start, it is based on a completed design, understood manufacturing processes, and assured funding. This process reduces the possibility of cost overruns and facilitates delivery of a quality product on schedule. When cost overruns occur, companies are expected to absorb the increases. At the same time, the process is inherently less amenable to changing technical needs.

## G. FUSION-RELATED ATOMIC PHYSICS

### 1. Accomplishments and Capabilities

A small fusion-related atomic physics program at IPP-Nagoya was initiated in 1977. The experimental program consists of a core of three IPP staff members, working with nine collaborators from different Japanese universities and industry. They refer to themselves as the NICE (Naked Ion Collision Experiment) group. Their primary focus has been on collisions of multiply charged impurity ions with hydrogen and helium atoms, and electrons. Using an electron-beam multiply charged ion source which they developed, the NICE group has concentrated primarily on charge-exchange collisions. They have made numerous cross-section measurements for multiply charged impurity ions, as well as translational-energy spectroscopic determinations of final-state distributions, which are important for diagnostics. They have developed empirical charge-state scaling laws, and have contributed significantly to both the database and to the general level of understanding of the charge exchange process. This group has also developed a crossed-beams experiment to measure electron-impact ionization cross sections. Because of their lack of access to a more powerful multiply charged ion source, this work has focused on singly and doubly charged impurity ions. The work of this Nagoya-based group has been widely published, and has been recognized at major international conferences for its innovation and contributions to the field.

At about the same time, with much the same type of manpower arrangement as the NICE team, an atomic and molecular data compilation project in support of fusion was initiated in the Research Information Center at IPP-Nagoya. This center has interfaced actively with the international data community through the IAEA Atomic and Molecular Data Center Network. Via the well-known IPPJ-AM series of blue books, the Nagoya Center has published more than 60 topical reports of compiled atomic data or other pertinent information for fusion research. Many of their compilations have also been published in the open literature.

The United States, through the ORNL atomic physics program, has benefitted from an active collaboration with this Nagoya activity for a number of years, both in data compilation and in experimental atomic physics. In fact, the Nagoya group is currently developing a novel electron gun and analyzer for use with the ORNL crossed-beams experiment and ECR multiply charged ion source beginning in the fall of 1989. The ORNL and IPP data centers share databases in order to maximize efficiency and minimize duplication of effort. In addition, ORNL has collaborated directly with IPP-Nagoya on several data compilations and assessments. The IPP-Nagoya atomic physics program in support of fusion research has been well focused, most prolific, and is most favorably recognized by the international community.

An atomic physics program also exists at JAERI in Tokai-Mura. This program involves a nucleus of three permanent staff, and a small number of university collaborators. Atomic data compilation for fusion is carried out in the Information Section of the Division of Technical Information, and focuses on atomic structure of plasma impurities and collisions of basic plasma constituents. The experimental atomic physics research consists mainly of accelerator-based measurements of fast charge-changing collisions in gases and foils, relevant to neutral-beam injection into plasmas. Thus, this work is complementary, and there is little overlap of the Nagoya and JAERI atomic physics efforts. The United States also has an active collaboration with the JAERI program, via the IAEA Data Center Network in the case of data compilation, and via personnel exchange in experimental atomic physics research.

### 2. Outlook

At the present time, the future of the IPP-Nagoya atomic physics program is uncertain. This is because the fusion program at IPP-Nagoya is being relocated from the Nagoya University campus to the new site at Toki, near Nagoya. There is some question whether the atomic physics group should relocate to the new site; there is also concern that the atomic physics program may be reduced or eliminated in the reorganization.

The JAERI effort will probably continue with the same level of effort and emphasis.

## CHAPTER V: PLASMA TECHNOLOGY
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# CHAPTER VI
# FUSION NUCLEAR TECHNOLOGY AND MATERIALS

## A. OVERVIEW

This chapter is concerned with an assessment of the fusion nuclear technology (FNT), materials research, and system studies programs in Japan. Fusion nuclear technology and materials (FNT/M) research includes blanket, neutronics, tritium, neutron-interactive materials and plasma-interactive materials. A review and an assessment of the Japanese FNT/M programs reveal three distinct stages of progress through three decades. During the 1970s, the Japanese program entered an introductory period. The Japanese FNT/M programs were modest and were aimed primarily at: (i) learning what the other world programs were investigating in fusion nuclear technology and materials, and (ii) initial planning of Japanese FNT/M research activities.

The decade of the 1980s can be characterized as a period of construction and focusing. During the 1980s, the Japanese program aimed at: (i) construction of important and powerful facilities for FNT/M research; (ii) targeting special technologies where the Japanese program is most likely to excel or those important and sensitive technology areas for which Japan had no domestic experience; and (iii) planning for an integrated technological capability that permits the construction and operation of a fusion experimental reactor (FER) in Japan.

Based on the achievements of the 1980s and present R&D plans, the Japanese program on fusion nuclear technology and materials is likely to enter a decade of leadership and distinction in the 1990s. It is projected that the Japanese FNT/M program will play a lead role in the world program in the 1990s.

The Japanese fusion program is coordinated by the Nuclear Fusion Council under the Atomic Energy Commission (AEC) of Japan. Fusion nuclear technology and material R&D is carried out at the Japanese Atomic Energy Research Institute (JAERI), the national laboratories, the universities, and industry. JAERI has the primary role for project management and the development of key technologies. 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, for practically all 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 national laboratories. One consequence 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 FNT/M program in the Japanese universities is comparable in funding with that in JAERI, but 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 technology 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 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 BEATRIX-II—for exchange of materials, information, and irradiation of solid breeders in fission reactors in the United States and Europe. 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 (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 lead 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: Fusion Neutronics Source (FNS) at JAERI and OKTAVIAN at Osaka University. Both have a yield of ~ $3 \times 10^{12}$ n/s, pulsed and steady-state operation, and other important experimental capabilities. These facilities adapted many technologies developed in the United States and were constructed and operated by scientists, many of whom were trained in the United States and Germany. It is interesting to note that the United States presently has no fusion neutronics facility in operation. There is a US-JAERI collaborative effort using FNS for fusion neutronics experiments. There is also a JAERI-German 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 (3-gram level) occurring in March 1988. Also, Japan is participating in the operation of the Tritium System Test Assembly (TSTA) at Los Alamos National Laboratory (LANL) to gain direct experience with tritium handling technology. The operating cost is shared equally between the United States and JAERI ($2 million each). A number of smaller-scale facilities for fundamental tritium studies are also in operation at Japanese universities. In addition, one of the Grant-in-Aid groups of the Japanese Ministry of Education, Science, and Culture (MOE) is carrying out an extensive research program on the environmental and biological effects of tritium.

The unique aspects of Japanese research on plasma-facing components can be summarized as follows:

- Systematic investigations of plasma interaction with graphites. An advanced graphite manufacturing industry plays a central role in this area.
- Studies of chemical sputtering and plasma-driven permeation (PDP) of hydrogen into materials.
- Radiation-enhanced corrosion of water-cooled plasma-facing components.

The progress made in Japan on fusion materials research during the past five years has been significant. Major areas of strength include non-neutron testing capabilities. Testing of materials properties in a neutron environment is accomplished by bilateral collaboration with the United States and certain European countries. Materials development concepts in the United States and Europe find immediate applications in Japan. The collaboration among universities, JAERI, the National Research Institute for Metals (NRIM), and industries is product-oriented and results in highly developed applications. Two major weaknesses appear in the Japanese program. First, theory and modeling of radiation effects are not as sophisticated as the experimental work. This may explain the apparent lack of original concepts for materials development and data analysis. Second, the neutron irradiation facilities are not convenient for material testing. At present, collaboration with other countries in this area is actively 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.

The 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 been in three large areas: (i) design of FER; (ii) major participation in international projects for world fusion reactors, such as the International Tokamak Reactor (INTOR, 1980-1987) and the International Thermonuclear Experimental Reactor (ITER, beginning in 1988); and (iii) 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 such activity among the world programs (only the European NET effort is comparable). 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.

The total annual funding for fusion nuclear technology and materials research in Japan is about $40 million (based on FY-1989, 130 yen per dollar, and

$150,000 per person). This is slightly larger than the European program and is 2.5 times larger than the US program in these areas.

Japan has consistently promoted international collaboration on fusion R&D and some examples in the fusion nuclear technology, materials, and system studies area were cited above. It is also important to note that Japan has been the only country that is willing to make direct payments for participation in another country's technology programs and the use of their facilities. This assessment concludes that the return on investment for Japan has been extremely high.

## B. INTRODUCTION

This chapter is concerned with an assessment of the fusion nuclear technology, materials research, and system studies programs in Japan. FNT/M research includes blanket, neutronics, tritium, and neutron-interactive and plasma-interactive materials.

The fusion program in Japan is coordinated by the Nuclear Fusion Council under the Atomic Energy Commission of Japan (Mori, 1989). The fusion nuclear technology and materials R&D is carried out at the universities, JAERI, national laboratories, and industry (Akiyama, 1989). The role of organizations in FNT/M R&D is shown in Figure VI.1.

The universities program is under MOE. An outstanding aspect of the Japanese program is the strength of the FNT/M research activities in the universities. The Japanese universities FNT/M program emphasizes fundamental research, and innovative concepts in addition to the support of the national technology development effort.

JAERI's program is under the Science and Technology Agency (STA). JAERI has the primary role for project management and for the development of key technologies. The FNT/M program at JAERI often has a narrow focus and is product oriented.

The national laboratories, under STA and the Ministry of International Trade and Industry (MITI), play a support role which is generally small except in specific areas. For example, there is a significant fusion-related material research program at NRIM.

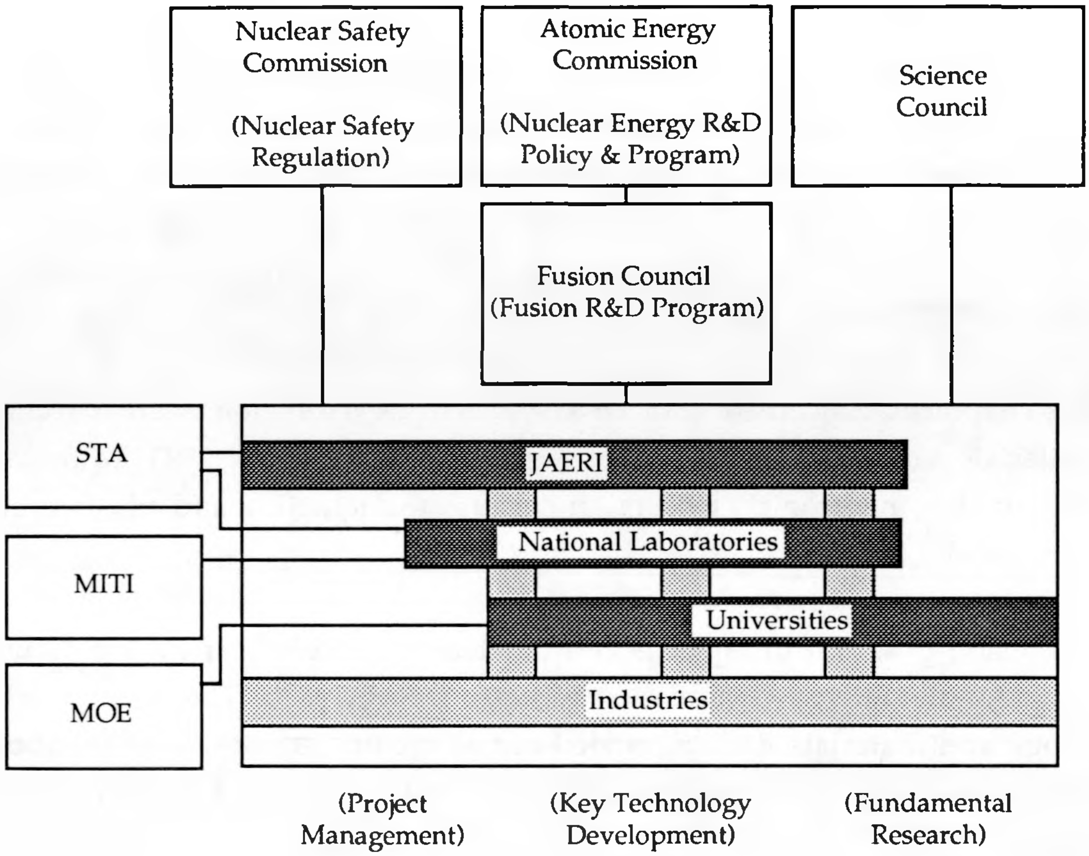



**Figure VI.1**
**ROLE OF ORGANIZATIONS IN FUSION NUCLEAR TECHNOLOGY R&D IN JAPAN**

A unique aspect of the fusion technology program in Japan is the role of industry. Industry has the primary responsibility for hardware construction, not only for large projects but also for small-scale facilities. Personnel from industry participate from the beginning of the conceptual design stage for research projects. As a result, technology transfer is efficient and automatic in the present fusion technology R&D programs in Japan.

The universities in Japan receive funding for fusion technology from MOE through several means. The largest is the Grant-in-Aid program for Special Research Projects on Nuclear Fusion. The efforts of the universities under this special project were organized for the period of 1984-1989 under six groups. The activities and key personnel for these groups are shown in Table VI.1. The annual funding for the fusion nuclear technology, materials, and systems studies program supported by the Grant-in-Aid is shown in Table VI.2 for FY 1988. The funding shown in Table VI.2 consists of two parts: (i) *projected,* which is a designation under a five-year plan; and (ii) *collected,* which varies from year to year based on priorities for various technical areas. The funding in Table VI.2 does not cover the salaries of personnel, and covers only the general category of materials and services. In Table VI.2, and in the rest of the funding tables in this section, we use a conversion rate of 130 yen for each US dollar. Japanese universities also receive direct funding for special projects to maintain existing facilities. An estimate of the funding for FNT/M/S under special projects is shown in Table VI.3.

The number of researchers in FNT/M/S programs in Japanese universities is shown in Table VI.4. An estimate of the fraction of time devoted by individual researchers was used to estimate the effective effort in terms of person years per year. The numbers in Table VI.4 show that the number of personnel and manpower in Japanese universities are larger than those in JAERI, and they represent a unique aspect of strength for universities in Japan, compared to other world programs.

The funding for FNT/M/S and other major fusion programs at JAERI for FY88 is shown in Table VI.5. Table VI.6 shows the funding and manpower at JAERI for FY89 for various areas of fusion nuclear technology and materials. The funding for ITER R&D is not included.

Table VI.7 shows a summary of the annual funding for system studies in Japan, including estimated salaries. The annual funding is approximately $5.8 million, not including the funding for ITER design. This is comparable to the present funding in United States and Europe.

## Table VI.1
## SPECIAL GROUPS AND KEY PERSONNEL FOR MOE SPECIAL RESEARCH PROJECTS ON NUCLEAR FUSION IN JAPANESE UNIVERSITIES (1984-1989)

| Function | Leader | Institute/University |
|---|---|---|
| Project Leader | Taijiro Uchida | Nagoya University, IPP |
| Vice Project Leader | Hideo Ikegami<br>Kazutaka Kawamura | Nagoya University<br>Tokyo Institute of Technology |
| Secretary | Hiroshi Sekimoto | Tokyo Institute of Technology |
| Advisory Board | Toshi Asada<br>Tomoo Ishihara<br>Yasunori Nishijima<br>Toshikazu Shibata<br>Yoshihiro Ichikawa | Tokai University<br>Japan Society for Promotion of Science<br>Kyoto University<br>Kinki University<br>Nagoya University |
| <u>Group I</u><br>Reactor Materials Plasma-Wall Interactions | Akira Miyahara<br>Shiori Ishino<br>Toshiro Yamashina | Nagoya University<br>Tokyo University<br>Hokkaido University |
| <u>Group II</u><br>Environmental and Biological Effects of Tritium | Shgefumi Okada<br>Yoshimasa Takashima | Kyoto University<br>Kyushu University |
| <u>Group III</u><br>Fundamentals of Reactor Plasma Control | Atsuo Iiyoshi<br>Tatsuhiko Yamanaka<br>Shigetoshi Tanaka | Kyoto University<br>Osaka University<br>Kyoto University |
| <u>Group IV</u><br>Superconducting Magnets | Takeshi Anayama<br>Kaoru Yamafuji | Tohoku University<br>Kyushu University |
| <u>Group V</u><br>Fusion Reactor Blanket Engineering | Kenji Sumita<br>Kenzo Miya | Osaka University<br>Tokyo University |
| <u>Group VI</u><br>Design and Evaluation of Fusion Reactors | Hiroshi Takuma (1986)<br>Makoto Okamato (1987-) | University of Electro-Communications<br>Tokyo Institute of Technology |

## Table VI.2
## ANNUAL FUNDING IN JAPANESE UNIVERSITIES BY RESEARCH SUBJECT FOR FUSION NUCLEAR TECHNOLOGY* (INCLUDING TRITIUM), MATERIALS, AND SYSTEM STUDIES SUPPORTED BY THE GRANT-IN-AID PROGRAM FOR SPECIAL RESEARCH PROJECTS ON NUCLEAR FUSION (BASED ON FY88)

| Research Subject | Million ¥** | | | US Total (Million $) |
|---|---|---|---|---|
| | Projected | Collected | Total | |
| Group 0: Overall Activities | 50 | | 50 | 0.38 |
| Group 1: Material and Plasma-Wall Interaction | | | | |
| (a) Low activation material, irradiation behavior and modeling, ceramics, insulator | 25 | 53.5 | 78.5 | 0.60 |
| (b) Graphite, tritium retention, tritium plasma | 29 | 17.5 | 46.5 | 0.36 |
| Group 2: Tritium (biological damage, environmental behavior) | 43 | 51.7 | 94.7 | 0.73 |
| Group 5: Blanket Engineering | | | | |
| (a) Hydraulics (liquid mist, MHD, cooling by solid-gas two-phase flow) | 8 | 3.6 | 11.6 | 0.09 |
| (b) Neutronics | 14 | 8.5 | 22.5 | 0.17 |
| (c) Tritium recovery | | 11 | 11 | 0.09 |
| (d) Disruption-FW behavior | | 15 | 15 | 0.2 |
| (e) Structural mechanics of material | | 18.9 | 18.9 | 0.14 |
| Group 6: Design and Evaluation | | | | |
| (a) Design database | | 9.6 | 9.6 | 0.07 |
| (b) Tritium processing | 8.4 | 10.4 | 18.8 | 0.14 |
| (c) Blanket concept, maintenance | | 7.5 | 7.5 | 0.06 |
| Total for Grant-In-Aid | 177.4 | 207.2 | 384.6 | 3.0 |

* Includes tritium environmental and biological effects.
** Assumes $1 = ¥130.

## Table VI.3
## ANNUAL FUNDING IN JAPANESE UNIVERSITIES FOR FUSION NUCLEAR TECHNOLOGY, MATERIALS, AND SYSTEM STUDIES FOR SPECIAL PROJECTS*

| Research Project | Million ¥ |
|---|---|
| A. Basic expense for researchers ¥1 million per group** (each group consists of professor, associate professor, and research associate) | 25 |
| B. Maintenance cost for large facilities (including utilities) | |
| 1. CTR Blanket Engineering Facility, Tokyo University | 60 |
| 2. HIT (high fluence irradiation facility, Tokyo University) | 40 |
| 3. Blanket Engineering Laboratory, Tokyo Institute of Technology | *** |
| 4. Tritium Laboratory, Toyama University | *** |
| 5. Tritium Laboratory, IPP Nagoya | *** |
| 6. OKTAVIAN, Osaka University | *** |
| 7. Isotope Separation Laboratory, Department of Nuclear Engineering, Nagoya University | *** |
| 8. Tritium Laboratory, Kyushu University, others | *** |
| Total | 225 |

* Estimated numbers.
** Basic expenses for researchers include university overhead, secretaries, books, computers, and partial support of experiments.
*** Estimates of distribution to individual laboratories are not available. The sum of all groups under B is 200 million yen.

**Table VI.4**
**MANPOWER ON FUSION NUCLEAR TECHNOLOGY, MATERIALS, AND SYSTEM STUDIES IN JAPANESE UNIVERSITIES**

| Subject | Gross No. | Effective No. Man Year/Yr. |
|---|---|---|
| 1. Material | | |
| 1.1 Irradiation effects on metals | 25 | 18.2 |
| 1.2 Ceramic insulator | 11 | 5 |
| 2. Plasma Material Interaction | | |
| 2.1 Graphite related | 16 | 8 |
| 2.2 Metal related studies | 17 | 10 |
| 3. Tritium | | |
| 3.1 Biological effects | 26 | 17 |
| 3.2 Environmental behavior | 8 | 4.6 |
| 3.3 Processing (separation, safety confinement, measurement) | 20 | 11 |
| 3.4 Metal-hydrogen interaction | 8 | 3 |
| 4. Blanket Engineering | | |
| 4.1 Tritium recovery, breeding materials | 16 | 9 |
| 4.2 Neutronics | 14 | 11 |
| 4.3 Hydraulics (cooling, MHD) | 14 | 9.7 |
| 4.4 Structural materials | 11 | 7.9 |
| 5. First-Wall Engineering | | |
| 5.1 PRC | 7 | 3.6 |
| 5.2 Fuel dynamics | 7 | 3.6 |
| 6. Design, System | | |
| 6.1 Reactor, blanket design | 11 | 8.7 |
| 6.2 Design, tool, database | 8 | 3.5 |
| Total | 219 | 133.8 |

**Table VI.5**

**JAERI's FUSION BUDGET FOR 1988 AND 1987**

| | Billion ¥ | |
|---|---|---|
| | FY 1988 | FY 1987 |
| 1. JT-60 (includes upgrade I ¥1.10 billion) | 17.08 | 23.46 |
| 2. JFT-2M | 0.94 | 0.93 |
| 3. SC magnet technology | 0.68 | 1.11 |
| 4. Tritium technology | 0.37 | 1.26 |
| 5. Other fusion R&D (material, neutronics, high heat flux test, ITER design, ITER R&D) | 3.18 | 1.59 |
| 6. US-Japanese cooperation (TSTA, MTX, etc.) | 1.11 | 0.84 |
| Total | 23.36 | 29.19 |

**Table VI.6**

**FUNDING AND MANPOWER FOR FUSION NUCLEAR TECHNOLOGY MATERIALS AT JAERI (BASED ON FY89 BUDGET)**

| | Budget* Million $** | Number of Personnel |
|---|---|---|
| High heat flux | 0.4 | 6 |
| Materials | 3.1 | 13 |
| Blanket | 1.15 | 5 |
| Neutronics | 1.2 | 7 |
| Tritium technology | 2.85 | 14 (+8) |
| Tritium TSTA collaboration | 2.0 | |
| Total | 10.7 | 45 (+8) |

* Does not include ITER R&D.
** Assumes $1 = ¥130.

**Table VI.7**
**SUMMARY OF ANNUAL FUNDING***
**FOR SYSTEMS STUDIES IN JAPAN**

| | Million $** |
|---|---|
| **Universities** | |
| Direct grant-in-aid | 0.13 |
| Manpower equivalent (12.2 man year/year x 0.8 x 0.150) | 1.46 |
| **JAERI** | |
| Direct budget | 1.54 |
| Manpower equivalent (20 man year/year x 0.8 x 0.150) | 2.60 |
| **Total** | 5.73 |

* Does not include ITER design (which is about 8 to 10 million dollars).
** Assumes $1 = ¥130.

A summary of the annual funding for FNT/M programs in Japan based on FY-1989 is shown in Table VI.8. The funding for the universities and JAERI are comparable. The total funding for the FNT/M programs is approximately $40 million. This is comparable to that in Europe and is about 2.5 times larger than the US funding.

Japan's fusion policy includes international collaboration as a key element. Japan has consistently promoted international collaboration on fusion R&D. Examples of present international cooperation programs for fusion technology in which Japan is a major participant are shown in Table VI.9.

Table VI.8
SUMMARY OF ANNUAL FUNDING* FOR
FUSION NUCLEAR TECHNOLOGY AND MATERIALS IN JAPAN
(FY89)

| | Million $** |
|---|---|
| **Universities** | |
| Direct grant-in-aid | 2.87 |
| Direct special projects | 1.73 |
| Manpower equivalent (121.6 man year/yr. x 0.8 x 0.150) | 14.6 |
| Subtotal Universities | 19.20 |
| **JAERI** | |
| Direct budget | 10.7 |
| Manpower equivalent (45 man year/yr. x 0.150) | 6.75 |
| Subtotal JAERI | 17.45 |
| Others (NRIM, industry, etc.) | 4.0 |
| **Total for Japan** | 40.65 |

* Does not include direct ITER R&D.
** Assumes $1 = ¥130.
*** Includes tritium biological and environmental effects.

**Table VI.9**
**INTERNATIONAL COOPERATION PROGRAM IN JAPANESE TECHNOLOGY R&D**

| Field | Name of Program | Participating Organization |
|---|---|---|
| Design | INTOR program<br>ITER program | United States, EC, Soviet Union<br>United States, EC, Soviet Union |
| Plasma-wall interaction | TEXTOR program | United States, EURATOM, Canada |
| Irradiation | HFIR/ORR joint exp.<br>FFTF joint exp.<br>Radiation damage R&D Program | US DoE<br>US DoE<br>United States, Canada, EURATOM, Switzerland |
| Neutronics | FNS joint exp. | US DoE |
| Tritium | TSTA program | US DoE |
| Superconducting magnet | LCT program | US DoE, EURATOM, Switzerland |

The rest of this chapter provides an assessment of the Japanese accomplishments and capabilities, and provides an outlook for the key technical areas of fusion nuclear technology, materials research, and systems studies programs in Japan. These programs are discussed in the following sections:

- Blanket (Section VI.C);
- Neutronics and Shielding (Section VI.D);
- Tritium Processing (Section VI.E);
- Materials and Plasma Facing Components (Section VI.F); and
- Systems Studies (Section VI.G).

## C. BLANKET

### 1. Introduction

The blanket in a fusion reactor operating on the DT cycle has two functions: (i) to convert the kinetic energy of neutrons and secondary gamma rays into heat, and (ii) to breed tritium. The primary blanket concepts being considered worldwide can be classified according to the physical state of the breeder:

- Liquid Metals

    - Self-cooled liquid lithium or 7Li-83Pb serves as the breeder and coolant

    - Separately cooled liquid lithium breeder cooled by helium or liquid 7Li-83Pb is cooled by water or helium

- Solid Breeder

    - Lithium-containing material in solid form is cooled by helium or water. Solid breeders considered around the world include $Li_2O$, $Li_4SiO_4$, $Li_2ZrO_3$, and $LiAlO_2$.

There are other blanket concepts such as molten salts and aqueous solutions that are presently not receiving much effort in Japan or in any other countries.

Other key materials in the blanket are the structural materials, neutron multipliers, and in some concepts the electric insulators and tritium permeation barriers. The primary structural materials considered worldwide are austenitic stainless steel, ferritic steel, and refractory alloys such as vanadium alloys. Except for hybrid (fission-fusion) concepts, the key neutron multiplier is beryllium.

Blanket R&D includes many technical disciplines: neutronics, thermal hydraulics, stress analysis, radiation effects on materials, tritium release and recovery, and electromagnetic effects. The classification of R&D varies among various countries. In this report, the relatively large activities of neutronics and materials are treated in separate sections. In this section, we deal with the remaining blanket topics.

Both liquid metal and solid breeder blankets are being pursued in Japan. Liquid metals are pursued only in Japanese universities, with no effort at JAERI. The largest program on solid breeders is at JAERI, but there are also substantial efforts at a number of Japanese universities on solid breeders.

Most of the blanket effort in Japanese universities is coordinated by Group V, Fusion Reactor Blanket Engineering, which is one of six groups organized under the MOE Special Research Projects on Nuclear Fusion supported by the Grant-in-Aid (see Table VI.1). The group is presently headed by Professor Kenji Sumita at Osaka University. This group is divided into subgroups: the Senior Advisory, Structure, Thermal, and Hydrodynamics subgroup (led by Professor K. Miya at Tokyo University); the Neutronics subgroup (led by Professor K. Sugiyama at Tohoku University); and the Tritium Engineering and Safety Group (led by Professor Y. Takahashi at Tokyo University). The JAERI blanket effort is carried out mostly in a number of divisions at the Tokai establishment with some effort recently started at the Naka site.

## 2. Liquid Metal Blankets

### a. Accomplishments and Capabilities

Most of the liquid metal research is focused on the effect of magnetic field on the pressure drop, fluid flow and heat transfer, normally referred to as magnetohydrodynamics (MHD). The centers of liquid metal MHD research include Osaka University, Tokyo Institute of Technology, Tokyo University, Kyoto University, and Tohoku University.

Table VI.10 summarizes the research activities and facilities on liquid metal MHD in Japanese universities. The largest effort appears to be at Osaka University. Table VI.11 lists the characteristics of the experimental research facilities at Osaka University while Table VI.12 summarizes the research activities of the last ten years on liquid metal MHD at Osaka University; this work is led by Professor K. Miyazaki.

(1) Program Coordination

It appears that Japanese activities on liquid metals are not well coordinated. This may reflect the fact that faculty members in Japan manage their own programs and are guided mostly by individual research interests. Although the level of overall planning in Japanese universities appears low, there does exist a Joint Research Plan on MHD, which is summarized in Table VI.13. (Note in Table VI.13 that JAERI is listed as a contributor to the Joint Research Plan, even though no work is performed there.)

(2) Topics of Interest

The Japanese carry out experiments, modeling and analysis, and design studies. These are summarized below. The topics of interest are somewhat broader than in the United States, but this flexibility is also related to the lack of a positive focus on specific design concepts. The Japanese scientists are definitely interested in both laminar flow and two-phase (He-Li) flow. Interest has also traditionally existed in boiling heat transfer and natural convection. It is also clear that electromagnetics and structural analysis are given stronger attention than in the US liquid metal program. This is a credit to the Japanese program.

(3) Experiments

Many of the liquid metal facilities are small bench-top experiments; however, there are a limited number of larger loops (see Tables VI.10 and VI.11). For example, there is a 5-T superconducting magnet at Osaka University, and a large 1.4-T facility at the Tokyo Institute of Technology. Many of the facilities are dormant.

## Table VI.10
## RESEARCH ACTIVITIES AND FACILITIES AT JAPANESE UNIVERSITIES ON LIQUID METAL MHD

| University | Activity | Facilities |
|---|---|---|
| Tokyo Institute of Technology (Profs. Inoue, Aritomi, et al.) | MHD pressure drop and heat transfer on single- and two-phase Li-He flow | 1. Li-He two-phase MHD flop loop: He 20kg/$m^2$s, Li 250kg/$m^2$s, 500°C, 100kw, 3 bar<br>2. Magnet: 1.4T, 0.3 x 1m, 0.12m gap |
| Tokyo University (Profs. Akiyama, Miya, Yagawa, Madarame) | 1. Blanket electromagnetics<br>2. Analyses of MHD problems<br>3. Design study of liquid metal cooling of fusion reactor<br>4. MHD on natural convection heat transfer of Na | 1. Electromagnetic structure test facility<br>2. Na loop<br>3. DC magnet |
| Kyoto University (Profs. Michiyoshi, Serizawa, et al.) | 1. MHD on natural convection heat transfer of Li, NaK, Hg<br>2. MHD on heat transfer of NaK-$N_2$ mist flow<br>3. Transient boiling of K in transverse magnetic field | 1. NaK-$N_2$ loop: NaK pump 30 lit./min.<br>2. DC magnet: 1T, 1m x 0.2m, 0.1m gap<br>3. DC magnet: 0.7T, 0.3m dia., 0.1m gap<br>4. DC magnet: 1T, 1m, gap 0.03m |
| Osaka University (Profs. K. Miyazaki, S. Inoue, N. Yamaoka, N. Nuunogaki) | 1. MHD pressure drop<br>2. MHD effects on heat transfer<br>3. Free surface flow for ICF reactor and accelerator target<br>4. Liquid metal MHD power generation | Detailed in Table VI.11 |

**Table VI.11**
**EXPERIMENTAL RESEARCH FACILITIES AT OSAKA UNIVERSITY**

I. Liquid Metal MHD Experiments

- NaK blowdown experimental facility
  - NaK: 230 lit., $N_2$: 10 bar (65 bar design)
- DC magnet (for transverse magnetic field to flow)
  - 2T, poles: 120 x 500mm, gap: 80mm, splittable, movable
- Superconductor magnet (for parallel magnetic field)
  - 5T, 100mm dia. x 300mm-1.0% uniform field bore, 1.2m long
- Li circulation loop
  - EM pump: 40 lit./min.-3 bar, Li: 20 lit., 500°C
- Small NaK circulation loop
  - EM pump: 20 lit./min.-2 bar, placed on DC magnet, rotatable
- NaK annular free surface flow device (LINAK)
  - NaK: 50 lit., Ar: 0-3 bar
- Large NaK circulation loop (to be constructed)
  - EM pump: 250 lit./min.-5 bar
- Variable frequency motor-generator
  - 3-phase, 40-250kHz, 90KVA

II. FBR Power System and Safety Experiments

- RF power supply for induction heating
  - 200kHz, 30kW
- DC power supply for resistance heating
  - SCR, 5V, 5000A
- Na and K film boiling experimental devices
- Na boiling exp. loop (needs repair)
  - Na: 80 lit., 950°C, 5 lit./min.

Table VI.12
RESEARCH ACTIVITIES ON LIQUID METAL MHD
FOR FUSION AT OSAKA UNIVERSITY

| FY | Subject | Duct | Magnet | Liquid Metal |
|---|---|---|---|---|
| 1980-1983 | Pool boiling | Circle | Transverse | K |
| | Pressure drop | Circle | Transverse | NaK and Li |
| | End effect of pressure | Circle | Transverse | NaK and Li |
| | Liner implosion, ICF | Annulus | Theta-pinch | NaK |
| | Heat transfer | Cir., pin | Transverse | Li |
| 1984-1985 | Temperature fluctuation | Cir, pin | Transverse | Li |
| | Pressure drop and end eff. | Rectangle | Transverse | Li |
| | Mag. guided flow, ICF | Free Annu. | SCM, para. | NaK |
| | Heat transfer, pool | Cir., pin | SCM, para. | Li |
| 1986-1988 | Heat transfer, flow | Cir., pin | SCM, para. | Li |
| | Pressure drop at end | Circle | SCM, para. | Li |
| | Pressure drop collid. jet | Hancox cell | Transverse | NaK/Li |
| | Pressure drop in para. channels and at joints | Double Cir. tube | Transverse | Nak/Li |
| | Transient of flow | Circle | Transverse | Li |
| 1989- | Boiling 2-phase flow and advanced concepts | Circle | Transverse | K + Li |

The quality of the data obtained from the experiments appears to be much lower than is customary in the United States. This partly reflects the academic focus of the work. Detailed velocity profiles are not normally taken, which makes the benchmarking of codes difficult. In addition, discrepancies and unexplainable data leave the impression that the tests are not carefully run. However, it is also true that there is little screening of the data to present only the most attractive results.

(4) Modeling and Analysis

Japanese modeling capabilities seem somewhat crude. In addition, the focus of the calculations is strongly coupled to individual design studies or experiments; models developed in this manner tend to be restricted. There appears to be no coordinated effort to produce a generalized MHD code.

**Table VI.13**
**JOINT RESEARCH PLAN ON MHD, HEAT TRANSFER, AND STRUCTURAL PROBLEMS CONCERNING LIQUID METAL (Li) COOLING OF FUSION REACTOR, BLANKET ENGINEERING GROUP FOR FY88 SUPPORTED BY GRANT-IN-AID FOR FUSION RESEARCH**

| | |
|---|---|
| Osaka University (OU) | K. Miyazaki, M. Nishikawa, S. Inoue, N. Yamaoka |
| Tokyo Institute of Technology (TIT) | A. Inoue, M. Aritome, M. Takahashi |
| Tokyo University (TU) | K. Miya |
| Osaka Prefect. University (OPU) | S. Namba |
| JAERI | T. Tone, M. Seiki |

1986 Subjects Indigenous to Individual Institutes

1. Heat transfer of lithium flow under parallel magnetic field by superconducting magnet (OU)
2. Heat transfer and pressure drop of Li flow in one-sided-heated rectangular duct (TIT)
3. Analyses of MHD pressure drop and stress (TU, JAERI, OPU)

1987 Pressure Drop and Heat Transfer of Liquid Metal Coolant

1. Vertical flow of NaK and Li (OU)
2. Horizontal flow of Li (TIT)
3. Analyses of MHD pressure drop, heat transfer, and stress

1988 Dynamics for Flow, Thermal and Magnetic Transients, and Structural Response

On the positive side, by focusing on actual component designs, the analyses tend to treat more complex geometries or flow situations. For example, at Tokyo University, Professor Madarame's work (and the methods he is developing) can treat geometries more complicated than the US codes can ever anticipate. Also, semi-empirical models are being developed for non-laminar flow situations (in particular, for the two-phase work proceeding at the Tokyo Institute of Technology and Kyoto University).

(5) Corrosion

Corrosion of structural materials is a key issue for liquid-metal blankets. The lack of significant research on liquid-metal corrosion in Japan is a noticeable deficiency.

(6) Tritium Recovery

At the universities, basic studies on tritium recovery from liquid breeder blankets have been performed. These studies have included tritium migration in and on the surface of lithium-lead and FLiBe. The chemical form of tritium in liquid metals has also been studied.

In the Phase III program of the Grant-in-Aid research project, which is planned to start in 1991, fundamental studies in tritium recovery from liquid breeders will include impurity control techniques and kinetic data on tritium migration and recovery. In-situ tritium release experiments for liquid breeders are also planned.

b. Outlook

Liquid metal blanket R&D is pursued only by Japanese universities and not by JAERI. Therefore, 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 next five-year plan (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 (for example, Tokyo University) 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.

### 3. Solid Breeder Blanket

#### a. Accomplishments and Capabilities

The major research activities on solid breeder blankets are carried out at JAERI. However, there are a number of important activities in this area in Japanese universities. In the late 1970s, Japan selected solid breeders as the primary blanket option. Furthermore, JAERI selected $Li_2O$ as the reference ceramic breeder. Thus, the Japanese program focused early on a blanket option with a specific breeding material. This focus of resources on only one option has enabled Japan to assume the world lead in $Li_2O$ blanket development.

The blanket development in Japan is closely tied to the next major fusion facility, FER, in Japan. This is illustrated in Figure VI.2, taken from presentations by Japanese scientists (Yoshida, 1988). The blanket R&D in Japan includes neutronics; material technology; radiochemistry; reactor irradiation; tritium breeding and recovery; thermal hydraulics; tritium technology; waste processing; and environmental safety. Figure VI.3 shows the short- and medium-term schedule while Figure VI.4 shows the long-term schedule for blanket R&D.

The JAERI solid breeder blanket R&D program can be classified into three areas: (i) characterization of materials, (ii) irradiation experiments, and (iii) development of manufacturing capability. The characterization of materials activities involves measurements of basic material properties such as electrical and thermal conductivities and tritium solubility. These activities are summarized in Table VI.14.

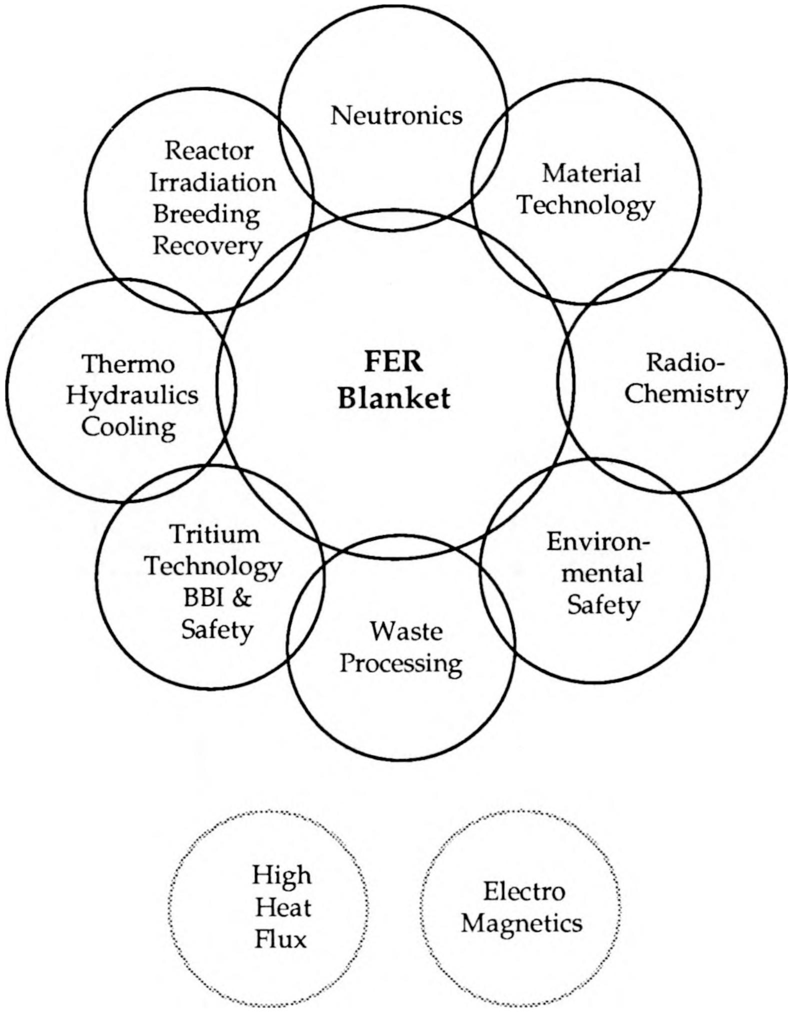



**Figure VI.2**

**SCHEMATIC OF JAPAN BLANKET R&D TECHNICAL AREAS AND RELATIONSHIP TO FER**

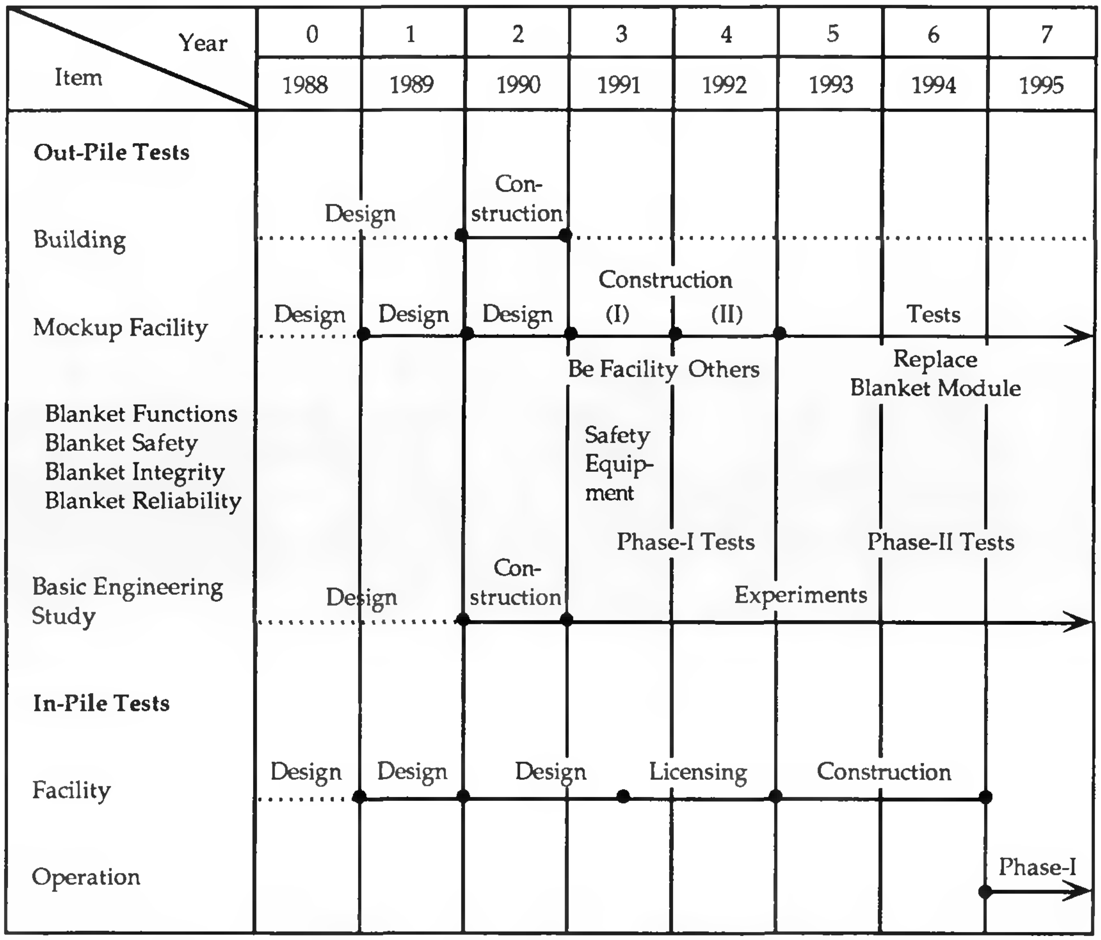
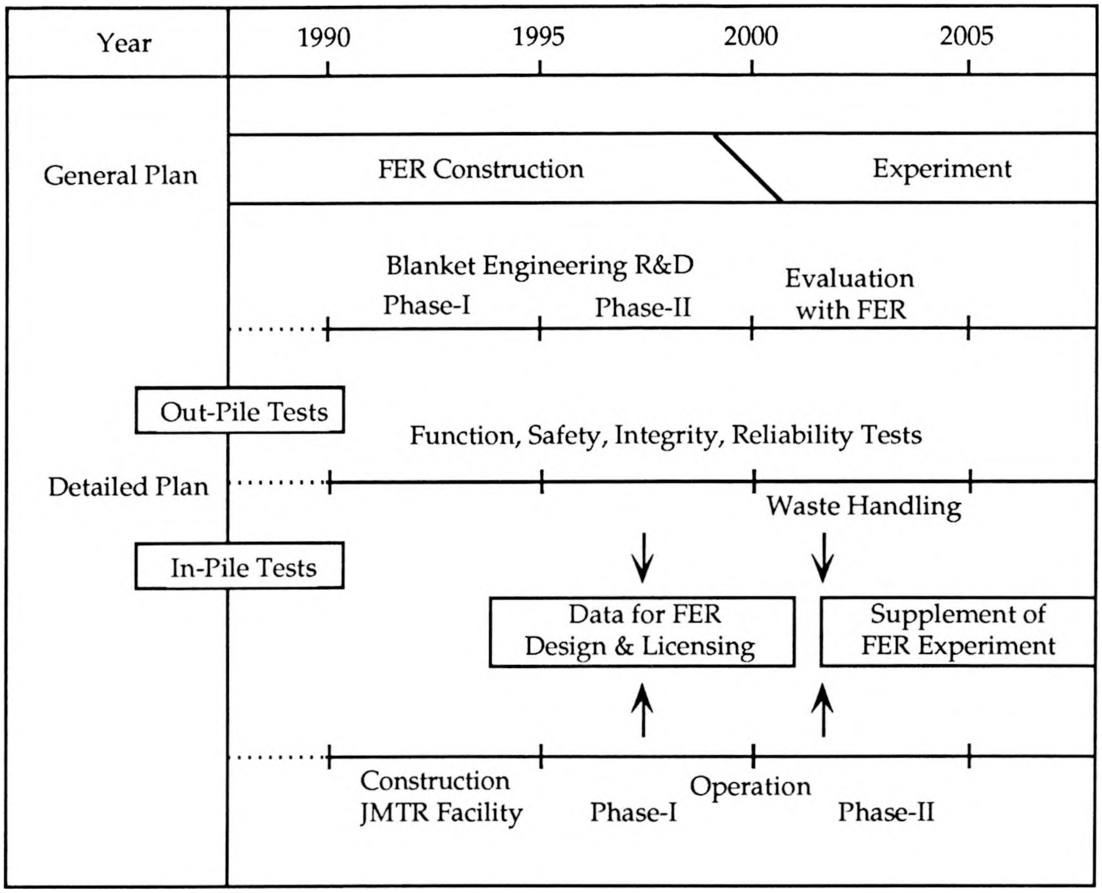



**Figure VI.3**

**BLANKET R&D SCHEDULE IN JAPAN FOR THE SHORT AND MEDIUM TERM**

The irradiation experiments at JAERI fall into two distinct categories: (i) irradiation in fission reactors in Japan, and (ii) irradiation in foreign fission reactors (in Europe and the United States). This is the largest and most expensive part of the blanket R&D. Fission reactor irradiation in Japan is carried out in JRR-2 and in JMTR. The focus of these experiments to date has been on measurements of effect of irradiation on solid breeder material properties, and measurements of tritium retention and release. Most of JAERI's measurements focused on $Li_2O$.




This program is based on the fusion next step device program (FER) launched by the Atomic Energy Commission of Japan in June 1987.

**Figure VI.4**
**BLANKET R&D SCHEDULE IN JAPAN FOR THE LONG TERM**

Japan has been a major partner in two international collaborative programs on solid breeder materials: BEATRIX-I and BEATRIX-II. These programs involve experiments in fission reactors of two types: closed capsules to investigate lifetime radiation effects on tritium release, and open capsules to measure the dynamics of tritium release under different operating conditions. The collaboration among EC, Japan, and the United States involved the exchange of materials and information, and the irradiation of solid breeder materials in fission reactors in the United States and Europe.

## Table VI.14
## SUMMARY OF SOME KEY RESEARCH ACTIVITIES AND FACILITIES ON SOLID BREEDER BLANKET AT JAERI

| Facility/Activity | Objective | Place | Miscellaneous |
|---|---|---|---|
| Manufacturing facility | Development of fuel manufacturing technique for fusion | JMTR (Department of Radioisotopes) | • 0.1 g-$T_2$<br>• Li-Al<br>• Gas chromatography |
| Manufacturing test facility (under planning) | Basic engineering testings for tritium manufacturing | JMTR (Department of Engineering) | • $LiAlO_2$, $Li_2SiO_3$<br>• 1-100g-$T_2$/batch |
| Tritium release experimental apparatus, chemical shape measurement apparatus | Research of tritium chemical behavior | Department of Radioisotopes | • $Li_2O$, $LiAlO_2$, $Li_2SiO_3$, $Li_4SiO_4$, $Li_2ZrO_3$, $Li_8ZrO_6$, Li-Al, Li-Pd |
| Tritium release experimental apparatus | Diffusion of behavior of tritium | Department of Fuels and Materials | • $Li_2O$ single crystal |
| Tritium release experiment under irradiation condition | Tritium collection | JRR-2 (Department of Fuels and Materials Research) | • $10^{13}$ n/cm$^2$s |
| Solubility measurement facility | Measurement of solubility | Department of Radioisotopes | • $Li_2O$ (powder, single crystal)<br>• 200 - 700°C<br>• 0.01 - 100 kPa, $T_2$, HT |
| Thermal conductivity measurement facility | Measurement of thermal conductivity which depends on the porosity and temperature | Department of Fuel and Materials Research | • $Li_2O$, $LiAlO_3$ |
| Electrical conductivity measurement facility | Effect of irradiation defect on electrical conductivity | Department of Fuels and Materials Research | • $Li_2O$ |

The large step in solid breeder blanket R&D at JAERI is the construction of an integrated blanket test for irradiation in JMTR. This integrated test will have a much larger volume than previous experiments as shown in Figure VI.5. It is important to note that the relevant neutron flux in JMTR is two orders-of-magnitude lower than that required for an optimum experiment. Higher flux capabilities are available in fission reactors in the United States and Europe. However, Japan designated the JMTR solid breeder experiment a high priority task. This reflects a strong intent in Japan to build domestic capabilities for those sensitive technologies that do not now exist in Japan.

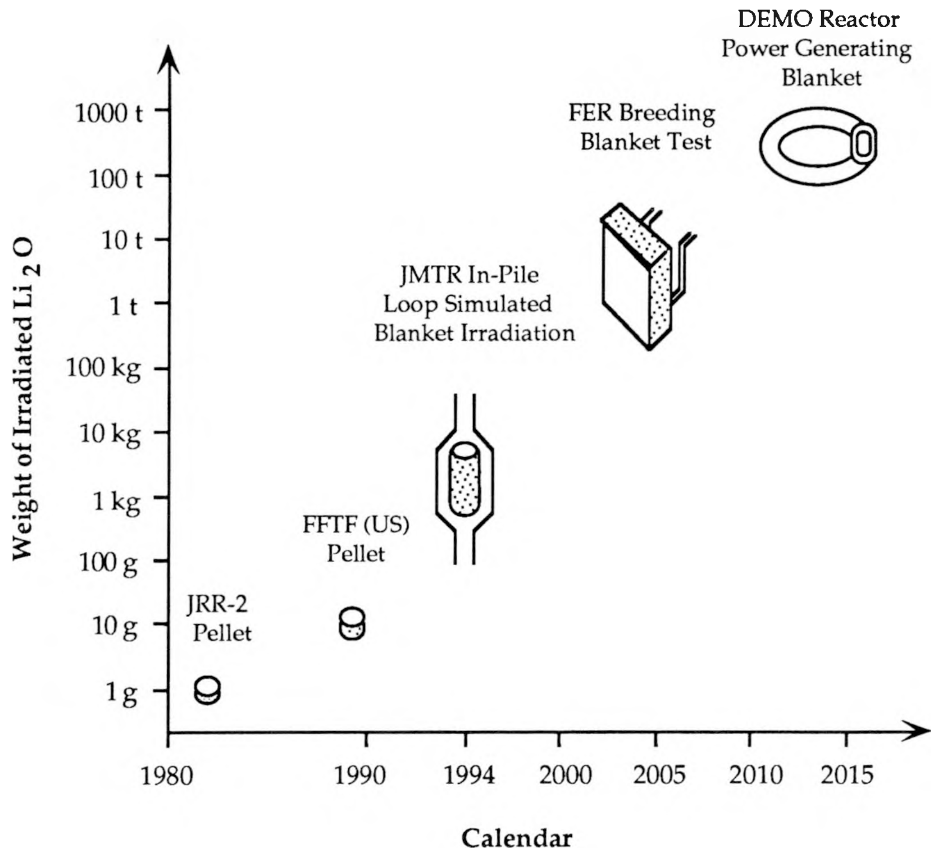



**Figure VI.5**

**COMPARISON OF BREEDING BLANKET IRRADIATION EXPERIMENT IN JMTR WITH OTHER EXPERIMENTS**

JAERI has also emphasized manufacturing technology and is developing such technology for solid breeders. The largest project in this area, now in the planning stage, is to construct a fabrication and processing technology facility with a special laboratory for handling beryllium.

The Japanese universities are carrying out various research activities on solid breeders that can be characterized as fundamental studies to support JAERI's mission-oriented program (Uchida, 1988). The research activities include measurements of thermophysical properties, basic processes of tritium release (for example, adsorption and desorption), and effects of irradiation at low fluences. Some of these experiments are conducted at Tokyo University, Kyoto University, and Tokyo Institute of Technology. At Tokyo University, in-situ tritium release experiments named "TTTEX" are performed using the fission research reactor YAYOI. Although the neutron flux level is low, the reactor has good features that permit its utilization for fundamental studies on tritium migration.

b. Outlook

The Japanese 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. The universities program plays an important role by performing fundamental studies and examining a broader range of materials and options. Furthermore, Japan has invested in international collaborative programs to use facilities not available in Japan. The next five-year plan (1990-1995) 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.

## D. NEUTRONICS AND SHIELDING

### 1. Introduction

The field of neutronics in fusion reactor development is concerned with predicting the neutron and photon transport and associated nuclear responses in all components of the system. Examples of nuclear responses are nuclear heating, tritium breeding, induced radioactivity, decay heat, gas production, radiation dose to materials and components, and biological dose. Neutronics calculations provide the following:

- evaluation of tritium self sufficiency;
- input to thermal/mechanical design calculations (for example, nuclear heating rates for thermal and stress analysis);
- input parameters to evaluate radiation effects on radiation-sensitive components such as superconducting magnets, cryopumps, and neutral beams;
- input parameters to evaluate radiation damage in materials (for example, gas production); and
- input to safety analysis (for example, radioactivity and decay heat).

Although radiation shielding is part of the neutronics as a technical discipline, it is often treated as a separate category because of special problems, such as radiation streaming, which require special treatment of neutron and photon transport in complex geometries with deep radiation penetration.

Neutronics and shielding analysis require the following elements:

- nuclear data library (for example, cross sections, secondary particle energy and angular distribution);
- transport code (calculates primarily flux, spectra); and

- nuclear response evaluation code (for example, to calculate nuclear heating from kerma factors and neutron and gamma fluxes).

Preparing a nuclear data library involves a large effort ranging from basic differential nuclear data measurement, nuclear data evaluation, and processing of evaluated data into a formatted library that can be used with a transport code.

From the above, it should be clear that neutronics analysis and design of a fusion system involves the use of large numbers (millions) of data points, each of which is separately measured, as well as the use of complex codes that have limitations. Thus, performing "integral" experiments to validate methods and data is a crucial part of neutronics and shielding R&D. In these integral experiments, mockups of the first wall, blanket, shield and other components are irradiated by a neutron source and integral parameters (for example, total tritium production or nuclear heating) are measured.

## 2. Accomplishments and Capabilities

Fusion neutronics research in Japan is carried out at JAERI and Japanese universities. The JAERI program is project-oriented, whereas the Japanese universities emphasize more fundamental and basic research. The Japanese Fusion Neutronics and Shielding Program is now the largest in the world in terms of facilities, manpower, number of experiments, and research topics covered.

During the 1970s, the US fusion program had an unquestionable lead in world programs in the areas of neutronics and shielding. The reasons for this were the existence in the United States of: (i) an extensive technology base of nuclear data and computer codes generated by the fission reactor program, basic energy sciences programs and weapons program; (ii) a number of large reactor studies which supported sophisticated and extensive neutronics analysis activities; and (iii) a special fusion neutronics R&D program that aimed at methods development, data improvement and integral experiments.

In the late 1970s, Japan initiated a strong fusion neutronics program. In the early 1980s, two major fusion neutronics facilities were completed in Japan: the

FNS facility at JAERI, and the OKTAVIAN facility at Osaka University. Both facilities were built specifically for fusion neutronics. Many of the scientists and experimentalists who built and operate them were trained in the United States and Germany. The designs of FNS and OKTAVIAN combined the best features of US facilities and technologies. The two facilities now have capabilities unparalleled anywhere else in the world.

While the Japanese neutronics program was expanding and starting new facilities in the early 1980s, the US neutronics program was reducing its activities and terminating all neutronics experimental programs. A similar situation occurred outside the fusion program for the broader base of nuclear data and neutronics methods development because of the reduction in support for the fission program in the United States. Since a significant part of fusion neutronics depends on data and methods obtained from the fission and other nuclear programs, such a decline contributed to a reduction in the US fusion neutronics program. In the meantime, the broad Japanese activities on nuclear data and method development outside the fusion program have expanded considerably in the 1980s, further strengthening the fusion neutronics program in Japan.

Table VI.15 provides a summary of neutronics and shielding facilities and research activities in Japan.

a. JAERI: Primary Activities

Two departments within JAERI support fusion research:

- Department of Reactor Engineering (Fusion Reactor Physics Laboratory, Reactor System Laboratory, Shielding Laboratory, and Reactor Physics Operation Facility); and
- Department of Large Tokamak Development (Fusion Reactor System Laboratory).

**Table VI.15**
**SUMMARY OF NEUTRONICS AND SHIELDING FACILITIES IN JAPAN**

| Organization/ Facility | Neutron Yield (n/sec) and Energy | Accelerator | Monitors | Primary Activities |
|---|---|---|---|---|
| JAERI, FNS | $3.2 \times 10^{12}$ n/s, $5 \times 10^{11}$ n/s 14 MeV | C.W. 400 KV, DC (20mA), pulse operation, Duoplasmatron | APM, Th-232 F.C., $BF_3$-long counter | Integral neutronics and shielding experiments; benchmark experiments |
| Osaka University, OKTAVIAN | $3 \times 10^{12}$ n/s 14 MeV | C.W. 300 KV, DC (20mA), pulse operation, Duoplasmatron | NE-213, TOF, activation foils | Neutronics integral experiments; cross-section measurements |
| Tokyo University, CTR Blanket Facility | $2.5 \times 10^{11}$ n/s 14 MeV | C.W. 200 KV, DC (3.5 mA) | He-3 P.C., Th-232 F.C., $BF_3$-long counter | Neutronics and shielding experiments, measurement technique development |
| Kyoto University, Research Reactor Institute | $5 \times 10^{11}$ n/s 14 MeV | 300 KV, DC, pulse operation (6 MA), Duoplasmatron | NE-213, activation foils, $BF_3$, Rem counter | Pulsed neutron experiments |
| Nagoya University | $10^{10}$ n/s | Van de Graaf, DC | APM, activation foils | Materials, neutronics |
| Tokyo Institute of Technology | $10^8$ n/s | Portable type | $BF_3$-long counter, NE-213 | Pulse neutronics experiments |
| Kyushu University | $10^9$ n/s | C.W. 200 KV, DC (100$\mu$A) | APM, activation foils, HE-3 P.C. | |

The primary experimental facility for fusion neutronics is FNS (Fusion Neutronics Source). It uses a 400 KeV deuteron accelerator. It has a rotating target (RTNS-II type) for a high neutron yield (~ $3 \times 10^{12}$ n/s) and a stationary target (yield is $5 \times 10^{11}$ n/s). It has both steady state and pulsed mode operation capabilities. In addition to the neutron source, there are many experimental hardware and instrumentation capabilities specifically constructed for fusion neutronics experiments. A schematic of the FNS facility is shown in Figure VI.6.

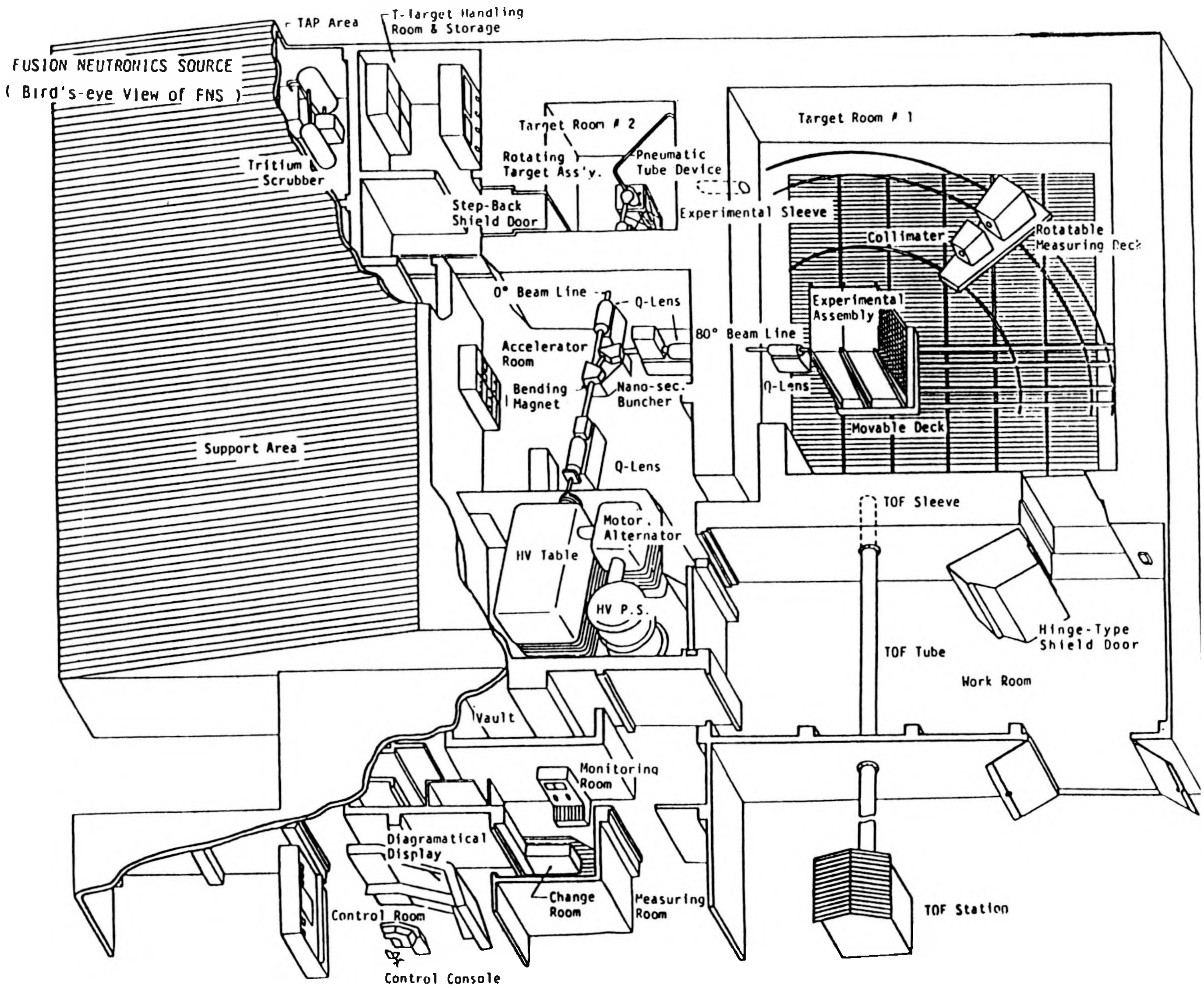



**Figure VI.6**
**SCHEMATIC OF FNS FACILITY AT JAERI**

The neutronics research activities at JAERI are mission-oriented in specified areas that support tokamak-type reactor development. Neutronics research subjects include:

- basic integral benchmark experiments;
- engineering-oriented integral experiments for blanket concept selection;
- fast-neutron-induced effects (activation, radiation damage, dosimetry);
- shielding experiments for fusion reactor design;
- measurement techniques development;
- upgrading Japan's evaluated nuclear data libraries (JENDL) and performing data testing; and
- system design for the next experimental reactor (FER).

Basic integral experiments concentrate on validating nuclear data for materials for fusion applications (Fe, Cr, N, for structural material, Li, O, C, Pb, Be, Oxide breeders, reflector, multiplier). Engineering-oriented experiments provide experimental data and code/data validation on tritium breeding and other neutronics parameters (nuclear heating) in prototypical blanket modules. Fast-neutron-induced effects measurements provide data on material activation, secondary gamma, charged particles and gas production. Shielding experiments are for deep penetration, streaming characteristics in narrow gaps, and multi-layered slit assembly. Measurements development techniques concentrate on local and zonal tritium production measurements, spectra and neutron heating. The Nuclear Data Center at JAERI is the official source for providing recent nuclear data needed for both fission and fusion applications. Nuclear data testing is shared by JAERI and the universities, based on results from integral experiments.

JAERI's fusion neutronics activities are led by T. Nakamura. Other key people include Y. Oyama, T. Ikeda, T. Maekawa, and M. Nakagawa.

b. Japanese Universities

The neutronics activities in Japanese universities are coordinated by the Neutronics Group, which is a subgroup of the MOE Group V—Fusion Reactor Blanket Engineering—supported by MOE Grant-in-Aid. Group V is chaired by Professor K. Sumita at Osaka University, and the Neutronics subgroup is led by

Professor K. Sugiyama at Tohoku University. The Neutronics research is carried out at several universities: Osaka University, Tokyo University, Kyoto University, Tohoku University, Tokyo Institute of Technology, and others.

Table VI.15 gives a summary of the Japanese university facilities. The most powerful facility is OKTAVIAN at Osaka University. It uses a Cockcroft-Walton type deuteron accelerator which is comparable to the RTNS-1 at LLNL and FNS at JAERI. It has been in operation since 1981. It provides a continuous DT neutron source of ~ $3 \times 10^{12}$ n/s using a rotating tritium target and a pulsed DT neutron source with about 2 n/s pulse width. A schematic of the OKTAVIAN facility is shown in Figure VI.7.

The primary fusion neutronics activities in the Japanese universities cover the following areas:

- basic double-differential cross-section (DDX) measurements (Tohoku University, Kyushu University, and Osaka University);

- general activation cross-section measurements (Tokyo University, Nagoya University, and Osaka University) and induced $\gamma$-cross-section measurements (Tokyo Institute of Technology);

- neutron measurements for plasma diagnostics (Tokyo University);

- neutron streaming shielding experiments (Tokyo University, Osaka University, and Kyoto University) and skyshine measurements (Tohoku University, Tokyo University, and Kyoto University); and

- innovative concepts for fusion design using He-3 blanket system (Tokyo University).

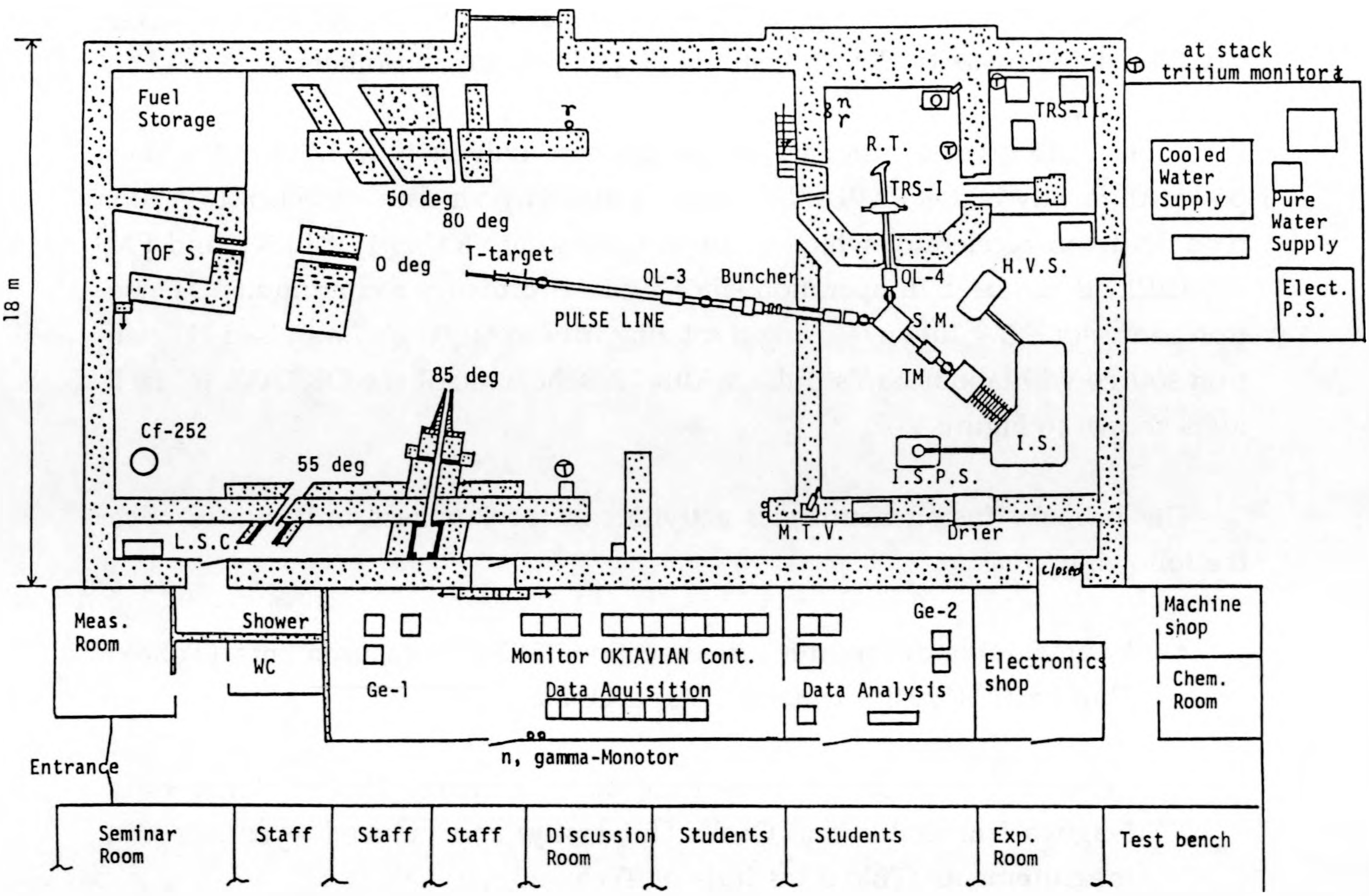



**Figure VI.7**

**OSAKA UNIVERSITY INTENSE 14-MeV-NEUTRON SOURCE FACILITY (OKTAVIAN)**

c. Code Development

The Department of Reactor Engineering at JAERI is a major contributor to neutron transport code development. Most of the neutronics codes used in Japan are based on codes developed earlier in the United States. Japan's recent activities include tailoring these codes (both Monte Carlo and Discrete Ordinates codes) to utilize double-differential cross-section data (DDX) rather than using the Legendre-polynomials form. Major neutronics codes that are used in Japan are Morse DDX, and DOT-DDX. PROF-DD is the major Japanese data processing code. Three-dimensional discrete ordinates codes in Japan are still in the developmental stage. Japanese universities also participate in code development (for example, Tokyo University for sensitivity/uncertainty codes and the TRISTAN three-dimensional transport code, and Kyoto University for deep penetration transport codes).

d. International Collaboration

Japan has strongly encouraged and participated in international collaboration. The largest international collaboration in fusion neutronics is between JAERI and the United States. Under this collaboration, joint integral neutronics experiments are being carried out at FNS (Abdou and Nakamura, 1988). The collaborations include pre- and post-experiment analyses, performing experiments, and experimental technique development. The collaboration started in 1984 as ANNEX-II of the US DOE-Japan fusion collaboration agreement.

There are other small collaborative efforts. Germany is collaborating with FNS on instrumentation technique development. There is also a small joint program between the United States and OKTAVIAN to conduct neutronics integral experiments on beryllium spheres. There have been numerous personnel exchanges in fusion neutronics between Japan and the United States, and also with Europe, which involved extended stays (months to years).

## 3. Outlook

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 to increase the neutron yield to $1 \times 10^{13}$ n/s and to provide 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 data base, to improve methods, and to perform new integral 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 Europe in 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.

## E. TRITIUM PROCESSING

### 1. Accomplishments and Capabilities

Japan had no significant tritium handling technology prior to active interest in fusion R&D. The experience with handling significant quantities of tritium was severely limited until the mid 1980s. The Japanese scientists recognized these limitations and started in the early 1980s to plan a major program aimed at gaining experience in tritium handling. The subcommittee for the Nuclear Fusion Council on R&D for reactor technology decided in 1986 that tritium technology is a key fusion reactor technology for which capabilities and experience within Japan must be developed.

The primary research activities on tritium processing in Japan can be conveniently classified into five areas (M. Okamoto et al., 1988):

- tritium processing program at JAERI;
- joint research project between JAERI and Los Alamos National Laboratory (TSTA);
- tritium processing activities at Japanese universities;
- environmental and biological effects of tritium activities in Japanese universities; and
- tritium production technology.

The tritium processing laboratories in Japan that serve the above activities (except for TSTA which is located in the United States) are listed in Table VI.16.

**Table VI.16**
**TRITIUM PROCESSING FACILITIES IN JAPAN**

| Facility | Organization/ Location | Level of T Handling | Primary Activities |
|---|---|---|---|
| **JAERI** | | | |
| TPL: Tritium Processing Laboratory | JAERI, Tokai | Grams T | Tritium processing (basic, engineering, and demonstration of fuel cycle) |
| **Universities** | | | |
| Nuclear Engineering Research Laboratory | Tokyo University | 100 Ci | Tritium separation, containment |
| Tritium Science Center | Toyama University | 5000 Ci | Tritium chemistry and T-material interaction |
| Tritium Laboratory | Tokyo Institute of Technology | 50 Ci | Isotope separation, tritium-plasma experiments |
| Tritium Laboratory | Kyushu University, Department of Nuclear Engineering | 1 Ci | Waste treatment, containment |
| Isotope Separation Laboratory | Nagoya University, Department of Nuclear Engineering | 1 Ci | Tritium isotope separation |
| Tritium Laboratory | Nagoya University, IPP | 10 Ci | Environment |
| **Other** | | | |
| Tritium Permeation, Recovery | Kawasaki heavy industry | $D_2$ | Permeation tests, recovery experiments |

JAERI's tritium processing programs aim at establishing the technology of handling large quantities of tritium in engineering systems, and establishing the technology for guaranteeing safety associated with the introduction of tritium into large-scale facilities. The primary facility at JAERI is the Tritium Processing Laborator (TPL), completed in December 1987. The first operation with tritium (about 3 gm) occurred in March 1988. The main focus of TPL is to prepare for the tritium fuel cycle in the Fusion Experimental Reactor. There is a plan to further upgrade the TPL facility.

While TPL is relatively large and has sufficient hardware capabilities to address fusion tritium processing issues, it is noted that the experimental work on TPL has thus far been severely limited. This may reflect the lack of prior tritium experience and a cautious approach in handling a new technology. In an effort to acquire more direct experience with tritium, JAERI entered into collaborative agreement with Los Alamos National Laboratory to perform joint experiments on TSTA. The operation of TSTA is funded equally by Japan and by the United States at $2 million/year each.

The tritium processing activities at Japanese universities and national research institutes emphasize basic and long-term research. These activities also provide a supporting function to JAERI through analysis of phenomena, functional tests of the equipment and materials, and other activities.

An interesting activity in Japan related to tritium is conducted by Japanese universities entitled, "Environmental and Biological Effects of Tritium." This work is the subject of Group II under the MOE Grant-in-Aid program for Special Research Projects on Nuclear Fusion (see Table VI.1). The research of this group is concerned with environmental and biomedical effects of tritium. Examples of research areas include the following:

- the transfer of tritium in the environment;
- biomedical effects of tritiated water;
- metabolism of tritium and its biological effects;
- oxidation of tritium gas by microbes;
- tritium content in Japanese bodies; and
- *in vivo* somatic mutation in mice induced by tritium.

No similar study is directly funded by other world fusion R&D programs.

Japan does not have an existing capability to produce significant amounts of tritium. On the other hand, substantial quantities (tens of grams) are required to support the fusion tritium processing experiments. Furthermore, Japan would need much larger quantities, hundreds of grams, for initial operation of FER. In addition, if FER does not have its own tritium breeding blankets, an external supply of several kilograms of tritium will be needed.

This situation is not encountered by weapons-producing countries with large fusion programs, such as the United States, the Soviet Union, and France. Japan, therefore, is including in its tritium R&D activities for fusion, the development of some tritium production capabilities through irradiation of lithium-containing materials in fission reactors. At present, Japan is in the process of completing the capability for producing 1 to 10 g tritium/batch. In addition, plans are being completed to produce 10 to 100 g tritium/batch in JMTR. In addition to producing tritium in fission reactor irradiation, other methods such as extraction of tritium from heavy water coolants are being explored.

### 2. Outlook

The Japanese program made significant progress over the past five years in developing hardware capabilities and initiating research projects related to tritium processing, handling and containment. Japan started with practically no capabilities in the late 1970s. At the end of the 1980s, Japan's capabilities are not far behind those of the United States. Japan plans to take the following steps:

- upgrade TPL;
- build a tritium mock-up test laboratory;
- build other small scale experiments dealing with various aspects of tritium physics and chemistry, and interaction with materials; and
- develop technology for tritium recovery from the blanket.

Given the normal firm commitments in Japan to five-year plans, it should be assumed that such plans will be implemented. Such capabilities and activities, together with the experience Japanese scientists are gaining at TSTA 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.

The primary tritium processing facility given in Table VI.16 is TPL at JAERI, with the primary objective to develop the tritium fuel cycle technology for FER. In addition to TPL, there are small scale facilities at the universities which are directed toward fundamental research on tritium physiochemistry and toward gaining experience in tritium handling. The more detailed specifications of TPL are given below. Brief remarks on the small-scale facilities in universities are also provided.

**Tritium Processing Laboratory at JAERI.** This facility is the primary tritium processing facility in Japan. It is located in the Department of Thermonuclear Fusion Research at the Naka Fusion Research Establishment at JAERI. Construction of this facility was completed in December 1987. The first operation with tritium (about 3 grams) occurred in March 1988. The facility is located in a new three-floor building with approximately 2,300 square meters of floor area. The specifications of the facility are as follows:

- Basement: Liquid waste storage tanks, waste processing room (solidification).

- First Floor: Glove box room (five boxes, total volume ~ $50m^3$) (detritiation room regeneration system for detritiation system), semi-hot experimental rooms, tritium gas storage room, tritium monitoring room, master data acquisition and control room, glove box clean up system, emergency room clean up system.

- Second Floor: Semi-hot experimental rooms.

- Tritium Inventory: 16 g $T_2$ (licensed capacity 60 g $T_2$).

- Glovebox Cleanup System: Flow rate, 150 $m^3$/hr.

- Room Air Cleanup System: Flow rate 150 $m^3$/hr at emergency once-through operation, 300 $m^3$/hr at emergency circulation operation.

**Nuclear Engineering Research Laboratory, Tokyo University.** Tritium separation, safety handling, removal, breeding materials, tritium plasma experiments, tritium-metal interactions; Glove box, $T_2$ : 10 Ci/day.

**Tritium Science Center, Toyama University.** Tritium chemistry, tritium-material interaction, tritium measurement; Glove boxes (3), $T_2$ : 5000 Ci.

**Tritium Laboratory, Department of Nuclear Engineering, Kyushu University.** Tritium separation, removal, safety containment; Glove box (1), 1 Ci.

**Tritium Laboratory, Tokyo Institute of Technology.** Tritium-Isotope separation, tritium-material interaction, tritium-plasma experiments; Glove boxes (2), NMR, surface analysis, $T_2$: 50 Ci.

**Isotope Separation Laboratory, Department of Nuclear Engineering, Nagoya University.** Tritium isotope separation (water distillation, thermal column) HT, 1 Ci.

**Tritium Laboratory, IPP-Nagoya.** Waste management, tritium safe containment, tritium-material interaction, Glove boxes (2), 10 Ci.

## F. MATERIALS AND PLASMA-FACING COMPONENTS

### 1. Introduction

During the late 1960s and early 1970s, worldwide efforts on nuclear materials research were extensive, with minor contributions from Japan. Research on nuclear materials was propelled by the expansion in nuclear power production, and particularly by the prospects for the commercialization of the fast breeder reactor. Materials development was considered to be fundamental to the economics of nuclear power. Japan, on the other hand, had strong components of basic materials research during this period, even though not directly with a technological orientation.

Prospects for fusion energy have stimulated further world-wide research on materials. Because many problems in fusion reactor materials stem from radiation interaction with matter, the transition from fast-breeder-oriented applications to fusion applications proceeded in a manner beneficial to fusion materials development. While this transition has been accompanied by an overall reduction in world (and particularly US) efforts on nuclear materials, Japanese contributions have been increasing. It is accurate to say that since the late 1970s, US materials research activities have been declining, while those of Japan have increased rapidly and are quite vigorous. This section presents an assessment of the progress made by Japanese researchers in the field of fusion materials, particularly during the past five years. An overview of research activities is presented in the following section. Recent contributions are classified into fundamental research, structural materials and ceramics, and the development of plasma-facing materials. A description of the various research organizations and their recent accomplishments follows in Section VI.F.3. The outlook for future Japanese fusion materials research is also outlined in Section VI.F.3.

## 2. Overview

Research on fusion reactor materials in Japan is loosely organized under the following three organizations:

- national universities and institutes;
- the National Research Institute for Metals; and
- the Japan Atomic Energy Research Institute.

The support for research at universities comes mainly from the MOE Grant-in-Aid program. The major mission of this research is focused on fundamental studies of radiation damage by simulation experiments (electron and ion irradiation), and theory and modeling. Innovative research is encouraged in universities where preliminary work is performed on new materials concepts. NRIM assumes the national leadership role in all aspects of materials development, including fusion materials. JAERI emphasizes neutron irradiation effects and the development of near-term solutions to technological, structural, and plasma-facing materials problems. While JAERI's researchers have experimental capabilities for the stimulation of plasma edge conditions and plasma disruption effects, they lack high-fluence neutron irradiation facilities. For this purpose, bilateral collaboration with the United States has been essential in Japan's materials development strategy, since the major high-fluence irradiation facilities exist in the United States. Collaboration with the European Community has proceeded on the same basis and the use of operating fission reactors is pursued whenever possible.

a. Fundamental Research

Significant contributions have been made by Japanese researchers on three aspects of fundamental research, while in one area their efforts are considerably weaker than in the United States. Advances have been made in three areas:

- 14 MeV cascade damage;
- microstructure evolution under irradiation (for example, Igata, 1985; Igata et al., 1986); and
- gas effects on materials (Igata et al., 1984; Ohnuki et al., 1986).

However, Japanese efforts in the areas of theory and modeling of radiation effects phenomena are lagging the United States (Kitajima, 1986; Kitajima et al., 1985).

The unique features of 14 MeV neutron collision cascade damage have been extensively studied by using the US facility, RTNS-II, located at Lawrence Livermore National Laboratory. This facility, which is no longer in operation, generated a reasonable neutron fluence up to $10^{19}$n/cm$^{-2}$ of 14 MeV neutrons. Fission-fusion damage correlations rely on a detailed understanding of the nature of radiation damage in fission as opposed to the fusion environment. The thrust of Japanese fundamental research in this area is to reveal the damage mechanisms and hence to be able to make useful design correlations. The presence of RTNS-II in the United States has attracted Japanese collaboration on 14 MeV neutron damage. On the other hand, the US program has benefited from the superb post-irradiation analytical and materials testing capabilities present in Japan. Joint research resulted in a greater understanding of the nature of 14 MeV collision cascade damage in different structural materials. Low-fluence mechanical properties testing, as well as computer modeling, resulted in a correlation between the production of dislocation loops by 14 MeV neutrons, and the degree of hardening and loss of ductility. The recent shut-down of RTNS-II in the United States may play a significant role in accelerating Japanese efforts for constructing a dedicated national 14 MeV neutron test facility.

While the interest in damage simulation by accelerators has declined in the United States, Japanese researchers have utilized their non-neutron irradiation facilities to study fundamental damage mechanisms. Extensive utilization of High Voltage Electron Microscopes (HVEM) and ion-beam accelerators have been made to study the effects of environmental and material variables on the radiation damage process. New facilities, which will be discussed in the following section, have produced an extensive database on the radiation response of materials to the following variables:

- co-production of gases (helium and hydrogen) and displacement damage;
- irradiation temperature;
- applied stress;
- alloy composition and impurity content; and
- prior heat treatment.

Extensive applications of the US computer code (MARLOWE) by Japanese researchers have been made over the past decade. MARLOWE was developed at ORNL, and is based on a static Monte Carlo simulation of binary collisions. MARLOWE and TRIM (developed by Sandia Laboratories for random targets) have been the work-horses for the simulation of collision cascade damage. Recently, Japanese modifications to MARLOWE were completed for time-dependent Monte Carlo calculations.

Modeling the effects of irradiation on the mechanical properties is achieved by incorporating measured size and densities of irradiated microstructures in metallurgical expressions for macroscopic properties. Simple models for the effects of irradiation on the loss of ductility and embrittlement of austenitic and ferritic alloys were advanced in Japan. These models are not new, and have not been established previously by the international metallurgical community. The work attempts to define temperature-fluence design windows for the use of steels in fusion structures (Nagakawa et al., 1985).

b. Development of Structural Materials and Ceramics

For near-term structural applications, the US program has successfully developed a low-swelling, high-temperature austenitic steel, termed the primary candidate alloy (PCA). Titanium additions to 316 SS produce a fine dispersion of carbides which suppress the propensity toward neutron swelling. Japanese efforts produced an alloy, JPCA, which is almost identical to the US counterpart (Igata et al., 1984; Aono et al., 1985). Ferritic/martensitic steels have also been developed in Japan in a similar direction to the European and US work on the steel, HT-9, for high-temperature applications (Nagakawa et al., 1985; Kayano et al., 1985; Asano et al., 1988). It was shown first in the United States that low-activation ferritic martensitic steels could be developed by substitution of the elements which result in long-term radioactivity by others which produce fast-decaying radioactive chains. Japanese research in this area is based on the same idea, and expands on the concept by investigating a large number of alloys and heat treatments. The Japanese work is directed mainly towards the practical aspects of structural applications, by optimizing the composition and heat treatments of steels (Kamada et al., 1985; Saneyoshi and Abe, 1985). Japanese research on low-activation vanadium alloys has benefited from previous efforts in Europe and the United States. Additions of iron, titanium, and chromium are pursued to improve and optimize the overall mechanical properties (Ohnuki et al., 1988, Matsui et al., 1986). It is concluded here that Japanese research on the development of steels and vanadium alloys is not highly imaginative and is based on earlier European and US work. However, beyond the conceptual stage of alloy development, the Japanese effort concentrates on the practical and technological aspects of new alloy systems.

Japanese research on the development of refractory metal alloys, on metal-matrix and ceramic-matrix composites, and on structural ceramics is well ahead of US and European efforts. It appears that the Japanese approach is to develop these materials for general high-temperature applications, as in the aerospace and energy production industries, as well as for fusion applications. Examples of key contributions on refractory metals are given in references (Furuya and Kainuma, 1984; Aono et al., 1988).

c. Development of Plasma-Facing Materials

During the past five years, progress in Japan has been made in a number of relevant research areas, the most important of which are discussed below.

**Graphite-Hydrogen Interaction.** A concerted effort on graphite behavior in plasmas was initiated around 1980, with a large project at Hokkaido University. The project is aimed at determining the vacuum and thermo-mechanical properties of graphites as well as the interaction of plasma ions with the graphite surface. Recycling of hydrogen atoms from graphites is studied at Nagoya University. Works by Miyahara and Tanabe (1988) and Ashida et al. (1987) show examples of recent Japanese work on graphite-hydrogen interaction.

**Interaction of Plasma Particles with Surfaces.** Past experimental measurements on reflection, sputtering, and implantation of low energy ions (below 100 eV) have been extremely difficult. Morita's group at Nagoya University has successfully measured the hydrogen reflection coefficient from material surfaces in this low energy range. Characterization of plasma-material interaction in this range is advanced in Japan, and appears to be at a level comparable with that in the United States.

**Coating Response to Plasma Disruptions.** Pulsed electron beam irradiation is used at Osaka University to test the thermal response of TiC-coated plasma-facing components. Surface damage induced by a simulated plasma disruption is systematically characterized for various coated materials. Work in this area is similar to the research performed at Sandia Laboratories in the United States. Detailed results on coatings can be found in references (Kato et al., 1985; Kawamoto et al., 1985).

**Chemical Sputtering.** New erosion mechanisms of plasma-facing components have been identified at JAERI as chemical sputtering by the formation of chemically-active oxides in the plasma scrape-off layer. Low-Z elements were found to be more prone to oxidation sputtering, which may affect the choice of the surface material in plasma-facing components (Ashida et al., 1985; Kiuchi and Kondo, 1988).

**Simulation of Plasma Disruption Effects.** Testing various forms of graphites at Osaka University has shown that sublimation is a dominant damage mechanism for heat fluxes above 37 $MW/m^2$ with a 1.5 second duration. However, tungsten-coated graphites exhibit surface melting under similar conditions.

### 3. Accomplishments and Capabilities

#### a. National Universities and Institutes

Fusion materials research in Japanese universities and institutes tends to focus on the fundamental aspects of radiation effects on structural materials, and on the effects of plasmas on plasma-facing components. Research is mainly supported by the Grant-in-Aid program funded by MOE as discussed earlier in Section VI.B. Research Group I for Reactor Materials and Plasma-Wall Interactions, which is one of six groups supported by the Grant-in-Aid program, is further divided into two subgroups: (i) structural materials, and (ii) in-vessel materials. The first subgroup, headed by Professor S. Ishino at Tokyo University, conducts experimental and theoretical investigations of irradiated materials under systematically established irradiation conditions. The main objective of the group is to develop methodology for predicting material behavior under the complex conditions of fusion reactors.

Evaluation of isotropic graphite for fusion applications is the main objective of the second subgroup, which is directed by Professor Toshiro Yamashina at Hokkaido University. This project started in 1980. During the period from 1980 to 1989, the behavior of 18 isotropic graphites (supplied by seven Japanese graphite companies) was investigated. The group's effort focused on the following:

- vacuum properties (gas desorption, surface roughness, and hydrogen permeation);
- interaction of graphite with hydrogen ions; and
- thermo-mechanical properties of graphite.

Low radioactivity vanadium alloys are developed by another subgroup, and the efforts are directed by Professor Nagasaki at Hokkaido University. They conduct the following investigations:

- high temperature strength of materials;
- microstructure and radiation damage; and
- improvement of corrosion resistance.

Research on low-activation ferritic/martensitic alloys is an important component of the Grant-in-Aid, NRIM, and JAERI programs. Two groups are conducting investigations of low-activation ferritic/martensitic steels. A corrosion resistance project (under Hamaguchi) is studying the dependence of corrosion resistance on the matrix concentration of elemental chromium (Cr) and the effects of irradiation on the segregation and further matrix depletion of Cr. This investigation does not have a parallel in the United States, and is important for water-cooled fusion blankets. Professor Hosoi at Nagoya University directs a subgroup to investigate the effects of radiation on the microstructure and properties of reduced radioactivation steels. The purpose of this research is to investigate the effects of tungsten (W) and manganese (Mn) on the microstructure (phase transformation, formation of metallic compounds, irradiation induced segregation, and helium bubble formation) and the mechanical properties (high temperature strength, Charpy impact strength, and fracture toughness) of Cr-W and Cr-Mn stainless steels.

Professor Kiritani at Nagoya University leads a group to study defect structures and mechanical properties of materials irradiated by fusion neutrons. The research started as a collaborative US-Japanese experimental program utilizing RTNS-II at the Lawrence Livermore National Laboratory until 1987. Reduced US funding effectively terminated the irradiation experiments at RTNS-II. However, Kiritani's group is engaged in performing post-irradiation experiments at the Oarai Branch of Tohoku University. These post-irradiation experiments are expected to be completed by 1990-1991.

Small-specimen-testing technology was developed in the United States by Lucas (UCSB) and others. An effort to utilize this technology was made in Japan, with a small group supported by the Grant-in-Aid at Nagoya University. As will be discussed later, both NRIM and JAERI have similar efforts in this area (Misawa et al., 1987). The Nagoya work is conducted primarily by Kazuya Miyahara and is aimed at tensile testing of irradiated structural materials. A small load cell was developed in collaboration with Kyowa Dengyo Co., Ltd., to eliminate frictional forces in the tensile testing of small specimens.

Radiation damage in ceramics is investigated at Kyushu University by Kinishita's group, with the main emphasis on evaluating the effects of radiation on displacement and kinetic processes, as well as an assessment of the property changes of ceramics under irradiation. The group is conducting experiments on $Al_2O_3$, $MgAl_2O_4$, Ge, TiB, SiC, $Y_2O_3$, BeO, and the high-temperature superconducting material $YBa_2Cu_3O_7$ (Baba and Sasaki, 1987, 1988).

The effect of plasmas on in-vessel components is the subject of investigation at Yokohama University (directed by Professor Usami) and Nagoya University (directed by Professor Morita). Usami's group is determining experimentally the ion reflection properties of and hydrogen recycling from plasma-facing components. Morita's group, on the other hand, is experimentally investigating ion-wall materials interaction in the low energy regime (below 100 eV). The main purpose of the project is to develop a database of physical and chemical processes of the interaction between wall materials and ions with energies in the range of 5 to 100 eV.

Research facilities on fusion materials in Japanese universities and institutes can be classified into the following categories:

- neutron irradiation facilities;
- damage simulation facilities; and
- computational facilities.

Table VI.17 lists the facilities and their main characteristics, while Table VI.18 lists the main US experimental facilities used by Japanese researchers in joint US-Japanese collaboration. Japan has made significant advancement during the past five years on research accelerators, high-voltage electron microscopes, heavy-ion irradiation facilities, materials characterization technology, small sample test equipment, as well as supercomputer technology. However, neutron-irradiation facilities are limited in Japan, and the incentive to use US neutron facilities (HFIR, ORR, FFTF, and RTNS-II) facilitated US-Japanese collaboration on fusion materials. The major thrust of the Japanese research efforts is experimental, with superb systematic investigations of the effect of materials and irradiation variables. Theory and modeling efforts are somewhat lower in quality than what is expected with such a large experimental program.

(1) Fundamental Damage Studies

The effects of helium and hydrogen on precipitation behavior and phase stability of steels have been studied. It has been shown that hydrogen is retained in steels up to about 300°C, enhancing interstitial loop nucleation and adding to the embrittlement of steels under irradiation. The effects of internal gases (hydrogen and helium) on the embrittlement of steels was studied in the HVEM under light ion bombardment and under stress conditions. It has been shown by Ishino's group that hydrogen embrittlement remains up to 400°C. This result contradicts previous assumptions on the role of hydrogen in the embrittlement of irradiated materials.

Progress has been made on modeling the irradiation behavior of materials under fusion conditions. This work, which is primarily carried out by Kitajima, Muroga, and Ishino, is based on stochastic microstructural evolution under cascade damage. The theory was originally developed by Kitajima, and later applied to fusion conditions by several Japanese investigators. The theory offers the potential for predicting the nucleation and growth phases of microstructural features under cascade damage. This is useful for extrapolation of the present database to anticipated fusion conditions. An effort was made by Muroga and coworkers to calculate and experimentally measure the rate of precipitate dissolution under irradiation. Their work is based on the MARLOWE code, which was developed at ORNL in the 1970s. The code performs Monte Carlo calculations of binary atomic collisions, thus simulating the early stages of radiation damage.

## Table VI.17
## MAIN FUSION MATERIALS RESEARCH FACILITIES IN JAPAN

| Research Facility | Main Characteristics | Comments |
|---|---|---|
| JOYO | A fast reactor neutron test facility. Neutron flux is $2.2 \times 10^{14}$ n/cm$^2$/s (E > 0.1 MeV). Temperature is 400-600°C. Attainable dose is about 5 dpa at a dose rate of $2 \times 10^{-7}$ dpa/s. | The facility is at Tokai-Mura, JAERI. Temperature control is ± 3 K. |
| JMTR (Japan Materials Test Reactor) | A mixed spectrum neutron reactor dedicated to materials testing. Neutron fluence of up to $1.5 \times 10^{23}$ n/cm$^2$ (E > 0.1 MeV) can be achieved. | |
| Osaka University, Electron Linear Accelerator | Beam energy, E = 20 MeV, 30 MeV; pulse width = 1.5 μs, electron flux (1.5 - $3.5 \times 10^{14}$/s), repetition rate = 120 pulses per second. | At the Institute of Scientific and Industrial Research of Osaka University. It is used for run-away-electron damage simulation. |
| Tokyo University, In-Situ Damage Facility | Crockroft-Walton type accelerator of maximum accelerating voltage of 400 kV. Ions are directed onto specimen in a 200 kV transmission electron microscope (JEM-200 C). Ion beam fluxes in the range $1.3 \times 10^{14}$ - $1.3 \times 10^{16}$ ions/m$^2$ can be produced. TEM images can be recorded on a video system. | This is one of the few facilities in the world which can provide in-situ observation of damage and microstructural evolution. |
| Kyushu University, Positron Annihilation Facility | The facility is used for determination of the characteristics of small defect clusters resulting from radiation damage. | The facility has high resolution for the measurements of positron life time (235 ps). |
| High Energy Ion Accelerator of the Muroran Institute of Technology | Ion irradiation for uniform displacement damage in thin samples. 16 MeV proton irradiation has been performed at 500 mA/m$^2$ in the temperature range 160-250 K. | Temperature is not uniform throughout the sample. |
| Osaka University, Low Energy Ion Accelerator | 20 keV He+ are implanted in plasma-facing components to study plasma-material interaction. Ion flux = $6 \times 10^{14}$ cm$^{-2}$s$^{-1}$, and the dose = $2 \times 10^{15}$ - $3 \times 10^{17}$ cm$^{-2}$. Damage is investigated with a JEM-200C X TEM at 120 keV. | Facility is used for thermal release experiments. |

## Table VI.17
## MAIN FUSION MATERIALS RESEARCH FACILITIES IN JAPAN
(continued)

| Research Facility | Main Characteristics | Comments |
|---|---|---|
| Nagoya High Heat Flux Text Facility | 10 MW neutral beam injection test stand at IPP. Ion source produces 75 A, 120 keV H + beams for 1 second. Vacuum is at $10^{-4}$ Pa. | Maximum achievable heat flux is 100 $MW/m^2$. |
| Hokkaido University, HVEM Electron Irradiation Facility | H-1300 High Voltage Electron Microscope (HVEM) with 1 MeV electrons. Damage rate is $2 \times 10^{-3}$ dpa/s. Post irradiation analysis is performed with an Energy Dispersive X-ray Spectrometer (EDS) in a 200 KeV Transmission Electron Microscope (TEM). | High temperature operation (620-820°C) is possible. Damage achieved is about 15 dpa. |
| Tokyo University, High Fluence Irradiation Facility | Used to simulate the simultaneous production of displacement damage and helium production in materials. 4 MeV nickel ions are simultaneously injected with 1 MeV helium ions at $3 \times 10^{-3}$ dpa/s. | The facility is very similar to the ANL facility (US). |
| Nagoya University, Ion Implantation Facility | Low energy (about 2 keV) hydrogen ions are implanted to a fluence of $4 \times 10^{17}$-$2 \times 10^{18}$ $cm^{-2}$ 1.5 MeV He+ ions are used for Elastic Recoil Detection (ERD). | Facility has a TEM and surface analysis. It is used for H-recycling studies. |
| Muroran Institute of Technology, Coolant Compatibility Facility | Stress corrosion cracking (SCC) studies are performed on miniaturized steel samples in hot water. | |
| Hokkaido University, Ion Implantation Facility | Low energy ion implantation with simultaneous 1000 kV HVEM electron irradiation. Ion fluence = $3.5 \times 10^{20}$ $H+/m^2$. | |
| Kyushu University, Ultra High Vacuum Irradiation Chamber | A conventional ion gun (0.5 - 5 keV) gives ion fluence = $10^{20}$ - $10^{22}$ $m^{-2}$. This is followed by thermal desorption (TD) of implanted deuterium and subsequent electron irradiation (1 MeV in HVEM). Microchemistry is analyzed by the Energy Dispersive X-ray Spectrometer (EDS) attached to TEM (JEM-2000 FX at 200 kV). | The facility is used to study hydrogen trapping by irradiation objects. |

## Table VI.18
## MAIN US FUSION RESEARCH FACILITIES USED IN US-JAPANESE COLLABORATIONS

| Research Facility | Main Characteristics | Comments |
|---|---|---|
| FFTF/MOTA (Fast Flux Test Facility) | A fast neutron irradiation facility with high-fluence characteristics. Specimen temperatures are in the range (350-600°C). The achieved dose is (5-10) dpa below the core position and (20-40) dpa in the active core per cycle (6 months). | The facility is in Hanford, Washington (US). MOTA is a Materials Open Test Assembly designated to fusion materials. The facility is used in US-Japanese collaborative research. |
| HFIR (High Flux Irradiation Reactor) | A mixed spectrum neutron irradiation facility. Temperature is in the range (70-600°C). High concentration of helium can be produced in nickel-containing steels. A dose up to 30 dpa/ year can be achieved. | The reactor is at Oak Ridge National Laboratory (ORNL), Tennessee (US). It is shut down at present. The facility was used in US-Japanese collaborative research. |
| RTNS-II (Rotating Target Neutron Source-II) | The only 14 MeV neutron irradiation facility which could be used for preliminary fusion material testings. Fluence up to $10^{19}$ n/cm$^2$ has been achieved. Samples were irradiated in the temperature range (25-550°C), including some low temperature irradiation at 20 K. | The facility is located at Lawrence Livermore National Laboratory (US). It is shut down at present due to lack of designated funds. The facility was used in US-Japanese collaborative research. |
| ORR (Oak Ridge Research Reactor) | A neutron irradiation research reactor. The fast flux and fluence for typical irradiation at ORR are (1-2) x $10^{14}$ n/cm$^2$ and (1-2) x $10^{21}$ n/cm$^2$ (E > 0.1 MeV). | The facility is at ORNL, Oak Ridge, Tennessee (US), and is used in US-Japanese collaborative research. |
| EBR-II (Experimental Breeder Reactor-II) | A fast neutron test facility. Fast neutron flux at the core is 1 x $10^{15}$ n/cm$^2$/s. | The reactor is at a US facility in Idaho, and is used in US-Japanese collaborative research. |
| Argonne National Laboratory (ANL) Dual Ion Beam Irradiation Facility | Used in collaboration with Tokyo University to study the effects of He/dpa ratios. 3 MeV nickel ions are injected simultaneously with 0.83 MeV He ions at the damage rate of 3 x $10^{-3}$ dpa/s. | High temperature irradiation facility. |

Fundamental studies on cascades and the effects of He co-production were conducted by in-situ observation of sub-cascade structures in Au at -150°C, and the results were compared to computer simulations of cascades. It was shown that collision cascades break up into subcascades with primary knock-on atom

(PKA) energy in the range of 20 to 30 keV. These in-situ experiments and their comparison with computer simulations represent the state of the art in the understanding of fundamental damage processes.

(2) Fusion Alloy Development

Several alloys and structural materials are actively being developed in Japan for fusion applications. These are:

- **Low activation vanadium-base alloys.** The emphasis is on improving the high temperature strength by addition of Fe, Ti, and Cr in order to increase solute hardening. Surface treatments of V-15Cr and V-15Ti alloys were performed by heating at 1173 K to 1523 K in SiC powder, in order to improve the oxidation resistance of the alloys. Surface treatments were found to be more effective in V-Ti alloys.

- **Low activation steels.** Both ferritic Cr-W steels and austenitic Cr-Mn steels are being developed as substitutes for Cr-Mo and Cr-Ni stainless steels. Fujita proposed a composition of 0.1% C-0.5%Mn-0.05%Si-9%Cr-2.5%W-0.2%V-0.12%Ta-0.05%N as one of the best reduced radioactivation, high-temperature steels. This steel is estimated to have a creep-rupture strength of 18 to 20 $kgf/mm^2$ at 600°C and $10^4$ hours. The shift in ductile-to-brittle transition temperature (DBTT) by neutrons was found to be small.

In Cr-Mn austenitic steels, the problem of phase stability under irradiation seems to be significant. A brittle sigma phase is formed in the temperature range of 300 to 600°C, which is most desirable for the operation of a power reactor. It has been found that ductility of the steel decreases with increasing Mn content.

For water-cooled steel blankets, Hamaguchi of the Muroran Institute of Technology has experimentally investigated radiation effects on stress corrosion cracking (SCC) and established that Cr depletion by irradiation is the primary cause.

(3) Microstructure—Mechanical Property Investigation

Kiritani's group at Nagoya University is concentrating on experimental and theoretical studies of the effects of fusion neutrons, produced by RTNS-II, on the development of microstructures. The group also has extensive experimental post-irradiation facilities to examine irradiated microstructures, and to perform small-sample mechanical property tests. Two major contributions have emerged from the efforts of Kiritani's group:

- a thorough experimental investigation of the nature of defects produced by fusion neutrons, coupled with computational simulations of fusion collision cascades; and

- determination of mechanical property changes, in the low neutron fluence regime, of fission and fusion irradiated materials. Efforts at deriving fission-fusion correlations have also been pursued by the group.

The high temperature deformation and fracture of ion- and neutron-irradiated materials have been investigated by Miyahara of Nagoya University. A high temperature-vacuum tensile testing machine for very small specimens has been developed in collaboration with Japanese industries. This tensile testing machine is accurate for small-size specimens where friction in the loading cell usually contributes to load uncertainty. The primary thrust of the study is to identify the fracture mode of irradiated small steel samples. While helium has been shown to lead to intergranular brittle fracture in type 316 SS, it leads to transgranular ductile fracture for Fe-Cr-Mn alloys.

(4) Research on Plasma-Facing Components

Emphasis in this area is in the development of graphite and SiC as plasma-facing and first wall materials. In 1986, the "Graphite Project" was initiated. Eighteen isotropic graphic materials supplied by seven Japanese graphite companies were characterized in the following areas:

- vacuum properties, such as gas desorption, surface roughness, and hydrogen permeation;

- interaction of hydrogen ions with the surface; and

- thermo-mechanical properties.

It has been shown that once graphites are baked in vacuum, they exhibit extremely small outgassing rate. Gas permeability measurements indicated that gas permeation was due to pore structure on the order of μm.

Experimental research on hydrogen recycling and chemical erosion showed that surface modified graphites with small metal additions display extremely small chemical erosion rate, on the order of $10^{-3}$ to $10^{-2}$ atom/ion.

Usami's group at Yokohama National University has developed a new system for the determination of surface-absorbed atomic hydrogen concentrations in plasma-facing materials. An excimer laser ($\lambda$ = 308 nm, 400 mj/cm$^2$, 20 ns) was used to desorb hydrogen thermally and determine its surface concentration.

An area of extreme importance, and also experimental difficulty, is the determination of surface reflection implantation, and sputtering of low energy (below 100 eV) plasma particles. A $Cu^+$ ion beam, generated with a Cultron-type ion source was used to bombard a gold film deposited on polished isotropic graphite at energies between 5 and 200 eV. Morita's group at Nagoya University determined that the reflection coefficient from the gold surface increases gradually from 0.1 at low energy, attains a maximum value of 0.4 at 50 eV and then decreases as the beam energy increases. By implanting 3 keV hydrogen in graphite, and solving mass balance equations for hydrogen diffusion, trapping, and detrapping, the effective migration energy for hydrogen in graphite was determined to be 0.2 eV.

Miyake's group at Osaka University characterized the thermal shock and fatigue properties of various candidate first wall materials under high heat loads. Pulsed electron beam irradiation was used to test the thermal shock and fatigue of TiC coated graphite, several kinds of graphite, and tungsten-coated graphite. The 10 μm thick TiC coating layers were chemically vapor deposited on substrates made of Poco DFP-3-2 graphite. Above 25 MW/m$^2$ surface heating

(1.5 duration), coated surfaces showed the formation of cracks. Surface exfoliation occurred at 37 $MW/m^2$ , and surface melting at 40 $MW/m^2$.

Sublimation was found to be the dominant damage mode for graphite at 37 to 38 $MW/m^2$, independent of the type of graphite used. No failure was observed below the sublimation limit. On the other hand, heating above 38 $MW/m^2$ (1.5 pulse) for W-coated graphite (10 μm) indicated surface melting but no exfoliation.

(5) Theory and Modeling

During of 18-20 January 1989, a US-Japanese workshop on radiation damage theory and modeling was held at NRIM (Tsukuba). Japanese scientists from national universities and institutes presented the state-of-the-art work of their research in this area. Theory and modeling research can be organized into three categories: (i) cascade damage simulation, (ii) microstructural evolution, and (iii) mechanical properties. These areas are discussed below.

**Cascade Damage Simulation.** Yamamura at the Okayama University of Science described a new computer code, DYACOCT, which simulates cascade damage in fusion materials. The code is an extension of the US codes MARLOWE (ORNL), TRIM (Sandia and IBM), and TRIPOS (UCLA). Using the Monte Carlo method, the code simulates the time-dependent slowing-down trajectory of energetic particles in a collision within the binary collision approximation. The code has been applied to the analysis of the time evolution of cascades, the structure of subcascades, damage efficiency, and vacancy cluster calculations. The code represents an advancement over existing US codes (MARLOWE, TRIM, and TRIPOS), because it treats the time-dependent nature of primary damage evolution.

Fukumura, Sekimura, and Ishino at Tokyo University are in the process of developing a new computer code for the simulation of collision cascades. The idea is to combine the binary collision approximation at high energies with molecular dynamics at low energies in a time-dependent simulation. However, it appears that they are still far from achieving this goal.

Computer simulations of cascade damage in D-T neutron-irradiated Au, Ag, Ni, and Al by the MARLOWE code were compared to experimental data from RTNS-II by the Hiroshima and Nagoya University groups in collaboration with LLNL. The experiments were done by cryotransfer of samples from RTNS-II to the TEM. Their work concluded that interstitials are ejected from the cascade core to distances larger than calculated by the MARLOWE code. Microscopic interstitial clusters were observed, and cascade overlap was observed at low fluence ($10^{16}$ n/cm$^2$ in Au), and attributed to the large ejection distance of interstitials.

The effects of cascades on the resolution of precipitates were studied by Muraga at Kyushu University. He performed computer simulations using the MARLOWE code for Fe and He in the energy range of 1 to 100 KeV. His work concluded that the resolution rate of small precipates (radius = 1 nm) is complete after irradiation to tens of dpa's, and that stoichiometry changes are expected by recoil resolution.

**Microstructure Evolution.** K. Kitajima of Kagoshima University is the leading Japanese theoretician in the area of microstructure evolution. He formulated a dynamical stochastic theory for microstructure evolution which incorporates the effects of collision cascades. The work is based on non-equilibrium statistical mechanics, and offers great insights into the mechanisms of nucleation and growth of microstructural features. It lacks, however, the detailed computational implementating for deciding on the dominant mechanisms. Smaller efforts on microstructure evolution theory exist in other universities. For example, Kamada of Nagoya University focused on investigating energetic conditions for interstitial loop punching from hydrogen bubbles, and found that the necessary pressure for this process is three times as high as the accepted theory of Greenwood, Forman, and Rimmer (UK-Harwell). Kuramoto of Kyushu University is performing numerical calculations of void swelling in metals. His work is based on well-established rate equations, and only parametric variations result from his calculations.

**Mechanical Properties.** N. Igata of the Science University of Tokyo has been modeling radiation effects on the following mechanical properties: low temperature irradiation effects (≤ 300°C) on BCC alloys; intermediate temperature irradiation effects (400 to 600°C) on BCC and FCC alloys; high temperature irradiation effects (> 800°C) on FCC alloys; and irradiation creep.

Igata's work is based on metallurgically-based correlations between microstructure type, size, and density and the resulting mechanical property. The work relies heavily on experimental measurements for these correlations. Igata's work relates the shift in the DBTT to neutron fluence in BCC alloys. One of the goals is to establish a design window for the operation of ferritic/martensitic steels under fusion conditions.

Mechanisms of ductility loss in neutron-irradiated Cu and Al are studied by S. Kitajima and S. Shinohara at Kyushu University. A combination of neutron irradiation and experimental data analysis revealed that the ductility loss in single crystals is due to the reduction in the work hardening rate by the sweeping out of radiation produced defects.

b. Japan Atomic Energy Research Institute

Fusion materials research in JAERI has concentrated on neutron irradiation effects on structural and tritium-breeding materials, tritium release and recovery under neutron irradiation, functional ceramic materials, and surface and transfer phenomena in plasma-facing materials.

JAERI's research activities emphasize fusion technology, particularly its near-term aspects. For these purposes, JAERI relies on bilateral agreements with the United States to conduct neutron irradiation experiments in the ORNL reactors, HFIR and ORR. Simulated fusion irradiation conditions can be achieved in these mixed-spectrum fission reactors, particularly for stainless steel structural alloys. Irradiation effects on tritium breeding materials are investigated through an International Energy Agency (IEA) cooperative program which started in March 1984.

In the structural materials area, the program focuses on the development of a modified version of 316 stainless steel. Titanium is added to produce a very fine dispersion of carbide particles, which trap helium atoms generated from nuclear reactions, and thus decrease the swelling rate of the alloy. This idea was developed earlier at ORNL, and the titanium-modified alloy was termed PCA, for Primary Candidate Alloy. The Japanese version of the alloy has been named JPCA, for Japan PCA. Welding technologies for fusion applications are to be developed under the US-Japan cooperative agreement. New activities have started at JAERI for the development of low activation ferritic/martensitic alloys and for the development of small sample testing techniques. It is to be noted that both of these areas were first pioneered in the United States, where the basic ideas and techniques were demonstrated.

Research on irradiation effects on tritium breeding materials is pursued through IEA cooperation as discussed in Section C of this chapter. This research is aimed at the development of a database for irradiation effects on tritium breeding materials, on tritium release and recovery under irradiation, and on tritium handling technology. The IEA cooperative agreement (BEATRIX-II plan) includes determination of a candidate material for the next fusion device, with good approximation of the neutron energy spectrum in the blanket region. The agreement was effective in March 1988.

New activities were started in the past two years on the development of ceramic materials for fusion applications. The focus of this research is on ceramics for tritium steam electrolysis and for electrical insulators and RF wave window materials. Other research activities are in the areas of surface phenomena in plasma-facing components and the radiation-assisted corrosion of water-cooled components. The emphasis in the former area is on the chemical sputtering due to the formation of chemically-active surface oxides and gas phase chemical reactions in the plasma scrape-off layer. Research in the latter area is motivated by the need to understand, and possibly mitigate, the synergistic effects of neutron irradiation and chemical processes in the corrosion of water-cooled fusion components.

A modest amount of theoretical and computational research is performed at JAERI. The following description is given of the main experimental research facilities for radiation damage and fusion materials at JAERI:

- **In-situ damage observation system.** This facility uses an ion gun of the duoplasmatron type, with an accelerating voltage of 10 kV, coupled with a JEM-100C electron microscope for in-situ damage analysis. The attained ion flux is on the order of 6 x $10^{18}$ $m^{-2}s^{-1}$ with a current of 1 $A/m^2$. The facility has been used to investigate He and H effects on SiC and TiC.

- **Van de Graaff tandem accelerator facility.** The system is used for light and heavy ion irradiation damage study. He ions have been used at 0.5 MeV and a current of 1 $mA/m^2$ to achieve a dose of 1 x $10^{20}$ $He/m^2$. Heavy ions have been used in radiation damage studies (84 MeV $C^{5+}$, 150 MeV Cl, and 10 MeV Br) at $10^{-8}$ torr vacuum.

- **Electron irradiation and analytical microscope facility.** A JEM-1000D HVEM is used at 1-MeV electron energy to produce a damage rate of 1.85 x $10^{-3}$ dpa/s. High temperature microscope at a voltage of 200 kV. The microscope can be used in the transmission (TEM) mode or the scanning transmission (STEM) mode.

(1) Structural Materials

JAERI has been heavily involved in bilateral collaborations with the United States on the use of the Oak Ridge Reactors HFIR and ORR. Fusion irradiation simulation conditions can be achieved in these reactors, particularly in stainless steel alloys. These reactors have mixed neutron spectra (low- and high-energy neutron fluxes) which can be advantageously used to simulate the displacement damage and helium generation rates anticipated in a fusion environment. Since 1983, JAERI has been carrying out irradiation experiments utilizing HFIR and ORR at ORNL under the US-Japanese collaboration agreements. In these experiments, simulated fusion irradiation conditions are achieved by fast neutron collisions for atomic displacements and by thermal neutron reaction which generate helium through the transformations $Ni^{58}$ $(n, \gamma)$ $Ni^{59}$ $(n, \alpha)$ $Fe^{56}$. Under the US-Japanese agreement, a modification of the reflector region will result in a stronger neutron flux. During the second term of the agreement (1988-1997), data which are more representative of fusion conditions are expected to be available on JPCA. A plan to examine the characteristics of welded materials under irradiation is intended during the second term of the agreement.

The characteristics of neutron-induced swelling of conventional 316 stainless steel (316 SS) as well as JPCA have been studied up to an irradiation dose of 30 to 50 dpa (equivalent neutron wall load of 3 to 5 $MW/m^2$ in a fusion device). Cold-worked (CW) 316 SS has higher strength than the solution-annealed (SA) version, thus allowing higher stress levels. However, welding changes the microstructure in the heat affected zone, thereby posing problems of possible premature failure in that zone under irradiation. JAERI's research concluded that the SA version of JPCA has the best possible combination of low swelling (achieved by a high density dispersion of fine TiC precipitates), high ductility, and good welding characteristics for fusion first wall structures.

The development of low activation materials is considered a key technology for future fusion reactors, and in this direction, JAERI is focusing on ferritic steel development for waste disposal considerations. Nippon steel company, in collaboration with JAERI, developed a new ferritic/martensitic steel (F82H). A good combination of low activation, high fracture toughness and thermal creep rupture resistance has been achieved in this alloy. F82H was shown to perform as well as 2 1/4 Cr-1Mo in terms of absorbed energy (about 32 kgf.m) and better than HT-9 in terms of creep rupture strength at 600°C.

Another effort at JAERI to develop a new structural material is devoted to designing a high temperature alloy (> 500°C) for water-cooled blankets. In this application, the most important factors to consider are the stress corrosion cracking and the irradiation-induced corrosion cracking. A version of type 316 SS is being developed with a combination of alloy composition optimization and heat treatment. The alloy is optimized by straining, aging, and recrystallization procedures. The optimized alloy shows reduced swelling rate under electron irradiation and lower mass loss in hot water compared to the standard 316 SS.

A series of comparative swelling experiments were conducted in ORR, HFIR, and FFTF on JPCA up to 10 dpa. The largest swelling rate was conclusively shown to occur in the ORR neutron spectrum, where the He/dpa ratio is about 20, and is considered to be the closest to fusion conditions. A high swelling rate of about 0.2 percent/dpa was demonstrated at 500°C. This result is considered to be the first one which shows the importance of the appropriate neutron spectrum in fusion experiments.

(2) Tritium Breeding Materials

This topic has been covered previously in the blanket section. Here, the research directly related to materials is summarized.

Radiation effects experiments on lithium oxide ($Li_2O$) have been carried out with both energetic oxygen ions and with fission neutrons. Radiation damage is deemed to be important because it can result in loss of structural integrity for the $Li_2O$ breeder material, and can also cause severely reduced tritium release rates. The focus of JAERI's experiments on $Li_2O$ is on measuring the effects of irradiation on the lithium ion conductivity. It is found that irradiation enhances conductivity at 443 K and results in a reduction at 989 K. These effects were attributed to the formation of $F^+$ centers and trapping sites. The work has been a part of the IEA international efforts (BEATRIX-II), using the fast reactor under international collaboration.

Tritium release experiments have shown that the release rate of generated tritium was much faster in $Li_2O$ than both $LiAlO_2$ and $Li_4SiO_4$. These results strengthen the Japanese arguments on the superiority of $Li_2O$ as a solid breeder because of the high lithium atom density and the potential low tritium inventory. European research, especially in France, is concentrating on $LiAlO_2$ which may require a neutron multiplier but is superior for high temperature operation.

JAERI has been at the forefront of Japanese involvement in international collaboration with the United States, the European Community, Canada, and Switzerland. Under the IEA research agreement (Annex II), solid breeder irradiation testing was carried out under BEATRIX-I and BEATRIX-II in the FFTF (United States). Structural materials irradiation testing was carried out at ORNL in the ORR and HFIR reactors. Irradiation tests were also performed in JRR-2 (Japan), DILOE (France), HFR (Netherlands), NRU (Canada), and EBR-II (United States). Other aspects of JAERI's international collaboration include participation in workshops, joint research on low activation and ceramic insulators, radiation effects theory, and the establishment of an international fusion materials handbook.

(3) High-Energy Neutron Source

In January 1989, a Japanese symposium on high-energy neutron sources for materials testing was held in Tokyo, and was aimed at investigating an R&D strategy for the development of an appropriate test facility. It was concluded that an accelerator-based neutron source would be more practical as compared to a plasma-based neutron source for testing fusion materials. JAERI's proposal for a medium intensity but flexible (energy tunable) neutron source appears to be gaining momentum and support in Japan. T. Kondo presented a concept named ESNIT (Energy Selective Neutron Irradiation and Test Facility). It was concluded that an energy tunable accelerator of tens of mA current capacity can be readily constructed. It is reasonable to expect that this facility will be built in Japan for two reasons: (i) a neutron source which gives greater capability than RTNS-II (United States) will give Japan independence in its experimental fusion testing program; and (ii) the concept of an energy-tunable, incremental dose neutron source makes it attractive to more than the fusion materials community, and can hence be considered as a good strategy for obtaining the necessary funding and broad-based support.

(4) Ceramic Materials

JAERI has initiated new programs on the development of ceramic materials for electrical insulation and tritium steam electrolysis. The work focuses on FCC stabilized zirconia for tritium steam electrolysis and on $Si_3N_4$ as high-strength RF window materials.

(5) Plasma-Facing Components

Research and development activities at JAERI for plasma-facing components that are subjected to high particle and heat flux tend to emphasize engineering aspects. A list of these activities is given in Table VI.19. They include development of bonding materials, steady-state and thermal shock heat load testing, and development of manufacturing technology in addition to basic research. The computer codes used for analysis of high heat flux components are shown in Table VI.20; and the primary facilities for steady and pulsed heat load testing at JAERI are shown in Table VI.21.

## Table VI.19
## R&D FOR HIGH HEAT FLUX COMPONENTS OF JAERI

A. High Heat Load Testings

- Steady heat load testings
  - Test for the removal of high heat load
  - Critical heat flux test using a swirl tube with fins attached outside
  - High heat load test for CFC composite materials which is considered for the divertor plane in JT-60
  - Thermal cycle fatigue test for T/Cu bonding material
  - Thermal cycle fatigue test for C/SS bonding material

- Thermal shock testings
  - Test for thermal shock characteristics for metallic materials like SS
  - Test for thermal shock characteristics for carbon material and CFC composite materials
  - Test for thermal shock characteristics for T/Cu bonding material

B. Development of Bonding Material

- Development of T/Cu bonding material
  - Improvement of bonding method
  - Test for mechanical characteristics
  - Test for thermal characteristics

- Development of carbon material and CFC/metal bonding materials
  - Development of bonding method
  - Test for mechanical characteristics
  - Test for thermal characteristics

C. Development of Manufacturing Technology

- Manufacture of scaled first wall model made of SS based on HIP bonding method
- High heat load test for the scaled first wall model and study of fracture mode --> improvement of manufacturing procedure
- Manufacturing of carbon, CFC/Cu bonding type divertor plate models based on various bonding methods
- High heat load test for reduced models and study of fracture mode --> improvement of manufacturing technique

D. Basic Research

- Sputtering characteristics of materials
- Development of structure materials
- Study of PMI

**Table VI.20**
**COMPUTER CODES USED FOR ANALYSIS OF HIGH HEAT FLUX COMPONENTS AT JAERI**

| | |
|---|---|
| HEAT: | Analysis code for unsteady heat conduction in 1D including melting and evaporation developed for disruption analyses. |
| DREAM: | Analysis code for unsteady heat conduction analysis in 2D including melting and evaporation developed for disruption analyses. |
| ADINA: | Elastic and plastic stress analysis code. |
| ADINA-JHAT: | Analysis code for crack growth. |
| LIFE-1D, LIFE-2D: | Life time evaluation code for high heat flux component. |
| STREAM: | Code for coolant flow. |
| SCREW: | Code for coolant flow. |
| HEATING-6VP: | Analysis code for unsteady heat conduction and heat transfer. |
| INHEAT: | Code of 2D heat conduction analysis based on inverse problem. |
| FLOW: | Analysis code for cooling system. |
| NASTRAN: | Elastic stress analysis code. |

**Table VI.21**

**HIGH HEAT LOAD EXPERIMENTAL APPARATUS AT JAERI**

| | |
|---|---|
| Heat source | |
| Electric gun | Plasma electric gun |
| Acceleration voltage | 20 - 100 kV |
| Acceleration current | ~ 4A |
| Sweep area | 0.7 cm Φ x 1. x 2. x 10. |
| Sweep time of electric beam | 1 ms continuous |
| Acceleration source | |
| Method | High frequency inverter method |
| Output frequency inverter | 5 kHz |
| Acceleration voltage | 20 - 2000 kV |
| Acceleration current | Maximum DC 5A |
| Polarized sweep coil for electric beam | |
| Polarize angle | 45° |
| Sweep frequency | Maximum 1 kHz (changeable) |
| Sweep angle | Maximum 16° (changeable) |
| Test sample section | |
| Heat flux | Maximum 100 kW/cm$^2$ |
| Applied area of electric beam | Maximum 30 cm x 60 cm |
| Sample inset apparatus I | |
| Dimension of sample | Maximum 30 cm x 60 cm |
| Sample insert apparatus II | |
| Dimension of sample | Maximum 10 cm x 10 cm |
| Length of sample for steady heat load test | Approximately 80 cm |
| **High Output Ion Beam Irradiation Apparatus** | |
| Heat source | |
| Ion source | NBI ion source JT-60 |
| Acceleration voltage (Vacc) | Maximum 100 kV |
| Acceleration current (Iacc) | Maximum 50 A |
| Pulse width | 0.03 - 10 s |
| Sweep area of beam | 12 cm x 27 cm |
| Test sample section | |
| Heat flux | Maximum 0.5 - 25 kW/cm$^2$ for Vacc = 80 kV and Iacc = 48 A |
| Sample for steady heat load test | |
| Maximum size | Width 20 cm x length 70 cm |

| Table VI.21<br>HIGH HEAT LOAD EXPERIMENTAL APPARATUS AT JAERI<br>(continued) | |
|---|---|
| Sample for thermal shock | |
| Maximum size | Approximately 30 cmΦ x 3 cm thickness |
| Beam target I (for steady heat load test) | |
| Cooling method | Forced cooling |
| Cooling tube | Swirl tube with fins |
| Capable heat load | ~ 5 kW/cm$^2$, 5s |
| Capable heat capacity | ~ 900 kW, 5s |
| Beam target II (for thermal shock test) | |
| Cooling method | Inertia cooling |
| Capable heat load | ~ 25 kW/cm$^2$, 0.1s |
| Capable heat capacity | ~ 4000 kW, 0.1s |

Research on erosion mechanisms in plasma-facing components focused on chemical sputtering by the formation of chemically-active oxides in the scrape-off layer. The magnitude of chemical sputtering by this oxidation mechanism is more than what is expected by physical sputtering alone. This result indicates that high-Z materials are more erosion-resistant than low-Z materials. This information is relatively new and should have an impact on the design of plasma-facing components.

Experiments on simulated disruption effects by the use of the neutral beam devices of JT-60 have shown that ferritic steels are more resistant to disruption effects as compared to austenistics. PCA showed low resistance and generation of deep cracks into the base alloy. It was concluded from these experiments that disruption-resistant steels should contain less than 0.1% C, 0.3% Si, and 0.015% P.

Unique experiments were performed on radiation-corrosion, where the hot water corrosion resistance of small steel samples is tested by corrosion tests after irradiation and strain hysteresis. A new material, SAR-F, was developed for both corrosion resistance and structural integrity. SAR-F contains 16-20% Cr; 25-40% Ni; and 2-2.5% Mo, B, and low C. The material was concluded to have good swelling as well as corrosion resistance. However, the use of such alloys, with high nickel and molybdenum contents, may not be suitable from an environmental standpoint because of the long-lived radioisotopes remaining after reactor shut-down.

(6) Theory and Modeling

The development of swelling-resistant alloys is accompanied by a moderate degree of modeling by K. Kiuchi. His work models the enhancements-to-void swelling by chemical interactions with precipitates and/or intermetallic compounds. It is concluded from his experimental analysis and simple theory that additions of minor alloying elements initially suppress swelling by point-defect trapping, but an increase in swelling results in the later stages of irradiation by point-defect collection at precipitates. An effective method to inhibit void swelling was determined, in which thermochemical treatments are combined with the selection of appropriate alloy compositions.

c. The National Research Institute for Metals

The National Research Institute for Metals was established in July 1956 as a research organization affiliated with the Japanese government Science and Technology Agency. NRIM started with an administration division and four research divisions. At the present, 12 research divisions comprise the research activities of NRIM. In July 1976, an office of NRIM was opened in Tsukuba Science City, and Tsukuba Laboratories of NRIM were established in 1979. The mission of NRIM is twofold: (i) R&D of advanced materials such as rare metals materials, intermetallic compounds, and synthetic materials; and (ii) reliability assessment of structural materials. In these two areas, NRIM conducts exploratory R&D of new materials. It also provides a central role for research in national projects and the performance of joint material studies with industries and universities. NRIM research is organized in the following five categories:

- advanced superconducting materials;
- nuclear reactor materials;

- intermetallic compounds;
- advanced powders; and
- material life prediction.

About two-thirds of the research on nuclear reactor materials is directed toward fusion reactor materials, even though the results of such research can be readily used in the fission industry. Research efforts on nuclear materials at NRIM represent about 10 percent of the total research activities on materials.

NRIM is headed by Dr. Ryuichi Nakagawa as the director-general of the institute. An advisory committee of about 16 members aid Dr. Nakagawa in setting the general policies and research directions for NRIM. Members of the advisory committee represent major Japanese industries and corporations, universities, and the public sector. The deputy director of NRIM is Dr. Kazuyoshi. NRIM research laboratories at Tsukuba are headed by Dr. Masatoshi Okada.

Research on radiation effects at NRIM is mainly experimental with less emphasis on theory development. There are three main experimental facilities to study radiation effects on materials. The first is a simulation facility where light ions are accelerated using a cyclotron to simulate fast neutron irradiation damage. The focus of the experimental program on this facility is to develop materials which are resistant to the harmful effects of irradiation, such as swelling, irradiation creep, and helium embrittlement. Protons, deuterons and helium ions are accelerated to energies in the range of 4 to 26 MeV with beam currents in the range of 20 to 50 $\mu$A. The second experimental facility is an in-situ analysis and evaluation facility for radiation damage in materials. The facility consists of a heavy ion accelerator to produce displacement damage, a light ion facility to introduce helium or hydrogen, and an electron microscope to observe microstructural changes under irradiation. Other analytical equipment, such as an X-ray spectrometer, an ion energy spectrometer, an electron energy spectrometer, and a TV camera, are attached to the facility to perform complete dynamic analysis of the sample while it is being irradiated. The technology of dynamical observation of in-situ radiation damage is quite developed in Japan, and is well ahead of comparable facilities in the United States and Europe. NRIM is heavily involved in the development of advanced superconducting materials for nuclear fusion, power generators, energy storage, and magnetically levitated vehicles. $Nb_3Al$, $Nb_3$ (Al, Ge), and $V_2$ (Hf, Zr) multifilamentary wire conductors are being developed in the third fusion experimental facility at NRIM. A high-field superconducting magnet which produced the world's highest magnetic field of 20 Tesla was constructed at NRIM. (Nb, Ti)$_3$Sn and $V_3Ga$ conductors were also developed at NRIM. (Nb, Ti)$_3$Sn and $V_3Ga$ conductors were also developed at NRIM. High-Tc superconducting materials, such as Y-Ba-Cu-oxide and the very recently discovered Bi-Sr-Ca-Cu oxide are being studied at NRIM for use at liquid nitrogen temperature. These studies focus on wire and thin film fabrication techniques.

The annual budget of NRIM has been growing steadily since its inception in 1956. In the 1960s and early 1970s, its annual budget remained in the neighborhood of ¥1000 million. The late 1970s and 1980s witnessed a very rapid increase in the annual budget, reaching a total of ¥5,491 million in 1988. This budget is divided into personnel (¥2,831 million) and research (¥2,563 million). The total number of personnel associated with NRIM reached its steady state level in the middle 1960s, and is almost unchanged in recent years. During 1988, the total staff was 437 (104 for administration and 333 scientific staff). While the budget for nuclear energy research represented only 9.5 percent of the total budget during fiscal year 1988, that for superconducting materials research was at the level of 39.4 percent. A fraction of the superconducting materials research budget was designated to the development of superconducting magnets for fusion applications, but this fraction was not readily known, and was possibly small.

(1) Alloy Development

The majority of research on fusion materials at NRIM is aimed at the development of radiation resistant alloys for the first wall and blanket structures. Some research is directed towards the behavior and properties of coated plasma-facing components. The idea of elemental substitution of alloying element to reduce the long-term radioactivity without sacrificing the high-temperature properties of ferritic/marsenistic steels was first developed in the United States by Ghoniem, Shabaik, and Youssef.[1] Now this idea is widely accepted, and significant research is conducted at NRIM on the development of Fe-(2-15)%Cr-(0-4)%W-0.1C and Fe-9%Cr-(0-1)%,V-0.1C steels. Alloys except for 12-15%Cr-4%W, and 9%Cr-1%V showed a single martensite phase. An interesting conclusion of the experiments on the impact toughness is that the minimum DBTT occurs around 0.25 percent W or V concentration for 9 percent Cr steels. The toughness characteristics of these optimum compositions was concluded to be superior to commercial alloys.

Molybdenum and molybdenum alloys have been particularly attractive to the Japanese materials community for the past two decades. The interest has been based on the potential high temperature capabilities of molybdenum alloys, which can be advantageous to high efficiency fusion reactors. Progress has been hampered by the lack of mature technology for joining and manufacturing molybdenum alloys, and by the embrittling effect of neutrons (a substantial shift in the DBTT). The recent experimental work at NRIM did not change the generally accepted conclusions on manufacturing and neutron embrittlement of molybdenum. It has been recognized for some time now that molybdenum alloys may have very limited applications in fusion reactors. However, the persistent Japanese efforts on the development of molybdenum can be attributed to one or both of the following possibilities: (i) the fusion material program lacks focus and coherence between research groups; or (ii) the development of structural molybdenum alloys is viewed as important for general high temperature applications, including fusion.

(2) Fundamental Damage Studies

Nagakawa, Yamamoto, and Shiraishi investigated the effects of electron (HVEM) and particle (cyclotron) irradiation on the evolution of microstructures under stress conditions. Single crystals of Fe-18Cr-14Ni, austenitic steels, Cu-Fe, γ-Fe and Mo were irradiated under the conditions shown in Table VI.22.

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1 *Proceedings of the Topical Conference on Ferritic Alloys for Use in Nuclear Energy Technology,* Snowbird, June 1983.

The group concluded that the degree of orientation of dislocation loops increases with the magnitude of the normal component of the applied stress to the plane of the loop. This result is in agreement with earlier US work by Brager et al. (HEDL). However, the NRIM study gives detailed stress dependence of the stress orientation process. Research on the mechanistic origins of dislocation loop alignment with stress is important to an understanding of the irradiation creep phenomenon. It has been found that stress alignment of loops is most effective during the nucleation phase of dislocation loops. Further, loop growth seems to erase the initial effects of stress.

**Table VI.22**
**IRRADIATION CONDITIONS FOR MICROSTRUCTURE EVOLUTION EXPERIMENTS AT NRIM**

| | Fe-Cr-Ni | Cu-Fe | Mo |
|---|---|---|---|
| Flux | 2-5 x $10^{21}$ e/$m^2$s | 9 x $10^{21}$ e/$m^2$s | 4.3 x $10^4$ $\mu$As/$cm^2$ (4.25 MeV P+) |
| Temperature | 633 K | Room temperature | 600 K |
| Stress | 0-50 MPa | Internal stress | Tensile tests |

(3) Mechanical Properties

Two areas of research are investigated by NRIM: irradiation creep and the micromechanics of fatigue crack irradiation.

Nagakawa's research objective is to evaluate the mechanisms of irradiation-induced creep. The work concluded that the stress induced preferred nucleation (SIPN) dominates a significant portion of the early stages of irradiation creep, particularly in solution-annealed materials. In heavily cold-worked materials, preferred absorption (PA) mechanisms were found to dominate. Experimental studies of creep transients associated with the startup/shutdown operations of irradiation confirmed earlier theoretical predictions by US scientists.[2] The short-term creep transient was experimentally confirmed to be associated with the excess vacancy flux which slowly migrates to dislocations.

(4) Theory and Modeling

Numerical solutions to point defect and interstitial loop cluster rate equations have been developed by Nagakawa to determine the dominant mode of irradiation creep, as discussed in the previous section. No major advances were made in this area, since theoretical research on the rate equations for microstructure evolution is well-established. However, the major contribution of this work is the identification of dominant creep mechanisms by careful comparisons with experiment.

The micromechanics of fatigue crack initiation are led by Nakasone. The objective of his research was to establish a fatigue crack initiation theory, and to obtain fatigue curves (S-N) for crack initiation, including radiation effects. His work considers a single array of vacancy and interstitial dipoles in an infinite body. The model seems to impose an artificial ratcheting mechanism for an extrusion resulting from a persistent slip band (PSB). The workers seem to be unaware of earlier models of intrusion/extrusion mechanisms, including radiation effects.[3]

## 4. Outlook

The advanced infrastructure of materials science and engineering with a mature manufacturing technology have helped Japan in making significant strides toward world leadership in fusion materials research over the past five years. The style of the Japanese research in this area has several characteristics,

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2 Gurol and Ghoniem, *Rad. Eff.*, 52(1980), 103; and Guriol Ghoniem and Wolfer, *JNM*, *99* (1981), 1.

3 Naughton, Ghoniem, and Lin, "Radiation Effects on the Micromechanical Aspects of Fatigue-Crack Initiation," ASTM-STP-956, 1987, 223-238.

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 electronic industries, have shaped the directions of their research. Universities and national institutes have concentrated on the use of electron and ion irradiation facilities to stimulate fundamental aspects of radiation effects and to draw conclusions on the expected nature of radiation damage under fusion conditions. Their early work tends to be non-discriminant, where they repeated many earlier experiments which were performed worldwide. However, the large amount and the variety of experimental information create a fertile environment for a systematic and mechanistic interpretation of the data. It is evident that continuation of experimental work on fundamental damage mechanisms has already placed Japan at the forefront of 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 at the experimental level. It is anticipated that they will continue to scan the vast experimental parameter space in a disciplined and systematic fashion. 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 developments of swelling-resistant steels, low-activation steels, and vanadium alloys are testimonials to this fact. In several areas, nevertheless, the newly-established materials manufacturing capabilities have helped the development of improved materials properties. Examples are the production of superior C/C graphite composites, SiC/SiC and SiC/Al composites for fusion applications. In many instances, the ideas generated by US institutions are pursued to perfection in Japan, even after such ideas are discarded in the United States for one reason or another. 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 they have 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 technical and less visionary. 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 earlier in this report. If the materials community in Japan is successful in building a national fusion neutron test facility (as is planned at JAERI), this will accelerate and widen the Japanese 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 significant funding cuts in the US fusion materials programs.

## G. SYSTEMS STUDIES

### 1. Introduction

System and design studies in Japan are carried out primarily at JAERI with a smaller effort led by the universities. Design studies at JAERI usually involve heavy participation by experts from industry who reside at JAERI for the duration of the study.

The first design study in Japan for a commercial fusion reactor started in April 1973 (Seki, 1989a-b) and was reported in an IAEA meeting in Culham in 1974 (Sako et al., 1974). The first design study of an experimental fusion reactor in Japan was started in 1975 (Seki, 1989a-b) for JXFR (Japan Experimental Fusion Reactor). In 1978, the International Tokamak Reactor (INTOR) design study started as a collaborative effort among the European Community, Japan, the United States, and the Soviet Union under the auspices of the IAEA. The INTOR effort was chaired by a Japanese scientist, S. Mori. Japan has made major contributions to the INTOR study which lasted about 16 years. Japan's contributions were particularly visible in the areas of configuration, maintenance, divertor engineering, and solid breeder blankets.

Along with the INTOR design, a fusion experimental reactor design was carried out as a national program. Among the interesting concepts proposed by Japan was a swimming pool type reactor concept in which the tokamak reactor is submerged in a water pool with water serving as a radiation shield.

### 2. Accomplishments and Capabilities

During the past five years the major systems and design studies have focused on the Next Fusion Device (FER) and on participation in the international studies of INTOR and ITER. The effort on design studies for commercial reactors has been much smaller than that for FER, INTOR and ITER.

In 1984, the FER was defined as the Next Fusion Device in Japan after JT-60 with the start of construction about 1993. A new multidisciplinary team with considerable industrial participation was formed (FER Design Team, 1988). A detailed and consistent design has been carried out. The major objectives of FER are to demonstrate a long ignited DT burning plasma and to demonstrate the feasibility of key reactor technologies (JAERI, 1988).

The design of FER is being conducted in line with the national research and development program recommended by the Subcommittee on the Next Step Device under the Fusion Council of Japan.

In the latest design of FER, a long ignited burning DT plasma with a burn length of ~ 800 seconds is achieved with the assistance of non-inductive current ramp up. In addition, the device integrated neutron fluence has been reduced to 0.3 $MWa/m^2$ in order to avoid installation of a tritium breeding blanket. Tests for the blanket and its associated subsystems are carried out in test modules.

Table VI.23 shows the major parameters for two design options now being considered for FER. Option 1 pursues cost effectiveness based on the best physics database of present devices. The device size is reduced with the use of non-inductive current ramp up (lower hybrid or neutral beam). Option 2 is based on more conservative physics assumptions in order to reduce the risk of not achieving the physics mission of the device.

The FER team includes experts in all aspects of the design for all components of the device and its facility. Detailed design and analyses are carried out in most areas using state-of-the-art methods and computer codes.

**Table VI.23**
**MAJOR PARAMETERS FOR TWO DESIGN OPTIONS BEING CONSIDERED FOR FER**

| | Option 1 | Option 2 |
|---|---|---|
| Operation mode | Non-inductive | Inductive |
| OH coil flux (V. s) | 75 | 130 |
| Burn time (s) | 800 | 500 |
| Major radius (m) | 4.42 | 5.10 |
| Minor radius (m) | 1.25 | 1.70 |
| Plasma elongation | 1.7 | 2.0 |
| Safety factor | 2.6 | 3.0 |
| Triangularity | 0.2 | 0.4 |
| Plasma current (MA) | 8.74 | 15.8 |
| Total beta (%) | 5.0 | 5.6 |
| Ion temperature (keV) | 12 | 12 |
| Fusion power (MW) | 409 | 733 |
| Neutron wall load ($MW/m^2$) | 1.1 | 1.1 |
| Divertor null points | SN | DN |
| Magnetic field on axis (T) | 4.9 | 4.7 |
| Breeding blanket | Test module | Test module |
| Ignition margin with Mirnov-type scaling | 1.0 | 1.5 |

As mentioned earlier, Japan was a key participant in the INTOR study until its completion in 1987. Japan has also played a key role in the ITER study now in progress. The ITER conceptual design activity was established by the European Community, Japan, the United States, and the Soviet Union under the auspices of the IAEA in October 1986. Technical meetings were held in 1987 to define Terms of Reference for the conceptual design activities of ITER. The design activities started in 1988 and the present conceptual design phase is scheduled to be completed in December 1990.

The overall objective of ITER is to demonstrate the scientific and technological feasibility of fusion power. ITER will accomplish this by demonstrating controlled ignition and extended burn of deuterium and tritium plasma with steady state as the ultimate objective, by demonstrating technologies essential to reactors in an integrated system, and by performing integrated testing of the high-heat-flux and nuclear components required to utilize fusion power for practical purposes.

Each of the four participants in ITER (the European Community, Japan, the United States, and the Soviet Union) has a design team that works "at home" developing specific areas of the design. The four teams have a joint session at Garching, West Germany, for about five months during each calendar year. The design team is led by four managing directors, one from each country. The chairman of the managing directors group is K. Tomabechi from Japan. It is also worth noting that the leader of the ITER systems studies group is F. Iida from Japan.

Each of the four countries spends about $16 million annually for ITER which is divided into $8 million for the conceptual design activity and $8 million to perform R&D of direct importance to supporting the design decisions. Japan's contributions to ITER have been of very high quality in most technical areas.

While Japan's effort on the design of the Next Fusion Device has been among the most comprehensive in the world, activities on conceptual design for commercial reactors have been modest. The commercial design effort is carried out by a small number of personnel and emphasizes specific areas such as reactor safety. Recently, there have been attempts to strengthen the effort and to develop a collaborative activity with the ARIES study in the United States.

## 3. Outlook

Japan now has an integrated multidisciplinary team for the design of a fusion experimental reactor. The team has experts in all areas such as physics, magnetics, nuclear engineering, materials configuration, maintenance, fabrication, costing and scheduling. The team uses state-of-the-art methods and codes. This design team is the largest in the world and only the NET team in Europe is comparable. During the 1990s, Japan will have full capability for developing a complete design of the next fusion facility.

## CHAPTER VI: FUSION NUCLEAR TECHNOLOGY AND MATERIALS REFERENCES


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## APPENDIX A
## ABOUT THE AUTHORS

**Ronald C. Davidson** *(Panel 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). Dr. Davidson 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. He 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. Dr. Davidson is a Fellow of APS and a member of Sigma Xi.

**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.

**C. Wendell Horton**. Dr. Horton is a Professor in the Department of Physics and is a research scientist in the Institute for Fusion Studies at the University of Texas. He is a Fellow of APS. He is author of over 100 refereed articles in plasma physics theory, and co-editor of two books on statistical and nonlinear plasma physics. He has developed the theory of drift wave turbulence and anomalous transport in plasma confinement devices along with theoretical studies of other problems in space and laboratory plasmas. During 1966-1967, Dr. Horton studied at the International Center for Theoretical Physics in Trieste, Italy, under M. N. Rosenbluth and R. Z. Sagdeyev. In 1973, he was a visiting scientist at the Max-Planck Institute for Plasma Physics at Garching. Since the formation of the Institute for Fusion Studies at Austin, he has been actively involved in the US-Japan collaboration in the fusion theory program.

**James F. Lyon.** Dr. Lyon is a Senior Research Staff Member and Stellarator Program Coordinator at Oak Ridge National Laboratory and an Adjunct Professor in Nuclear Engineering at the University of Tennessee. He received SB (1960), MS (1962), and EE (1964) degrees in electrical engineering from MIT and a PhD in physics from the University of Tennessee (1970). At Oak Ridge, he has worked on mirror experiments (DCX-2, INTEREM, IMP) for eight years, on tokamak experiments (ORMAK, ISX-B) for 10 years, and on stellarators for the last seven years. Dr. Lyon led the teams which developed the ATF torsatron and the TJ-II flexible heliac designs. Internationally, he has worked on tokamak and stellarator programs in the Soviet Union, France, England, Japan, and Germany. He is the principal US investigator for the US-Spain collaboration on fusion and serves on a number of international stellarator committees. He has also served on numerous review panels for the DOE and received the DOE Certificate of Appreciation for his work on the Fusion Engineering Device. Dr. Lyon is a Fellow of APS, has served on the Executive Committee for the APS Division of Plasma Physics, and is author/co-author of over 80 published papers. His current interests are stellarator confinement and studies of next-generation experiments and reactors.

**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 (PPPL) 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, PROGRAMS, AND SELECTED TERMS

| | |
|---|---|
| A | amperes (current) |
| AEC | Atomic Energy Commission |
| ANL | Argonne National Laboratory (United States) |
| ANS | American Nuclear Society |
| APS | American Physical Society |
| ASDEX | Axisymmetric Divertor Experiment device at Garching, West Germany |
| Asperator-H | Heliac stellarator experimental facility located at Tohoku University, Sendai—began operation in 1988 |
| ATC | Adiabatic Toroidal Compressor located at Princeton University, Princeton, New Jersey |
| ATF | Advanced Toroidal Facility (Oak Ridge National Laboratory) |
| B | billion |
| BBI | breeder blanket interface |
| C | Celsius (centigrade) |
| CHS | Compact Helical System torsatron built at the Institute of Plasma Physics, Nagoya, Japan—began operation in 1988 |
| Ci | curie |
| cm | centimeter |
| CPU | central processing unit |
| CTCC-II | flux conserver type spheromak at Osaka University (Japan) |
| CVD | chemical vapor deposition |
| CW | cold worked |

| | |
|---|---|
| DBTT | ductile-to-brittle transition temperature |
| D-D | deuterium-deuterium |
| DOE | US Department of Energy |
| Doublet III-D (Divertor) | tokamak at General Atomics in San Diego, California—used in partnership with the Japanese Atomic Energy Research Institute group from 1979 until 1984 |
| dpa | displacement per atom |
| DT | deuterium-tritium |
| | |
| EBR | Experimental Breeder Reactor |
| ECH | electron cyclotron heating |
| ECR | electron cyclotron resonance |
| EDS | Energy Dispersive X-ray Spectrometer |
| ERD | elastic recoil detection |
| ESNIT | Energy Selective Neutron Irradiation and Test Facility |
| ETL | Electro-Technical Laboratory (Japan) |
| eV | electron volt |
| | |
| Fe | iron |
| FEL | free-electron laser |
| FER | Fusion Experimental Reactor—next-generation Japanese tokamak |
| FFTF | Fast Flux Test Facility |
| FNS | Fusion Neutronics Source—major Japanese fusion neutronics experimental facility, located at the Japanese Atomic Energy Research Institute, completed in the early 1980s |
| FNT/M/S | fusion nuclear technology/materials/systems |
| FRC | field reversed configuration |
| FRM | field reversed mirror |
| FWCD | fast-wave current drive |

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| GA | General Atomics |
| GAMMA-10 | tandem mirror experiment at Tsukuba University's Plasma Research Center—as of late 1989 it was the only tandem mirror experiment studying concept improvement |
| GB | gigabyte(s) |
| GFLOPS | gigaflops, billion floating point operations per second |
| GHz | gigahertz |
| GJ | gigajoule(s) |
| HAZ | heat-affected zone |
| HEDL | Hanford Development Laboratory (Richland, Washington) |
| Heliotron-E | the leading stellarator facility in the world, located at Kyoto University's Plasma Physics Laboratory (Japan) —began operation in 1980 |
| HFIR | High Flux Irradiation Reactor |
| H-mode | high confinement operating regime in tokamaks |
| HVEM | high voltage electron microscope |
| IAEA | International Atomic Energy Agency |
| IBWH | ion-Bernstein-wave heating |
| ICFT | International Center for Fusion Theory (Japan) |
| ICH | ion cyclotron heating |
| ICRF | ion cyclotron radio frequency |
| ICRH | ion cyclotron resonant heating |
| IEA | International Energy Agency |
| IFS | Institute for Fusion Studies (Austin, Texas) |
| ILE | Institute for Laser Engineering |
| INTOR | International Tokamak Reactor |
| IPP | Institute of Plasma Physics (Nagoya, Japan) |
| IPPCC | Institute of Plasma Physics Computer Center (Japan) |
| ITER | International Thermonuclear Experimental Reactor |

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|---|---|
| JAERI | Japanese Atomic Energy Research Institute |
| JENDL | Japan's evaluated nuclear data libraries |
| JET | Joint European Torus—a tokamak located at the Culham Laboratory, Culham, England |
| JFT-2 | first tokamak to operate in Japan (1972) |
| JFT-2M | moderate-size tokamak at Japanese Atomic Energy Research Institute in Tokai—program focuses on improvement of tokamak performance by means such as strong plasma shaping to achieve high beta-value, enhanced modes of confinement, and RF current drive |
| JIFT | Joint Institute for Fusion Theory, started at Hiroshima University (Japan) |
| JIPP T-IIU | moderate-size tokamak at the Institute of Plasma Physics at Nagoya, Japan—began operation in 1983 |
| JMTR | Japan Material Test Reactor—facility used for solid breeder blanket research and development |
| JPCA | Japan(ese) primary candidate alloy |
| JRR-2 | Japanese Atomic Energy Research Institute—facility used for solid breeder blanket research and development |
| JT-60 | large tokamak at the Japanese Atomic Energy Research Institute in Naka, Japan—construction began in 1978 and initial plasma operation occurred in 1985 |
| JT-60U | JP-60 Upgrade, also located at Naka—due to be ready for operation in the early 1990s |
| JXFR | Japan Experimental Fusion Reactor |
| K | Kelvin |
| k | thousand |
| LANL | Los Alamos National Laboratory (United States) |
| Lawson criterion | plasma confinement conditions necessary for break-even at temperatures greater than 10 keV, expressed at $n\tau_E > 6 \times 10^{19}\ m^{-3}$, where n = plasma density, and $\tau_E$ = energy confinement time in seconds |
| LHCD | lower hybrid current drive |

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| LHD | Large Helical Device—experimental facility to be located in the new National Institute for Fusion Science at Toki, Japan |
| LHH | lower hybrid heating |
| linac | linear accelerator |
| LLNL | Lawrence Livermore National Laboratory (United States) |
| m | meter(s) |
| M | million |
| mA | milliampere(s) |
| MA | mega-ampere(s) |
| MB | megabyte(s) |
| MeV | megaelectron volt |
| MHD | magnetohydrodynamic |
| MHz | megahertz |
| MIT | Massachusetts Institute of Technology, Cambridge, Massachusetts |
| MITI | Ministry of International Trade and Industry (Japan) |
| mm | millimeter(s) |
| MOE | Ministry of Education, Science and Culture (Japan) |
| Monbusho | Japanese acronym for Ministry of Education, Science and Culture |
| MOTA | Materials Open Test Assembly |
| ms (msec) | millisecond(s) |
| MTX | Microwave Tokamak Experiment |
| MVA | million volt-amperes |
| NBI | neutral beam injection |
| NBT | Japanese alternate confinement experimental facility |
| NEA | Nuclear Energy Agency |
| NICE | Naked Ion Collision Experiment |
| nm | nanometer(s) |

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|---|---|
| NMFECC | National Magnetic Fusion Energy Computer Center (Japan) |
| NRIM | National Research Institute for Metals (Japan) |
| ns (nsec) | nanosecond(s) |
| NUCTE-II and III | field reversed configuration device at Nihon University (Japan) |
| NYU | New York University |
| OCT-S | field reversed configuration device at Osaka University (Japan)—began operation in 1983 |
| OECD | Organization for Economic Cooperation and Development |
| OKTAVIAN | major fusion neutronics facility located at Osaka University (Japan)—completed in early 1980s |
| ORNL | Oak Ridge National Laboratory (United States) |
| ORR | Oak Ridge Research Reactor |
| Pa | pascal |
| PA | preferred absorption |
| PCA | primary candidate alloy |
| PDP | plasma-driven permeation |
| PDX | Poloidal Divertor Experiment located at Princeton University, Princeton, New Jersey |
| PIACE-II | field reversed configuration device at Osaka University (Japan)—began operation in 1979 |
| PKA | primary knock-on atom |
| PLT | Princeton Large Torus |
| PPPL | Princeton (University) Plasma Physics Laboratory |
| ps | picosecond |
| PSB | persistent slip band |
| Q | ratio of fusion power to input power |

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|---|---|
| R&D | research and development |
| REPUTE-1 | reversed field pinch device built by Hitachi and located at Tokyo University—has never worked satisfactorily as an RFP and recent studies have shifted to ultra-low-q tokamak operation |
| RF | radio frequency |
| RFC-XX-M | part of the mirror program at the Institute of Plasma Physics, Nagoya (Japan)—the fourth in a series of experiments on RF plugging of end losses with ion cyclotron heating |
| RFP | reversed field pinch |
| RFX | two mega-ampere reversed field pinch machine at the Instituto Gas Ionizzati in Padua, Italy |
| RTNS-II | Rotating Target Neutron Source II |
| SA | solution annealed |
| SCC | stress corrosion cracking |
| SHATLET-M | modulator torsatron experiment located at Tokyo University |
| SIPN | stress-induced preferred nucleation |
| SPAC | a series of relativistic electron ring experiments conducted from 1973 to 1987 which focused on the potential for injection of relativistic electron beams into toroidal devices |
| SS | stainless steel |
| STA | Science and Technology Agency (Japan) |
| STEM | Scanning Transmission Electron Microscope |
| $T$ | temperature |
| T | tesla |
| T-3 | early Soviet tokamak located at the Kurchatov Atomic Energy Institute in Moscow—completed in 1960 |
| T-10 | large Soviet tokamak located at the Yefremov Electrophysical Apparatus Institute in Leningrad—brought into operation in 1975, the T-10 was constructed in the early 1970s as an advance beyond the T-3 (1960) and the T-4 (1970) |

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|---|---|
| TD | thermal desorption |
| TEM | Transmission Electron Microscope |
| TFTR | Tokamak Fusion Test Reactor located at Princeton University's Plasma Physics Laboratory, Princeton, New Jersey |
| TNT-A | small non-circular cross-section tokamak at Tokyo University used for studying magnetohydrodynamic plasma control and magnetic fluctuations—in operation as of late 1989 |
| TORIUT-4 and -5 | thin shell tokamaks at Tokyo University that were used to study very-low-q tokamak regime and the transition of the reversed field pinch configuration—replaced by REPUTE |
| TPE | Toroidal Pinch Experiment at Tsukuba University's Electro-Technical Laboratory (Japan)—initiated in 1971 as a fast toroidal screw pinch and modified in 1975 as reversed field pinch with fast field control |
| TPE-1RM-15 | reversed field pinch at Electro-Technical Laboratory at Tsukuba University (Japan)—one of the many follow-ons to the TPE described above; has made contributions to the understanding of confinement scaling in RFPs; has obtained the highest current density and electron temperature in RFPs |
| TPL | Tritium Processing Laboratory |
| TRIAM-1M | moderate-size superconducting tokamak at Kyushu University's Research Institute for Applied Mechanics (Japan)—it is the world's first tokamak to come into operation using the $NB_3Sn$ superconductor |
| TS-3 | small external field type spheromak effort at Tokyo University |
| TSS | time-sharing system |
| TSTA | Tritium Systems Test Assembly |
| Troyon coefficient | limit on the amount of pressure that can be confined in a tokamak |
| UCLA | University of California, Los Angeles |
| UCSB | University of California, Santa Barbara |

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|---|---|
| UK | United Kingdom |
| US | United States |
| VP | vector processing |
| WT-2 | small tokamak at Kyoto University (Japan)—first tokamak in the world to demonstrate a fully non-inductive mode of tokamak operation; termed the RF tokamak; replaced by WT-3 |
| WT-3 | small tokamak at Kyoto University (Japan)—came into operation in 1986 and was able to extend the RF tokamak concept to currents in the 50-kA range; in operation as of late 1989 |
| ZT-H | 1.7-mega-ampere reversed-field pinch machine at Los Alamos National Laboratory (United States) |
| $\beta$ | beta: ratio of plasma pressure to magnetic field pressure |
| $\mu$A | microampere |

## APPENDIX C
## JAPANESE JOURNALS CITED IN TEXT/REFERENCES
(* not translated)

| Abbreviation | English Translation Title | Original Japanese Title |
|---|---|---|
| Progr. Theor. Phys. | Progress of Theoretical Physics | Riron Butsurigaku no Shinpo |
| J. Phys. Soc. Jpn. | Journal of the Physical Society of Japan | Nihon Butsuri Gakkai |
| | * | Kakuyugo-Kenkyu |
| | * | Laser-Kenkyu |
| Jpn. J. Appl. Phys. | Japanese Journal of Applied Physics | * |

## APPENDIX D
## JAPANESE RESEARCH FACILITIES CITED IN TEXT

Department of Thermonuclear Fusion Research, Naka Fusion Research Establishment at JAERI

Electro-Technical Laboratory, Tsukuba (ETL)

Hiroshima University, Hiroshima

Hiroshima University Institute for Fusion Theory

Hokkaido University

Institute for Laser Engineering, Osaka University

Institute of Physical and Chemical Research

Institute of Plasma Physics, Nagoya University (aka IPP-Nagoya)

International Center for Fusion Theory at IPP-Nagoya

Japanese Atomic Energy Research Institute

Koriyama University

Kyoto University, Kyoto

Kyushu University, Fukuoka

Ministry of Education, Science, and Culture (MOE)

Muroran Institute of Technology

Nagoya University, Nagoya

Naka Fusion Research Establishment

National Institute for Fusion Science, Toki

National Institute of Radiological Sciences (NIRS)

National Research Institute for Metals (NRIM)

Nihon University

Niigata University

Nuclear Engineering Research Laboratory, Tokyo University

Okayama University

Osaka University

Plasma Physics Laboratory, Kyoto University, Uji

Plasma Research Center, Tsukuba University

Research Institute for Applied Mechanics, Kyushu University

Supercomputer Center at Tokyo Institute of Technology

Technical University of Nagaoka

Tohoku University

Tokyo Institute of Technology
Tokyo Observatories
Tokyo University
Toyama University
Tritium Processing Laboratory
Tritium Science Center, Toyama University
Tsukuba University
University of Electro-Communications
Utsonomiya University
Yukawa Institute, Kyoto

## APPENDIX E

## FASAC REPORT TITLES

(* asterisk before 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
- West European Magnetic Confinement Fusion Research
- Japanese Magnetic Confinement Fusion Research

*(in production)*

**FY-86/89**

- Soviet Oceanographic Synthetic Aperture Radar Research
- * Soviet Research in Low-Observable Materials
- Soviet and East European Research Related to Molecular Electronics
- Soviet Phase-Conjugation Research
- Soviet Atmospheric Acoustics Research
- Precision Timekeeping Research in the Soviet Union
- Soviet Optical Processing Research
- Soviet Satellite Communications Science and Technology
- FASAC Integration Report III: Soviet Information Sciences
- * Soviet Radiation Cone Research
- West European Nuclear Power Generation Research and Development

*(in production/cont.)*

**FY-86/89** FASAC Special Studies:

- Non-US Artificial Neural Network Research
- * Soviet Low Observable Research
- Comparative Assessment of World Research Efforts on Magnetic Confinement Fusion
- Effects of US Export Restrictions on Foreign Acquisition of High Technology