TWENTY YEAR REPORT FOR ACTIVITIES REGARDING U.S./JAPAN FUSION RESEARCH COLLABORATION

(Expert Summary for 1980 [Nov.1979]-2000)

June 22, 2000

U.S./Japan Coordinating Committee on Fusion Energy

Under Agreement between the Government of Japan and the Government of the United States of America on Cooperation in Research and Development in Energy and Related Fields

PREFACE

Preface

Fusion is a reaction providing energy to the sun and stars. In the future, when this reaction is used as an energy source on earth, fusion power can be a most attractive energy source because of almost inexhaustible fuel and its high safety and low environmental effect. The first fusion related research for energy was conducted and reported in the 1950s, and considerable progress has been made, but it will still need several tens of years more before the development of a fusion reactor can be considered successful.

In 1977, President Carter and Prime Minister Fukuda discussed a new US-Japan cooperation on fusion. Following development of the necessary agreement basis, the research cooperation began on the Doublet III Tokamak machine in San Diego where a group of Japanese researchers was dispatched and worked together with the US researchers and engineers, producing many world-leading results. A number of Annexes to the main umbrella Agreement have been added covering almost all areas of fusion research and development, and more than 100 people per year traveled to other each other's country for the research cooperation. Major items of the results are shown in the following pages along with several photos related to the cooperation.

This cooperation has been continuing, for more than 20 years, with many excellent results being obtained across the wide range of activities. Probably this cooperation is the first accomplishment in the world providing a proof that people with totally different history and culture could really cooperate and produce world leading results, even not so many years after a very tense initial relationship between the groups representing the two countries. Part of the reason for this is that the research is completely oriented toward peaceful purposes.

Regular exchange of people, including many who stayed in the other country for years, enhanced mutual understanding of cultures. Friendships developed through this cooperation resulted in not only many good research results but also a merging of people and culture. Fusion research cooperation led to the fusion of people and cultures.

Although many more years of fusion research and development will be required before the realization of a fusion reactor, the fusion work reported here has resulted in positive contributions, and to some, an important spiritual return as well. Based on the results of the US-Japan collaboration we can have confidence to undertake larger scale international cooperation, such as the ITER project, which was started by four Parties, the US, EU, USSR and Japan.

We hope this report will help readers understand the meaning and importance of fusion research and international cooperation.

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CHAPTER 1 Doublet III and DIII–D

Objectives

The cooperative activities in the Doublet III project were initiated at the end of August 1979, intended to perform the advanced tokamak research, making use of plasmas with non-circular cross sections.

Activities

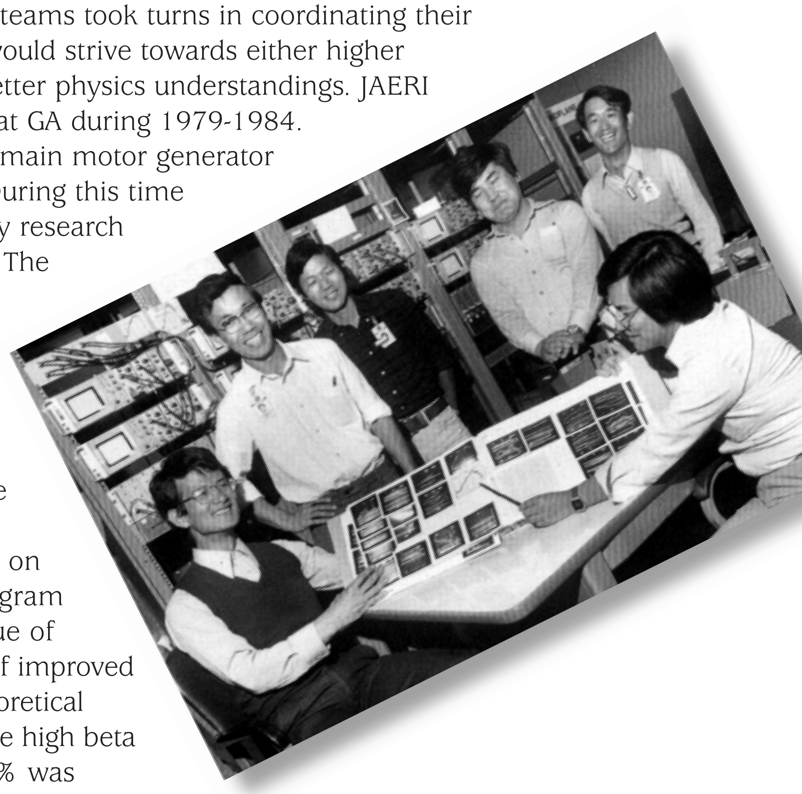
The Japan Atomic Energy Research Institute (JAERI) entered into an agreement with the U.S. DOE to collaborate on the Doublet III (later DIII-D) tokamak at General Atomics (GA) in San Diego. This Agreement has been extended to the present and has provided close collaborative coupling of the research programs at JAERI and GA for 20 years. In the last 20 years, JAERI has sent to GA a total of at least 65 person-years of scientists and engineers. During a period from 1979 to 1984, many JAERI scientists spent five years in residence in San Diego and one spent ten years on Doublet III and DIII-D. This experience built enduring mutual respect and friendships between JAERI and GA scientists and engineers. This collaboration has indeed strongly progressed in the last 20 years, providing significant scientific achievements with much contribution to Japan's JT-60 program and thus leading the world fusion program.

Administration

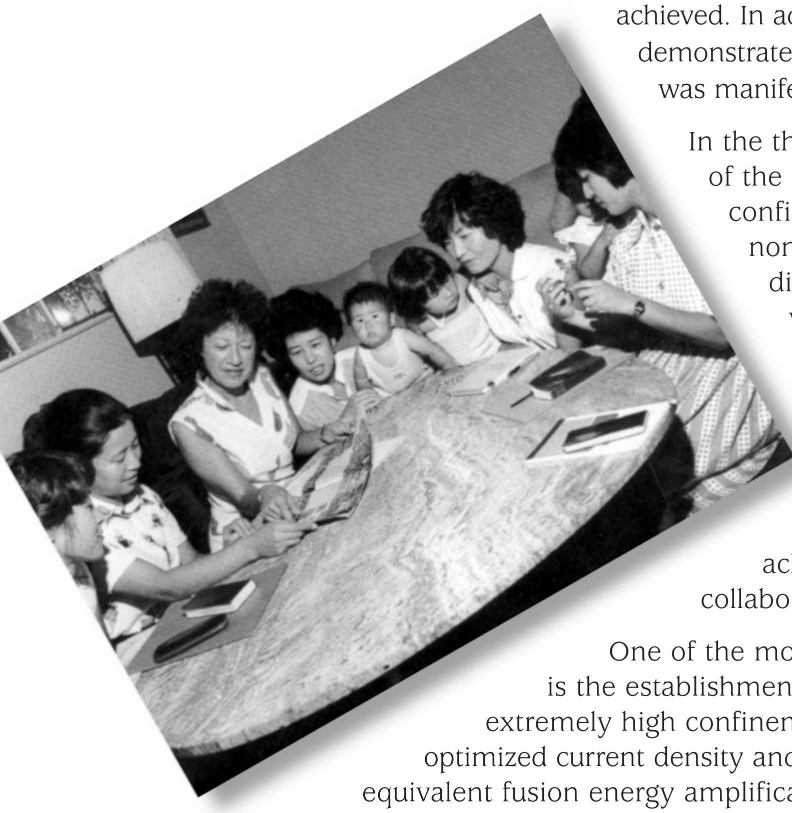
The Steering Committee Meeting is held every year throughout the period of collaboration between the U.S.DOE and JAERI in order to coordinate the collaborative work program. During a period between 1979 and 1985, JAERI provided a financial contribution of $70.1M, out of which $8.5M was for the Big Dee project.

Accomplishments

The period of collaboration in the last 20 years can be categorized into three stages. In the first period starting from 1979 to 1984, the U.S. and JAERI teams took turns in coordinating their independent experimental programs, and each team would strive towards either higher plasma performance by the shaping optimization or better physics understandings. JAERI had a physics group of about 10 members on average at GA during 1979-1984. Major facility components provided by JAERI were the main motor generator and two of the four 7 MW, 80 kV neutral beam lines. During this time the U.S. provided the JAERI team with dedicated facility research time, diagnostics instruments, and operations support. The JAERI team on Doublet III made significant scientific discoveries and developed physics understanding while they trained a generation of young scientists and future JAERI program leaders.



The second stage from 1985 to 1994 is highlighted by the modification of the Doublet III device (Big Dee project). The Doublet III device was enlarged in size and named as DIII-D, to which 12 visitors from JAERI on average per year participated in the experimental program and theoretical studies. In particular, the principal issue of controversy in this period was to untangle the physics of improved plasma confinement by the direct comparison with theoretical models, and the EXB shearing model was proposed. The high beta study also advanced in this period, and the value of 13% was



achieved. In addition, the neutral beam current drive was first demonstrated on DIII-D, and fast wave current drive of 0.16 MA was manifested, corroborating the theoretical predictions.

In the third period from 1995 to present, sustainment of the integrated performance, namely improved confinement with high beta, accompanied by a large non-inductive current drive fraction and significant divertor heat and particle disposition capabilities, was accentuated, in part, facilitated by the reactor-relevant results produced by the large tokamaks and progress in the ITER Engineering Design Activities (EDA) design. It should be noted, however, that the prominent results at JT-60 and other large tokamaks during this period actually benefited much from the outstanding achievements produced under this U.S.-JAERI collaboration program.

One of the most outstanding achievements in the recent years is the establishment of the reversed shear plasmas, which exhibit extremely high confinement properties at relatively high density, by the optimized current density and pressure profile control. Accordingly, the DT equivalent fusion energy amplification gain of 0.32 was obtained on DIII-D, and the world record Q value of 1.25 was achieved on JT-60U. Strenuous effort has also been devoted to the sustainment of reversed shear profile, as well as the improvement of the normalized beta, which is a figure of merit for the effectiveness of a fusion reactor. As a result, the product of H factor (confinement improvement factor over the L-mode scaling) and normalized beta of 7 was sustained for 1.5 s. In addition, comparative investigations on the internal transport barrier, which is thought to be a key for the improved confinement in reversed shear plasmas, was also performed between JT-60U and DIII-D. Furthermore, stabilization of resistive wall mode in the reversed shear plasmas has lead to an increase of normalized beta up to 2.8. On the other hand, collaborative work is in progress related to the scaling of pedestal width an edge MHD stability analysis.

Development of an advanced divertor, which is capable of effective heat and particle control, is another important issue of investigation considered under this collaborative framework. It was demonstrated that efficient pumping from the divertor private flux region resulted in the achievement of H factor of 1.9 at a density 1.4 times the empirically evaluated density limit.

Exploratory experiments on the tailoring of the current density profile with electron cyclotron current drive are expected to suppress the neoclassical tearing mode and improve the normalized beta in a steady state. Accordingly, relevant work for an increase of the electron cyclotron current drive power is in progress in DIII-D, which is considered to take a significant role both in the reversed shear experiment and investigations of dominant electron heating plasmas anticipated in a fusion reactor.

CHAPTER 2 FPPC (Fusion Physics Planning Committee)

The FPPC (Fusion Physics Planning Committee) is one of two Joint Planning Programs of US-Japan collaboration on the experimental fusion research. In the initial phase of the US-Japan collaboration, the experimental collaboration was planned and conducted to promote various concepts of fusion (tandem mirror, bumpy torus, helical system, tokamak, and so on) including fusion technology. Since 1992, the collaboration has been planned and conducted to promote physics of core plasma physics, edge physics and so on. The separation of the FPPC and FTPC (Fusion Technology Planning Committee) was established in 1991. The physics of inertial fusion is also discussed in this program.

Objectives.

The FPPC (Fusion Physics Planning Committee) is responsible for organizing US-Japan collaboration on the experimental research of fusion plasma physics. The present subsections are now 1) Planning, 2) Plasma core phenomena, 3) Plasma edge behavior and control, 4) Heating and current drive, 5) New approaches and diagnostics development. The physics of various concepts of magnetic and inertial confinement can be discussed together by this scheme of subsections, which allows us to deepen the understanding of complex behaviors of confined plasmas.

Activities

The objectives are pursued by workshops and exchange visits of researchers. In 19 years under US-Japan collaboration, 261 workshops and exchanges of visits were conducted and 607 researchers were sent to US on various themes related to FPPC. In Japan, 212 workshops and exchange of visits were held and 573 researchers were sent to Japan.

Administration

As for US-Japanese universities collaboration, 4 key-persons from Japanese universities are designated for the promotion of collaboration in each subsection of FPPC. The steering committees of FPPC are attended by US key-person of FPPC and a person in charge from JAERI and a person in charge from universities and 4 key-persons for 4 subsections from Japanese universities.

Accomplishment and highlights

2.1 Plasma Core Phenomena

(1) High triangularity research in JT-60

In 1994, the high triangularity ($< \sim 0.5$) experiment started by modification of the poloidal coil system with good suggestions from a General Atomics (GA) scientist participating at JT-60U. After that, the high triangularity shape produced significant improvements in plasma performance. The grassy ELM regime, first discovered by a JAERI scientist working on the DIII-D tokamak in the early 90's, was also established in JT-60U.

(2) Collaborations on Heliotron E before ATF operated and on CHS and LHD afterwards

(a) export of the PROCTR transport code to Heliotron E and application to its experiments;
(b) extensive study of MHD equilibrium and stability in Heliotron E; (c) extensive participation in the ATF experiment by the Kyoto group; (d) participation in pellet injection experiments in LHD; and (d) the CHS data acquisition and analysis system was exported from ATF.

2.2 Plasma Edge Behavior and Control

(1) Boronization in JT-60

In 1992, information on the boronization system of DIII-D at General Atomics (GA) was very beneficial in the design, construction and operation of the boronization system in JT-60. The key person from GA participated in the boronization experiments of JT-60U, leading to the successful improvement of plasma performance in JT-60U.

Divertors and Remote Radiative Cooling: In the mid 1980's, the JAERI team on Doublet III pioneered ways to make divertor plasmas in the Doublet III vacuum vessel, introducing to the world such concepts as remote radiative cooling and the high recycling divertor. More recently, the DIII-D team has researched close and pumped divertor geometries and results from those studies were influential in modifying the divertor in the JT-60U tokamak to a closed pumped type divertor.

(2) Material test in JFT-2M

A long-term test has been conducted in the JFT-2M tokamak to determine the effects of environmental exposure on the mechanical and chemical behavior of a low V-4Cr-4Ti alloy. Absorption of interstitials by the alloy appears to be limited to the very near surface, and neither the strength nor the Charpy impact properties of the alloy appear to be changed from the exposure.

(3) Plasma-facing material

Under the U.S.-Japan collaboration, basic behavior of the lithium coating, which is successfully conducted in TFTR, of plasma-facing material was investigated in a small apparatus in Japan with very interesting information. The Japanese scientists proposed to use metal high-Z materials as plasma-facing material and successfully received the useful data of discharge from Alcator-mod molybdenum diverter and TEXTOR tungsten limiters. These experimental results are crucial for the design of the first wall of the International Thermonuclear Experimental Reactor (ITER) and future fusion power reactors.

(4) Pumped Limiter and Helical Island Divertors

In the late 1980's, divertor concepts applicable to helical systems were explored by a GA team working on the JIPPT-2 (later CHS) device.

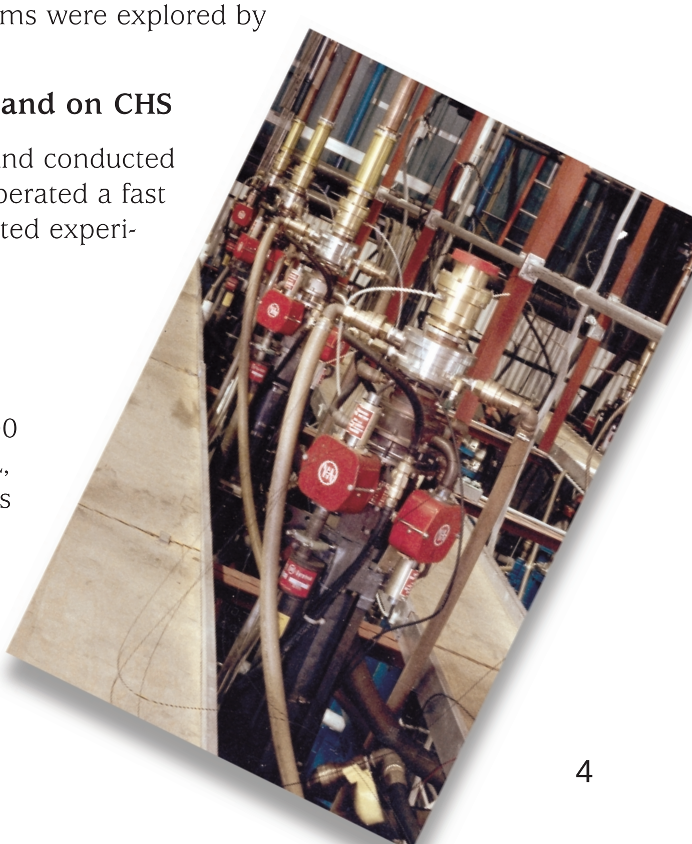
(5) Collaborations on Heliotron E before ATF operated and on CHS

(a) ORNL installed a pump limiter from ISX-B on Heliotron E and conducted experiments with for two years; and (b) ORNL installed and operated a fast pressure gauge in the local island divertor on CHS and conducted experiments for two years.

2.3 Heating and Current Drive

(1) ECH program in JFT-2M

This program was initiated in 1979-1981 with the loan of a 200 KW, 38 GHz gyrotron for ECH experiments on JFT-2 (GA, PPPL, MIT team). In 1992, a loan of 60 GHz gyrotrons to JFT-2M was proposed from GA to upgrade the ECH system. Installation of 3 gyrotrons including superconducting magnets, gyrotron tanks, radio frequency (RF) transmission lines, windows and antennas was completed on JFT-2M in March 1996. They have been quite useful in JFT-2M experiments up to now.



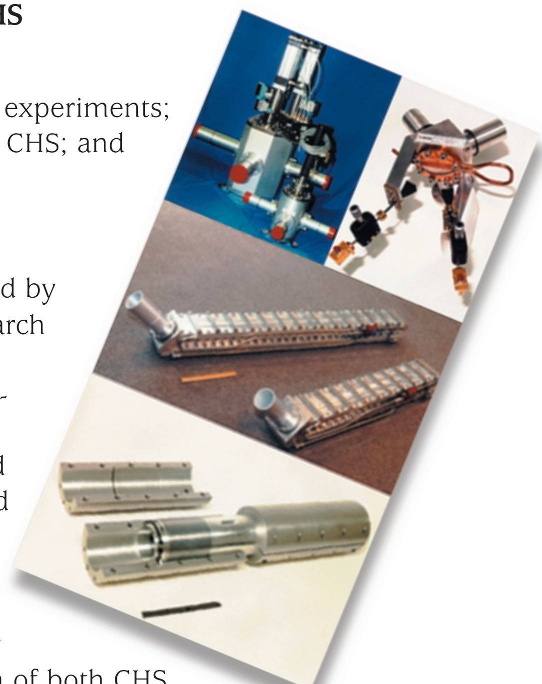
(2) ICRF Experiments on CHS

The U.S. collaborated with Japan in establishing ICRF heating capability in the CHS as well as W-AS helical devices. Also, the U.S. and Japan collaborated on the development of the folded wave-guide antenna, an ORNL invention for applications on LHD. The ICRF heating of toroidal plasmas using folded wave-guide antennas is considered to be important in fusion reactors. The U.S. and Japan have also been working on the combline antenna invented at GA. This antenna has the advantage that it has only one feed but has multiple emitters with variable phase difference, and could be very economical for the LHD experiment.

(3) Development of various ECH components in GA

GA has developed a number of high-quality submillimeter wave components in plasma diagnostics and ECH heating. JAERI has used many of these components such as corrugated waveguides, notchfilters.

(4) Collaborations on Heliotron E before ATF operated and on CHS and LHD afterwards



(a) ORNL loaned a 35-GHz gyrotron to Heliotron E for two-frequency ECH experiments;
(b) ORNL contributed equipment and participated in ICRF experiments in CHS; and
(c) ORNL collaborated on folded waveguide ICRF experiments in LHD.

2.4 New Approach and Diagnostics Development

Remote diagnostics in JT-60: Scintillating fiber neutron detectors developed by the Los Alamos National Laboratory (LANL) were installed on JT-60U in March 1994 for the triton burn-up studies. In 1995, JAERI developed the remote diagnostics system for the neutron detectors using Internet and TV conference equipment. The U.S. collaborators could control the diagnostics and acquire the data from their home institutes. Collaborations to produce and publish atomic and molecular data for fusion between NIFS and JAERI and U.S. laboratories have been productive for more than 20 years.

(1) Optimization of helical systems/stellarators

Search for improved helical system/stellarator configurations is intensively pursued in both the U.S. and Japan. Extensive contributions to the design of both CHS and LHD were made by researchers at ORNL. In recent years the U.S.-Japan collaboration in this area has been conducted through several workshops and personal exchanges. Dr. Paul Garabedian at New York University (NYU) made major contributions to the design of the new Heliotron J at Kyoto University as well as to development of the quasi-axisymmetric (qa) stellarator approach being developed in both Japan and the U.S. The proposed CHS-qa at NIFS and NCSX at PPPL would address similar issues for the qa stellarator through different designs. Detailed comparisons of ideas and designs in this area is very useful to both groups.

(2) Collaborations on Heliotron E before ATF operated and on CHS and LHD afterward

(a) extensive contributions to the design of both CHS and LHD; and (b) ORNL developed and installed an innovative compact 2-D neutral particle analyzer on LHD.

Early cooperative work was done with scientists from GA on the Gamma-10 and RFC-XX devices.

(3) Participation in the LHD experiment

Participation in the LHD program is an important element of increased collaboration between the U.S. and Japan. ORNL developed and installed an innovative compact 2-D neutral particle analyzer on LHD in collaboration with NIFS. PPPL installed a TFTR 1-D scanning neutral particle analyzer on LHD and started measurement of the ion energy distribution along different tangential lines of sight. These measurements will enhance the understanding of the effect of the electric field on trapped particles due to the loss cone in LHD. PPPL also installed an ECE diagnostic on LHD and conducted experiments with magnetic probes. A researcher from MIT made a significant contribution to the understanding of the “breathing” phenomenon in LHD. LANL developed and installed a 2-D infrared bolometer on LHD and conducted experiments with it in collaboration with NIFS. ORNL also participated in hydrogen pellet injection experiments in LHD.

Extensive long-term collaborations occurred between the Heliotron E and ATF programs. The ORNL PROCTR transport code was applied to analysis of Heliotron E experiments and later to CHS. Extensive study of MHD equilibrium and stability was carried out in Heliotron E by an ORNL researcher, and there was extensive participation in the ORNL ATF experiment by the Heliotron E group. The ATF data acquisition and analysis program was exported to the CHS experiment for joint experiments on CHS. MIT installed an impurity diagnostic on Heliotron E and conducted experiments.

To summarize, the U.S. labs contributed significantly to the Japanese stellarator program:

(a) PPPL installed a TFTR 1-D scanning neutral particle analyzer on LHD (1.4); (b) PPPL installed an ECE diagnostic on LHD and conducted experiments with magnetic probes (1.4); (c) MIT installed an impurity diagnostic on Heliotron E and conducted experiments (1.4); (d) LANL installed a 2-D infrared bolometer on LHD and conducted experiments (1.4); (e) NYU (P. Garabedian) made major contributions to the design of Heliotron J at Kyoto (1.4); (f) MIT was involved in the understanding of the “breathing” oscillation in LHD (1.4); and (g) GA was involved in collaboration on a combline ICRF antenna for LHD (1.3).

(4) Diagnostic Highlights from 20 Years of the US/Japan Bilateral

The Los Alamos National Laboratory and the National Institute for Fusion Science have an on-going (4-year) collaboration to develop infrared imaging bolometers for long-pulse plasma operation. Built in the US, and based on Dr. Glen Wurden's idea (US Patent 5,861,625, Jan. 19, 1999), a prototype has been installed by Japanese colleagues on the Large Helical Device in Toki, Japan. Further refinements and data analysis are underway.

The Los Alamos National Laboratory and JT-60U implemented a remote collaboration capability that allows real-time audio/video/data transfer. This system enabled remote control of a scintillating fiber neutron detector diagnostic that was installed by LANL (Glen Wurden) on JT-60U for triton burn-up studies.

The University of California, Davis (Neville Luhmann/Calvin Domier) and the University of Tsukuba (A. Mase) have successfully collaborated on an ultrashort pulse reflectometer (USPR) that was installed on the Gamma-10 mirror machine. Data from the USPR show promise for simultaneous density profile and density fluctuation measurements. Prof. A. Mase (currently affiliated with the University of Kyushu) is investigating the fabrication of a similar diagnostic for the Large Helical Device at NIFS.

The Oak Ridge National Laboratory and JT-60U collaborated on the successful installation and performance verification tests, on JT-60U, of a confined alpha particle diagnostic developed by ORNL. On JT-60U, the system will be used for the measurement of an ion tail, similar to an alpha particle distribution in a burning plasma experiment.

The collaboration between RPI and Japan on the development and installation of heavy ion beam probe (HIBP) diagnostic systems on several U.S. and Japanese fusion facilities has contributed significantly to a special issue on HIBPs in IEEE Transactions on plasma science. The collaboration is also the subject of an internal report by the Japanese National Institute for Fusion Science.

CHAPTER 3 JIFT (Joint Institute for Fusion Theory)

The Joint Institute for Fusion Theory (JIFT) is one of the three programs through which the U.S.-Japan Fusion Research Collaboration is organized. For twenty years, JIFT has contributed to the development of productive working relationships between Japanese and U.S. scientists in carrying out theoretical and computational research on fusion plasmas and related scientific issues.

Objectives

The distinctive objectives of the JIFT program are: (1) to advance the theoretical understanding of plasmas, with special emphasis on stability, equilibrium, heating, and transport in magnetic fusion systems; and (2) to develop fundamental theoretical and computational tools and concepts for understanding nonlinear plasma phenomena.

Activities

The JIFT objectives are pursued through collaborations between U.S. and Japanese scientists by means of three types of exchange program activities: workshops, exchange visitors, and joint computational projects. The JIFT program each year usually has four topical workshops (two in each country), approximately six exchange scientists (three from each country), and a fluctuating number of joint computational projects (on the order of a dozen). So far, during its 19 years of successful operation, JIFT has sponsored 114 long-term visits by exchange scientists, 71 topical workshops, and 111 joint computational projects.

The workshops typically have an attendance of 25-35 participants of whom usually three to seven scientists (depending on the particular workshop) travel to the workshop from the non-host country. Scientists from countries other than the U.S. and Japan are also often invited to participate in JIFT workshops, either as “observers” or members of multilateral collaborative programs.

Of the approximately three exchange visitors in each direction every year, one (called the “JIFT Visiting Professor“) is supported by the host country, while the others (called “Exchange Scientists”) are supported by the sending country. The visits of the Exchange Scientists usually last from several weeks to a month or two in duration, whereas, the Visiting Professors normally stay for at least three months.

The third category of JIFT exchange activities consists of joint computational projects. In general these are continuing collaborations on various problems of current interest, which initially develop out of interactions at workshops and through individual exchange visits.

Administration

JIFT has a Steering Committee of eight members, four from each country, with two co-chairmen. The Co-chairman on the Japanese side is the Director of the Theory and Computer Simulation Center at the National Institute for Fusion Science (NIFS). The Co-chairman on the U.S. side is the Director of the Institute for Fusion Studies (IFS) of the University of Texas at Austin. Two other members of the Steering Committee, called co-executive secretaries, are responsible for the ongoing daily oversight of the progress of JIFT activities. Also, on the Japanese side there is an official advisor, who is from the Japan Atomic Energy Research Institute (JAERI); and on the U.S. side there is an advisory committee whose membership is drawn from universities and national laboratories.

The Japanese and U.S. members of the Steering Committee select the topics and the participating scientists for the JIFT exchange visits, workshops, and joint computational projects. Criteria include having a balanced representation of critical issues in magnetic fusion research, which includes both

fundamental problems as well as questions of near-term significance, and also taking into account the specific capabilities and interests of both countries. The Steering Committee submits annual reports concerning JIFT activities to the U.S.-Japan Executive Secretaries Meeting.

Accomplishments

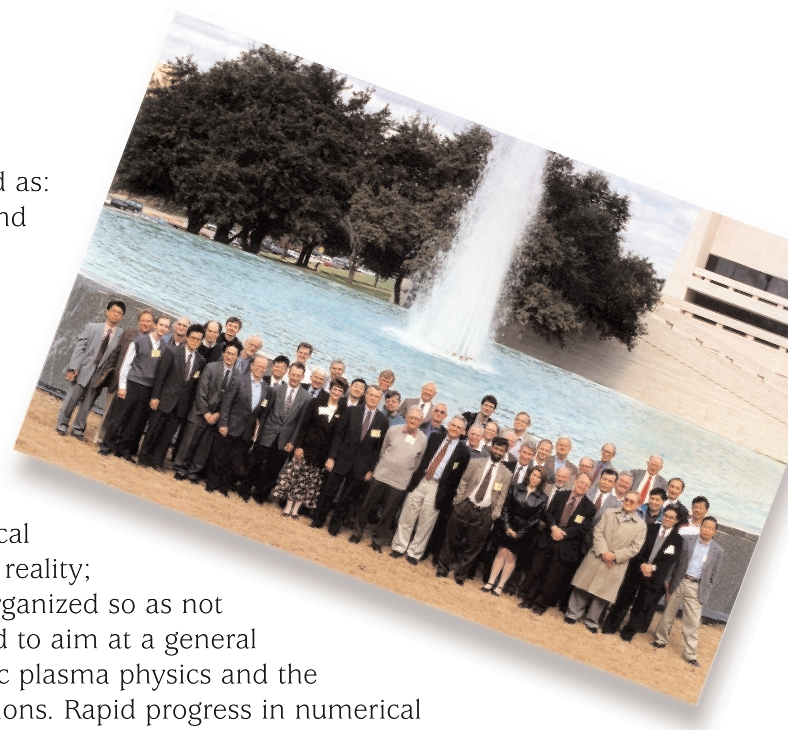
A number of general benefits have resulted over the years from the JIFT program. In particular, the following may be cited: JIFT has provided efficient communication channels for the latest theoretical research results, techniques, and directions; JIFT activities have attracted serious participation from allied fields such as fluid turbulence, statistical physics, computational science, and space plasma physics, which brings new scientific tools into the fusion program and enhances the stature of fusion physics; JIFT exchanges have contributed to efficient utilization of international research facilities; and, JIFT emphasis on large-scale computational studies has reaped significant mutual benefits from the supercomputer resources and code-building expertise of both countries.

JIFT activities have led to the publication of numerous scientific papers, as well as review articles and books. JIFT research has also been featured in a number of invited talks at major international meetings (e.g., the biennial IAEA Conference on Plasma Physics and Controlled Nuclear Fusion which is now called the IAEA Fusion Energy Conference).

Through JIFT, close and long-lasting scientific connections have been established between the U.S. and Japanese fusion theory communities. Not only have senior scientists profited from these collaborations, but also young scientists—and even, on occasion, two advanced graduate students—have had many opportunities to enhance their research careers. The lectures given by JIFT visiting professors during the first decade of the program were published in a book for the benefit of scientists and students.

Themes

The topics of the 35 workshops held during the past nine years are indicative of scientific themes that JIFT has pursued. These topics can be partially categorized as: (1) MHD equilibrium, stability, sawteeth oscillations, and disruptions; (2) High-beta plasmas and beta limits; (3) Highly energetic particles and their effects on stability; (4) Turbulent transport, transport barriers, and confinement; (5) Theory and new concepts for helical confinement configurations; (6) Bootstrap current; (7) Edge physics; (8) Dense plasmas; (9) Interactions of intense electromagnetic waves with plasma and matter; (10) Dynamo phenomena; (11) Reconnection; (12) Self-organization; (13) Numerical simulation codes, visualization techniques, and virtual reality; and (14) Innovative concepts. The workshops were organized so as not to focus on only one specific fusion device, but instead to aim at a general scientific understanding of fusion plasmas and of basic plasma physics and the development of tools for large-scale computer simulations. Rapid progress in numerical simulation methodology has especially marked the past decade of JIFT activities.



Significant Highlights

Through the years, a number of JIFT workshops and scientific exchanges have made significant the oretical contributions to the design and data analysis of helical confinement configurations and stellarators (e.g., Heliotron E, CHS, and LHD in Japan and ATF in the U.S.). New concepts for improved configurations have also been considered, relevant to the current U.S. stellarator design effort and to future plans for Japanese helical systems. For example, a JIFT visiting professor invented a new topology (so-called "wavy" vertical field coils) for a quasi-axisymmetric stellarator that simplifies coil shapes, has improved access, and may allow the design of a divertor. Two well-known books on the physics and numerical simulation of helical plasmas have been written as the result of JIFT activities.

A long-standing JIFT effort was the benchmarking of stability predictions from various MHD codes that were applied to a common three-dimensional stellarator equilibrium configuration. The results of this important work, pursued over several years among Japanese, U.S., and Russian scientists, were published in a detailed paper. Three-dimensional plasma equilibria including magnetic islands were extensively studied with the HINT code. Progress was made in analyzing whether island formation is a global effect due to the Pfirsh-Schluter current or a local effect due to resistive interchange. The phenomenon of "self-healing" was discovered, and its physics mechanism compared to that for the neoclassical tearing mode. These studies suggested that the bootstrap current can play an important role in suppressing islands, which is of interest to current LHD experiments.

Several workshops focused on understanding the universal properties of high-beta plasmas, not limited to any specific device. Stability beta limits and the bootstrap current fraction have been explored. Other problems considered were neoclassical tearing modes, resistive wall modes, equilibrium and stability for the field-reversed configuration, stability for the spheromak and the reversed-field pinch, and liquid lithium walls.

Another area of continuing interest in workshops and scientific exchanges has been the physics of particles with high energies. Fruitful results have been obtained in theoretical understanding of the burst modes observed in CHS experiments, in interpreting observations of toroidal Alfven instabilities in JT-60U and TFTR deuterium-tritium discharges, in modeling ripple loss of fast particles, and in developing theory and simulations for the nonlinear behavior of fast particle instabilities.

Many published papers and invited talks at various conferences have resulted from collaborations on plasma turbulence and anomalous transport. A recent book written on this subject is now a standard reference in the field. Other books were published as proceedings of JIFT transport workshops. A particular result was a new understanding of how the Hasegawa-Mima equation and Hasegawa-Wakatani equation, as well as the Waltz model, contribute to plasma turbulence. Also, insight has been gained concerning the formation of sheared plasma flow due to Reynolds stress.

A long-standing JIFT collaboration on the physics of spheromak plasma and magnetic reconnection resulted in MHD code simulations of internal reconnection events in a spherical torus device, which reproduced experimental results extremely well. Also, a simulation of collisionless reconnection with a particle code revealed physics of interest to the reconnection experiment at the Princeton Plasma Physics Laboratory (PPPL). The comparison of theoretical predictions and simulation results of collisionless reconnection has been very fruitful for both countries.

Dynamo simulations for the generation of the earth's magnetic field attracted attention from the general physics community. These simulations showed the importance of self-consistent nonlinear dynamic processes.

Over several years, macro-scale particle simulations and gyro-kinetic particle simulations were compared and discussed. This led to a new direction to develop hybrid MHD-Vlasov simulation methods.

A JIFT exchange scientist made a breakthrough in object-oriented simulation techniques, viz., expression templates, and applied it to develop high-performance particle simulation capabilities that were then utilized for efficiently running a large Monte-Carlo type of code on a parallel processor computer.

Visualization methods, including virtual reality, have been recognized as critically useful for present and future large-scale simulations. JIFT research activities have made use of the NIFS CompleXcope and the Virtual Reality Simulation Laboratory. At a JIFT workshop on Nonlinear Plasma Simulation and Visualization held jointly with the 1998 International Conference on Numerical Simulation of Plasmas, two Japanese fusion scientists won Buneman Awards for their work in this field.

Another continuing JIFT research area has been plasma complexity in systems that are nonlinear, non-equilibrium, and open. Simulations of plasma self-organization, both on macro-scales and on micro-scales, excited considerable interest in the formation of order and structure. Also, recently the self-organization of plasmas with flow is being jointly studied in several areas—the stability of non-Hermitian plasmas with flow, the interpretation of the H-mode as self-organization of a shear-flow plasma at the edge, and double curl Beltrami flow–diamagnetic structures.

A well-attended annual series of workshops on the interaction of high-intensity electromagnetic waves with plasma and matter have attracted scientists from research areas such as ultrashort pulse laser-plasma interactions, laser acceleration, laser Compton scattering, nonlinear plasma dynamics, fast ignitor concept, energy research, X-rays, and laser astrophysics. This has stimulated opportunities for cross-field synthesis. The proceedings of the most recent of these workshops will soon be published.

CHAPTER 4 Data Linkages

4.1 ESnet between LBNL and NIFS (DOE/MONBUSHO ANNEX II)

The Data Link between the Energy Sciences Network (ESnet) at the Lawrence Berkeley National Laboratory (LBNL), in California (U.S.), and the NIFSnet at the National Institute for Fusion Science, NIFS (Japan), consists of leased communication circuits operated under Annex II, which started in December 1988 and was extended twice in 1993 and 1998. The Data Link was upgraded from 64 kbps to128 kbps (256 kbps Max) in 1996 to accommodate the needs of increased data transfer.

The U.S.-Japan Data Link has been invaluable for communications between fusion research collaborators in the U.S. and Japanese Universities. It provides visiting scientists with access to their home institution's computer systems. It also provides the means of exchanging information between the U.S. and Japanese scientists by electronic mail and file transfers of theoretical, experimental and design data, as well as computational programs.

The Data Link has made great contributions to joint code developments and usage, and joint data analysis and theory/experimental comparison and enhanced the productivity of the U.S.-Japan fusion research activities. The U.S.-Japan (NIFS) Data Link is important in promoting the U.S.-Japan Fusion Cooperation Program and it should be maintained and enhanced to meet future program requirements.

4.2 ESnet between LBNL and JAERI (DOE/JAERI ANNEX IX)

The Data Link between the Energy Sciences Network (ESnet) at the Lawrence Berkeley National Laboratory (LBNL), in Berkeley, California (U.S.), and the Japan Atomic Energy Research Institute (JAERI), at Naka (Japan), consists of leased international communication circuits operated under Annex IX, which started in January 1990 and was extended twice in 1995 and 2000. The Data Link was upgraded from 64 kbps to 128 kbps in 1993 and from 128 kbps to 768 kbps in 1997 to accommodate the needs of increased data transfer.

The U.S.-Japan Data Link has been invaluable for communications between U.S. and JAERI research collaborators. It provides visiting researchers with access to their home institution's computer systems. It also provides the means of exchanging information between the U.S. and the JAERI scientists by electronic mail and file transfers of theoretical, experimental and design data, as well as computational programs.

In the early phase, the Data Link made great contributions to joint code developments and usages, and joint data analysis and theory/experimental comparison and enhanced the productivity of the U.S.-Japan fusion research activities. Recent remote collaboration activities between JAERI and U.S. laboratories, such as Princeton Plasma Physics Laboratory (PPPL), Los Alamos National Laboratory (LANL), etc., have demonstrated the potential value of a high capacity Data Link for joint fusion research. The U.S.-Japan (JAERI) Data Link is important in promoting the U.S.-Japan Fusion Cooperation Program and it should be maintained and enhanced to meet future program requirements.

CHAPTER 5 FTPC (Fusion Technology Planning Committee)

5.1 DOE/MONBUSHO

The U.S./Japan-Monbusho (MOE) collaboration on fusion technologies has now been active and successful for 20 years. It produces a mutually beneficial scientific bilateral collaboration between the MOE Universities and NIFS, and the DOE research institutions and Universities.

There are five FTPC categories at present,

(1) Superconducting Magnets

(2) Plasma Heating Related Technologies

(3) Blankets

(4) In-Vessel/High Heat Flux Materials and Components (HHFC)

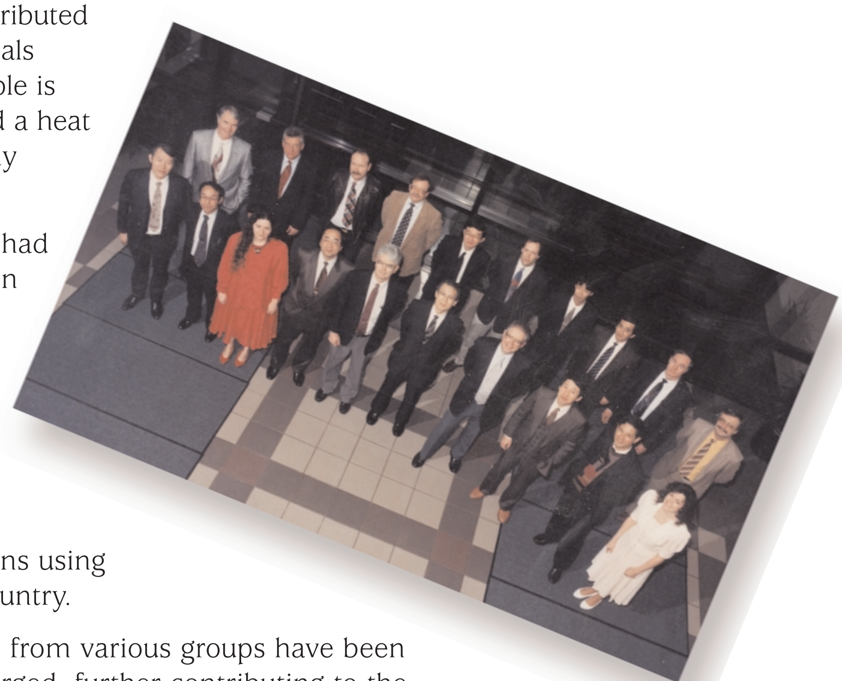
(5) Others

During the 20 years of this FTPC, unique and individual activities in these categories provided numerous useful results for the fusion program. The Japanese Universities engage in a wide variety of technologies, based on their own research interests. In addition, since NIFS was founded in 1988, these activities increased through the coordinating efforts of the fusion research network. In general, MOE funded research has historically focused on issues of basic technology development. This is a conspicuously different approach than JAERI. JAERI has strong obligation and responsibility for mission oriented research directed at Tokamak type fusion devices, and this focus has become especially tight after the start of the ITER EDA. This may be recognized as a restriction in general that may limit flexibility of DOE-JAERI collaboration. Therefore, the U.S.-Japan MOE collaboration is complementary in allowing a full mix of collaborative research that meets the requirements for both sides.

Each year FTPC plans several workshops and related personnel exchanges. The outline of this U.S.-Japan collaboration is shown in the Figures attached, which show the workshops and personnel exchanges for the past 10 years, and give detailed information on activities in each category. Workshops covering basic activities in several technology areas will be summarized. These were organized for HHFC, Blanket, Reactor Design, and Heating Systems. Information has been actively exchanged and scientific evaluations useful to both sides were effectively executed.

The materials research has been covered by Joint Projects (FFTF-MOTA and JUPITER Projects). These are independently described in other chapters of this report.

In the HHFC area, workshops highlighted the effort to develop components needed for fusion devices. As a result of this series of workshops, the research programs of both sides were well organized and optimized. Several institutions, NIFS, JAERI, Sandia, etc. have high heat flux test sources and tests have been conducted that contributed significantly to the development of robust materials and components. An especially important example is testing of grades of graphite which will withstand a heat flux of 5 to 10MW/m2. These graphites are widely utilized by present large tokamaks and by LHD.



For the blanket technology, originally each side had different interests, in liquid, ceramic, and molten salt blankets and the associated individual data bases. Information exchange has been useful and has stimulated collaboration. In this context, Japanese Universities contributed to development of an evaluation framework and models, based on their original component test data. These workshops have successfully contributed to the further development of designs using the existing experimental data bases in each country.

In the technology area of reactor design, output from various groups have been combined and design ideas were effectively merged, further contributing to the emergence of new ideas. These workshops helped to develop and apply design evaluation principles and methodologies. The systematic approach used in the U.S. and the multiple path approaches in Japan have been well highlighted by these workshops, and have helped each side move toward more attractive designs.

There are three main subjects in the plasma heating category, i.e., NBI, ECRH and ICRF. These have different research concepts and issues, depending on experimental device applications, i.e., energy, power, frequency, etc. Exchange of the results from different component tests and plasma experiments has effectively allowed each side to move into the next upgraded steps. NIFS, JAERI, ORNL, PPPL, MIT, and GA are the major institutions which have large development programs. Furthermore, after an experiment is started, both sides continued to exchange data and personnel. This allows further results on plasma experiments to be used to develop and apply MW class heating power to the experimental devices.

Late in the 1980's, when the LHD project started, several superconducting magnet technology (SC) workshops were held. These made a large contribution to the evaluation of the existing design data base and helped to develop the necessary recommendations used in final design. Personnel exchanges afterwards contributed to the SC technology development for both sides.

Recently, two new categories of Fusion Technology Planning have been introduced. These are Tritium and Blanket Heat Exchange/Removal, and workshops have been organized and the activity levels are increasing. Since the start of operation of LHD in 1998, personnel exchanges related to LHD technologies have dramatically increased. Major areas of collaboration are HHFC, Heating, Pellet Injection, and others. LHD has provided these new possibilities for collaboration, in addition to the LHD physics collaboration.

As we move to the future of the US/Japan-MOE collaboration on fusion technology, the FTPC activities will continue and expand. The FTPC remains an important component of the US/Japan fusion collaboration.

5.2 DOE/JAERI

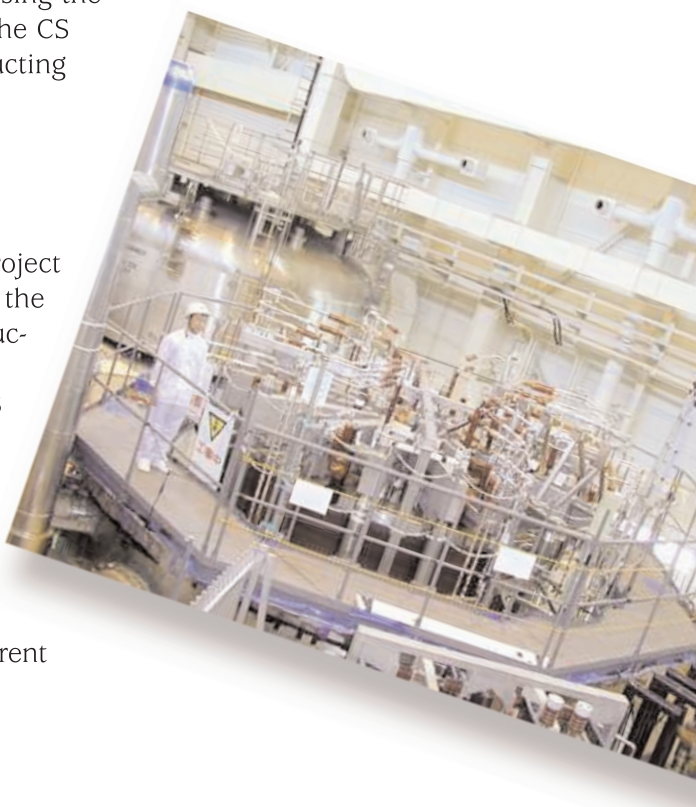
(1) Superconducting Magnets

DOE-JAERI collaborative programs for the development of superconducting coils for fusion have successfully been carried out including the program in the development of superconducting poloidal coil technology (Annex-V) which began in 1988 (see Chapter 8.3).

Installation and testing of the ITER Central Solenoid Model Coil

The ITER Central Solenoid (CS) Model Coil was developed through international collaborations by the U.S., Japan, the European Union (EU), and the Russian Federation under the ITER technology R&D program. The CS Model Coil has an outer diameter of 3.6m, a height of 2.8m and winding weight is 110 ton. It is composed of the Inner Module that was wound by the U.S. and the Outer Module that was wound by Japan. Since the U.S. had to withdraw from the ITER Program in July 1999 at congressional direction, the installation and testing of the CS Model Coil have been carried out at the JAERI Naka Fusion Research Establishment based on the agreement as recorded in the Minutes of the 20th U.S.-Japan Coordinating Committee on Fusion Energy (CCFE) held on May 17, 1999.

Under this agreement, five scientists and engineers were assigned to JAERI for installation, and the installation work was successfully completed by the end of 1999 by the U.S.-Japan installation team. The experiment of the CS Model Coil was started with the initial cool down in March 2000 that was followed by the charging experiment from April 11, 2000. On April 19, 2000, the CS Model Coil was successfully charged up to 46kA and 13T, generating a stored energy of 640MJ. Another important goal to demonstrate stable pulsed operation by charging to 13T at 0.4T/s and discharging from 13 T at 1T/s was successfully achieved on May 24, 2000, by using the power supply of the JT-60. By these results, the objectives of the CS Model Coil were fulfilled and a new frontier in the superconducting magnet technology was opened.



Past Activities on Magnets

1980's

Large Coil Project on Superconducting Magnets - While this project to design, build and test superconducting magnets was under the auspices of the International Energy Agency, it was a major success in fusion collaboration. This lead to a collaboration between the US and Japan involving the loan of one of the US coils to Japan. This coil, along with a Japanese counterpart, are now on display at NAKA as a tribute to this collaboration.

1990's

Demonstration Poloidal Coil - This test in Japan involving US and Japanese superconducting magnets provided important insights on the behavior of superconducting magnets during current ramping.

(2) Plasma Heating Related Technologies

The most noteworthy activity during the 20 year period is the annual bilateral exchange workshop on RF Heating Technologies, hosted alternatively by the two countries. These workshops have provided a forum to develop close communication between the RF technologists in both counties and to establish many mutually beneficial collaborative activities. These exchanges have been typically 6-10 per year with 20-30 participants.

For example, the most pronounced collaboration in the JAERI-DOE collaborative program was the development of a new high power tetrode tube. It was developed by the U.S. and tested on the JT-60 ICRF system from 1988 – 1992 (ANNEX VII). The tests validated the performance of the tube X2274 at an output power level of 1.5 MW for 5s at 130MHz, setting a world record. Use of this tube permitted the upgrade of the JT-60 ICRF system with minor modifications.

In addition, there have been a number of joint projects, some of them are listed as below.

ECRF

1) Cryogenic window development (1992 - 1994)

JAERI fabricated the cryogenic sapphire window and demonstrated the 400kW x 1sec transmission using DIII-D ECH system in 1994. This was the world's first demonstration of a high power transmission of the cryogenic window.

2) Distributed window test (1994 - 1995)

New concept of robust ECH window developed by GA was tested in the JAERI teststand. The high power density, which is required for the ITER window, was demonstrated.

3) High Efficiency ECH System Design and millimeter wave component development (1994 - 2000)

GA has the most experience of millimeter wave transmission components and JAERI has the most experience of the energy recovery gyrotron operation. These technology information exchanges contributed to the development of gyrotrons and a better design of the ECH system of both sides, which were applied to the JT-60U, DIII-D and ITER.

4) The CPI gyrotrons on LHD were based on a Japanese design and make use of a visor at the output of the Vlasov launcher. Tests showed that the output beam profile was very unsatisfactory. MIT worked with NIFS to install a corrective external mirror system that was already validated on DIII-D gyrotrons and improve the beam profile.

ICRF

1) Tetrode test (1988 - 1992, see 8.3)

Eimac fabricated 2 megawatt prototype tetrodes and JAERI successfully tested in Japan at a higher frequency than it would have been possible in the US.

The new U.S. tetrode tube X2274 was tested in the JT-60 ICRF system and demonstrated 1.5 MW for 5 seconds at 130 MHz, which was a world record at that time (1988-1992).

2) Feed-through test (1993 - 1995)

The test of various designs of the ICRF feed-throughs from Japan and the U.S. was done using the T-60 ICRF system and the results contributed to the design optimization.

Japan is now fabricating and installing a Folded Waveguide Antenna system on LHD in collaboration with ORNL. Although this antenna concept was invented and validated on test-stands in the US, this would be the first time it would be used on a large functioning fusion experimental device.

Inadequate funding in the US has prevented the fabrication and tests of a "Combline Antenna" invented in the US. But the collaboration with Japan has made it possible to conduct preliminary tests in Japan and validate the concept. The collaboration on the topic is still in progress.

NBI

The collaborative efforts between Japan and the US using the quardrupole accelerating system developed in the US and a source composed of several merging beams validated in Japan established the viability of producing very high energy negative ion based neutral beam systems for JT-60.

The collaboration has been very fruitful and new activities like remote steering ECH antenna are planned. We can expect further progress of collaboration in this area.

(3) Blankets

Objectives

The in-pile functional tests of blanket mock-up will be planned in the JMTR. Now, the design of blanket mock-up is conducted and the fabrication development of pebbles (ceramic tritium breeders and neutron multiplier), un-irradiated and irradiated properties of pebbles, etc., have been investigated for the in-pile functional tests. To make clear in-pile functional tests of blanket mock-up in detail, the following items will be discussed during the next three years.

- Experimental procedures for the in-pile functional tests
- Fabrication development and characterization of ceramic tritium breeders (pebble)
- Characterization of beryllium with high fluence, etc.

Results

Meetings are held once per year for three years and the planning for in-pile functional tests of blanket mock-up is discussed. In 1998, an information exchange of the activity for blanket irradiation study of JAERI and the U.S. was carried out in the U.S. In 1999, a coordination on experimental sharing of JAERI and U.S. was performed in the U.S. On the development of tritium breeder pebbles, irradiation test results of ceramic breeder with FFTF and JMTR will be evaluated. On the development of neutron multiplier pebbles, tritium release behaviors at low neutron fluence and reactivity with water will be evaluated. On the development of irradiation technique, technology assessment of dosimetry and control of irradiation environment will be discussed. In 2000, detailed planning on the cooperation of JAERI and the U.S. will be discussed.

(4) In-Vessel/High Heat Flux Materials and Components

High Heat Flux Materials and Components

In the development of high heat flux materials and components, collaborative studies on erosion of plasma facing materials, and studies on thermal hydraulics of high performance cooling tubes for fusion reactors have been carried out both in an electron beam test facility in JAERI and in a high heat flux test facility at the Sandia National Laboratories New Mexico (SNL). As a result of the collaborative studies, the dependence of critical heat flux on subcooling has been clarified on the high heat flux cooling tubes, and this result has strongly affected the design of fusion experimental reactors. Furthermore, the workshop on "Plasma wall interaction and high heat flux components for next fusion devices" has been held to discuss the latest results from JAERI and the U.S. every year. In this workshop, many of the first results in the world have been reported and have lead the direction of research in this field, e.g., erosion enhancement of carbon based materials by hydrogen and helium mixture beams.

Remote Welding Cutting of Vacuum Vessel

Aiming at the development of remote assembly and disassembly of the tokamak vacuum vessel, the cooperative activities concerning the experimental evaluation of remote welding and the cutting of the vacuum vessel were initiated in 1999. For this joint activity, one U.S. member from ORNL/Boeing was assigned to JAERI for three months and participated in the remote welding test between the ITER full-scale sector model and full-scale port extension by using full-remote welding robots fabricated by the U.S. Home Team during the ITER-EDA.

(5) Others

Remote Handling Technology

Aiming at the development of remote handling technology for a fusion experimental reactor, the collaboration activities on the control of telerobotic manipulation of heavy payload was initiated in 1998. Through the technical discussions between both the U.S. and Japan participants, it was agreed to hold workshops and conduct joint simulation and critical feature experiments. The information exchange on the sensor-based force control of heavy payload manipulator is being continued to develop possible future joint experiments.

Safety Monitoring Program

To insure the safety and health of US and Japanese scientists when they work in each other facilities, the US-Japan Safety Monitoring Program was established. This Program has been instrumental, since its beginning in 1995, in enhancing the safety awareness of all foreign collaborators visiting and working in various facilities and in safe operation of equipment exchanged between institutions.

CHAPTER 6 Annex I Programs –Materials–

6.1 DOE/MONBUSHO MATERIALS PROGRAM (DOE/MONBUSHO ANNEX 1)

This collaboration is the joint research project between DOE of U.S. and MONBUSHO of Japan in Fundamental Studies of Irradiation Effects in Fusion Materials Utilizing Fission Reactors. For twenty years, this program has contributed to the research and development of fusion materials through productive efforts between Japanese and U.S. scientists in carrying out a series of irradiation experiments, post-irradiation testing, and analysis on the subjects.

Objectives

The objective of the collaborative program is to understand materials behavior in fusion reactor irradiation environments with particular attention to the correlation of the effects of fission and fusion environments and high and low fluence phenomena. Research program has been focused mainly on (1) the elementally process of radiation damage caused by D-T fusion neutrons at low fluence levels in the first phase, (2) the cumulative radiation effects at high temperatures caused by fast reactor irradiation at high fluence levels in the second phase, and (3) the dynamic and variable-complex irradiation effects during fission neutron irradiation in the third phase.

Activities

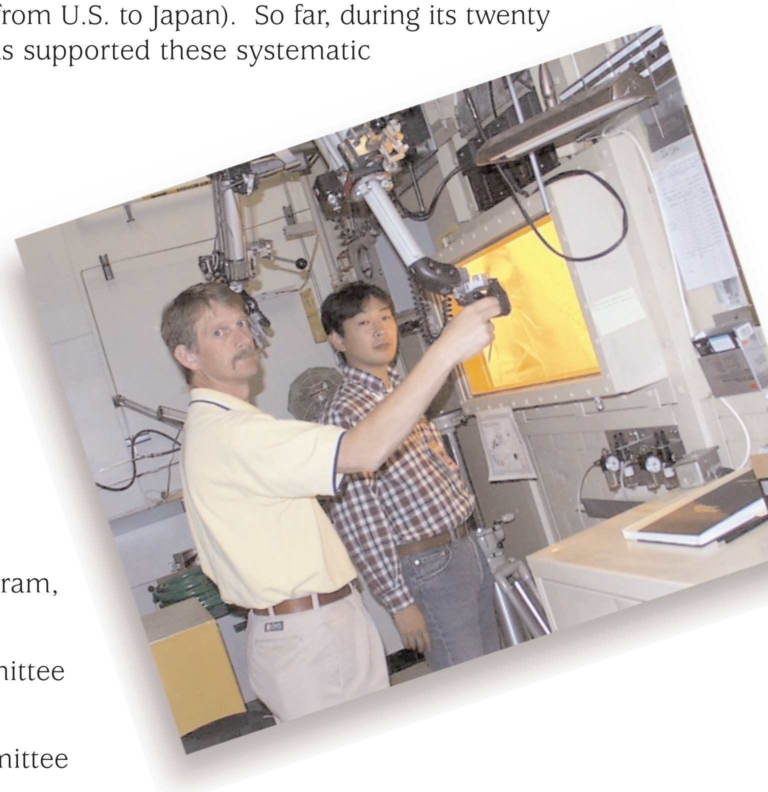
The activities of the collaborative program include: (1) planning of the experimental program, (2) design and conduct of the irradiation experiments, (3) post-irradiation testing, examination, and evaluation, (4) exchange of personnel and information necessary to carry out the collaborative program, and (5) prompt exchange of data and results arising from the collaborative program.

The first phase of the Japan-U.S. collaboration on fusion was the 'RTNS-II Program' for fiscal years 1981-1986, and this program utilized the Rotating Target Neutron Source (RTNS-II) at the Lawrence Livermore National Laboratory (LLNL) in Livermore, CA. The second phase, known as the 'FFTF/MOTA Program', was performed during fiscal years 1987-1994 and used the Fast Flux Test Facility (FFTF) in conjunction with the Materials Open Test Assembly (MOTA) at the Hanford site in Washington. The third phase, which began in 1995 and is scheduled to end at the conclusion of fiscal year 2000, is called the JUPITER Program. It uses the mixed spectrum High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL) in Oak Ridge, TN and Advanced Test Reactor (ATR) at Idaho National Engineering and Environment Laboratory (INEEL) in Idaho Falls, Idaho.

The various important irradiation experiments has been carried out in these phases. Irradiation experiments using low-fluence fusion neutrons from cryogenic temperature to high temperatures were done in the first phase. A series of elevated temperature irradiation at high damage levels using precisely temperature-controlled assembly were performed in the second phase. The in-situ type experiments and varying temperature irradiation using mixed-spectrum reactor has been done in the third phase. Associated in-situ experiments, post-irradiation testing and analysis have been performed during and after these irradiation experiments.

These activities are persuaded through collaboration between U.S. and Japanese scientists by means of two types of exchange activities: workshops and exchange assignees. The program each year usually has several workshops (about two in each country) and approximately about ten exchange assignees (about eight from Japan to U.S. and about two from U.S. to Japan). So far, during its twenty years of successful operations, the materials program has supported these systematic workshops and long-term assignees.

Administration



The general management of the collaborative program has been carried out by the Steering Committee. The Steering Committee has been composed of two persons for each party. These are Representatives of DOE and MONBUSHO sides and the Program Coordinator for each party. Each party has one vote in the Steering Committee and all decisions have been approved by unanimity. The Steering Committee has functions described as follows;

(1) Develop the Annual Program of Work,

(2) Review the implementation of the Collaborative Program,

(3) Recommend the Annual Program of Work to both parties for approval by the US-Japan Coordinating Committee on Fusion Energy,

(4) Select the time and place for the next Steering Committee meeting, and

(5) Consider other matters pertinent to the execution of the Collaborative Program as mutually agreed upon.

Each party designates, in writing to the other, its Representative who serves as co-chairman of the Steering Committee. Each party designates, in writing to the other, one Program Coordinator. Communication concerning planning and execution of the Collaborative Program, including planning and arrangements for the Steering Committee meetings and communication with the Steering Committee, has been channeled through the Program Coordinators.

Accomplishments and Highlights

The first phase of program utilizing RTNS-II clarified the elementary process of radiation damage of various materials caused by 14 MeV neutrons through D-T fusion reactions in the low fluence level up to 0.01 dpa. The second phase of program obtained important results on cumulative irradiation effects for fluences up to about 100 dpa. The third phase of program are studying dynamic effects and variable-complex irradiation effects in fusion reactor materials. The following are the results for the last ten years.

1) Highlights of materials development research in the FFTF/MOTA Program

In this program, high fluence neutron irradiation experiments were performed using the precisely-temperature-controlled MOTA test vehicle. A Post-irradiation evaluation was done at the Pacific Northwest National Laboratory (PNNL) in Richland, Washington. Irradiation experiments using the Experimental Breeder Reactor-II (EBR-II) at Argonne National Laboratory-West in Idaho Falls, ID and the mixed spectrum reactor, HFIR, at ORNL were also performed in the later period of the program. Important results on alloy development and the optimization of low activation structural materials which can survive up to high neutron-fluences were obtained. Some notable results are finding the optimum concentration of chromium for resistance to radiation embrittlement in low activation ferritic steels, designing a Fe-Cr-W alloy system with superior high-temperature strength and fracture toughness compared to conventional steels (which has been selected as one of the internationally important research objectives), and selecting guidelines for designing low activation vanadium alloys with acceptable ductility after high fluence irradiation. For functional materials, establishment of a heat treatment to suppress the irradiation embrittlement of molybdenum for high heat flux materials, and evaluation of the irradiation performance of composite materials were successful.

2) Damage mechanisms information obtained from the FFTF/MOTA Program

Several experimental studies to provide information on damage mechanisms were conducted. These studies on the influence of additional elements on the swelling properties of austenitic steels and vanadium alloys, the application of various helium production methods and related mechanistic studies of helium effects, the prediction of swelling by computer simulation, and the study of irradiation history effects were performed with successful results. Of special note was the evaluation of irradiation history effects. This study raised new issues about predicting the behavior of fusion reactor materials under non-steady state operation.

3) Development of irradiation experiment technology in the FFTF/MOTA Program

The irradiation technique called the Dynamic Helium Charging Experiment (DHCE) was developed by a collaboration on design and experiment to study the fusion relevant effect of helium in vanadium alloys. An experimental technique for the in situ measurement of electrical resistivity of ceramics in reactors was also successfully developed. For post-irradiation- evaluations, a fully automatic, high-temperature, in cell tensile testing machine called MATRON and a remote-control impact testing machine were developed. The small specimen test technologies developed in this program were also found to be useful for various other research and technology areas. The design windows of fusion structural materials such as austenitic steels, ferritic steels and vanadium alloys were clarified, and materials with wide design windows were proposed through this program.

4) The outline and study of dynamic irradiation effects in the JUPITER Program

In this program, dynamic irradiation behavior of materials was obtained using HFIR instrumented capsules, and the effects of nuclear transmutation and varying temperature on material irradiation performance were studied using high thermal- and fast-neutron fluences. The in-situ technique to directly measure the electrical properties of ceramics was successfully used to follow the change of electrical conductivity of alumina ceramics during high-temperature irradiation to a fluence of 3 dpa.

This result is very useful for the design of insulating materials for the International Thermonuclear Experimental Reactor, ITER. Irradiation creep was studied for vanadium alloys, and the influence of applied stress was established.

5) The investigation of variable and complex irradiation effects in the JUPITER Program

Irradiation techniques using capsules with and without a europium thermal-neutron shield were developed. This is a very powerful tool to study the effects of nuclear transmutation of both gas and solid elements in low activation fusion materials. A multi-stage variable temperature capsule was developed, and high-temperature cyclic irradiation was successfully completed to study the effects of variable irradiation conditions on the microstructural evolution and the associated mechanical properties change of materials. These techniques are very important in experimentally evaluating materials behavior under fusion operating conditions where irradiation conditions vary strongly and transmutation reactions are abundant.

6) Modeling study in the JUPITER Program and development of the next research project

It is necessary to investigate material behavior at the atomic scale and to correlate the microstructures with macroscopic properties in order to better predict materials performance in fusion conditions where there are dynamic and variable/complex irradiation effects. In the JUPITER Program, molecular dynamics techniques were used to calculate the defects structure of reference materials. The results were successfully applied to aid in understanding the experimental results.

Based on the above important results on the irradiation properties of low activation materials, the next research project called JUPITER-II with the subtitle of 'Materials Integration Utilizing Reactor Irradiation and Related Basic Research for Advanced Blankets' is being jointly planned and will encompass a variety of fusion technology areas in order to study the issues of materials systems which will be used interactively with coolant, etc., in fusion reactors.

6.2 DOE/JAERI MATERIALS PROGRAM (DOE/JAERI ANNEX I)

This program has contributed for twenty years to the development of fusion reactors by the scientific and engineering products about the irradiation damage on the structural materials obtained by U.S. and Japanese Scientists.

Objectives

The objective of this collaboration is to design, conduct and evaluate joint irradiation experiments in the High Flux Isotope Reactor (HFIR) of the Oak Ridge National Laboratory for the purpose of investigating the irradiation response of Japanese and U.S. structural and special purpose materials to high levels of atomic displacement and Helium content in order to establish the database on the properties and behavior of such materials and to evaluate their performance for the use in future fusion reactors.

Activities

The collaborative Program consists of the following;

(1) planning of the collaborative program;

(2) design and conduct of irradiation experiments in HFIR;

(3) technology development for evaluation, post-irradiation testing;

(4) exchange of personnel and information necessary to carry out the collaborative program; and

(5) exchange of results arising from the collaborative program.

Three phases of the collaborative Program have been completed. These phases had begun in '83, '88 and '94, respectively. Phase IV of the program started in '99 and is expected to continue until March 2004.

Phase I of the program focused on the effects of high concentrations of transmutation produced helium coupled with displacement damage on mechanical properties and swelling behavior of the Japanese and US austenitic stainless steels. Phase II was also devoted to the understanding of the irradiation effects of austenitic alloys. Spectral and isotopic tailoring techniques were developed and utilized to reproduce the ratio of the generation rates of helium and the displacement damage (He/dpa ratio) typical of the fusion reactor environment. Also, irradiation behavior of the variety of weld materials was evaluated. In phase III of the program, examination of the irradiation response of advanced materials for DEMO reactors was initiated. Materials of the reduced activation ferritic/martensitic steels, vanadium alloys, SiC/SiC composites and titanium aluminides were included. Also, in situ test techniques to evaluate thermal conductivity and electro-resistivity of ceramic materials (SiC/SiC composites, Alumina etc.) during irradiation have been developed in the collaboration, and the measurements were carried out. During the phase IV, it is expected to obtain the understanding of the effect of helium on the loss of fracture toughness by irradiation for the improvement of the reduced activation ferritic/martensitic alloys. Development of the reduced activation ODS ferritic alloys and SiC/SiC composite materials are also the important subjects in this phase.

Administration

The general management of the Collaborative Program has been carried out by a Steering Committee. The Steering Committee has been composed of four members, two each are assigned by JAERI and DOE and conduct following assignments.

(1) Plan the Collaborative Program, and develop the annual work plan which shall be included the annual budget and the financial contributions of JAERI and DOE.

(2) Review the cost and the projection of expenditures.

(3) Review plans for joint paper publication.

(4) Discuss personal assignments.

(5) Recommend the annual program of work, budget and personnel assignments and other such matters to JAERI and DOE approval.

(6) Report to the Japan-U.S. Coordinating Committee on Fusion Energy through the Contact Persons on the technical progress in the current annual work and make recommendations for approval of the next annual work plan and budget and for the financial contributions of JAERI and DOE to the Collaborative Program to the next annual program of work.

Accomplishments and Highlights

One of the major outcomes from phase I of the Program is the optimization of the chemical composition and the heat mechanical treatment of the Japanese and US austenitic stainless steels. The features of phase II are (i) utilization of the spectral and isotopic tailoring techniques to reproduce the ratio of the generation rates of helium and the displacement damage (He/dpa ratio) typical of the fusion reactor environment, and (ii) the evaluation of irradiation behavior of the variety of weld materials. Results from phase I and II are utilized to establish service conditions of the austenitic alloys for the first wall of ITER, although the postulated service conditions at the beginning of the Program was considerably different from that of ITER. One of the major accomplishments during phase III is the development of the Japanese and U.S. reduced activation ferritic/martensitic alloys. These alloys exhibited superior resistance for irradiation and low induced activities after fusion neutron irradiation. Another important result of phase III is the evaluation of electrical and thermal properties of ceramic materials under irradiation using the in sit measurement technique. During the phase IV, it is expected to obtain the understanding of the helium effect on the degradation of fracture toughness for the improvement of the reduced activation ferritic/martensitic alloys. Development of the reduced activation ODS ferritic/martensitic alloys and SiC/SiC composites are also the important subjects in phase IV.

Several of the highlights during three phases are briefly described below.

• Austenitic stainless steel

(i) Irradiation response to high damage levels

Changes of microstructures, tensile strengths and fatigue properties induced during irradiation to high damage levels (e.g. 50 dpa; displacement per atom, 5000 appmHe; helium atoms were produced by transmutation reactions) were examined.

Results indicated that titanium modification, increase of nickel content by several percent and cold working to introduce dislocations are quite effective to suppress microstructural changes including swelling during irradiation. This shows that the concept of the alloy designing for Japan and US PCA worked well; optimization of the chemical composition and the heat mechanical treatment of the alloys.

Irradiation caused increase in strength at temperatures below 400C, while a slight softening occurred at temperatures above 500C. Increase in strength below 400C is accompanied with a severe reduction of uniform elongation. Decrease in uniform elongation may introduce difficulties in structural designing. Although the severe decrease in elongation values, ductility (evaluated from reduction of area) levels are quite high even after irradiation.

No strong irradiation effect is detected for post irradiation fatigue properties, except for the behavior at low strain amplitude levels. The reduction at the low amplitude levels seems to be the result of dislocation channeling induced by irradiation hardening.

(ii) Behavior of weldment

Welding introduces variety of microstructures including segregation (nonuniform distribution) of alloying elements. This nonuniformity clearly affected the distribution of cavities formed during irradiation. That is, swelling in the region with higher nickel content was small.

Although the relatively strong effect of welding on the microstructural evolution during irradiation, the effect on mechanical properties is rather small. This indicates that welding introduces no large problems to irradiation resistance of mechanical properties.

(iii) Spectral tailoring experiment

Ratio of the production rates of He atoms and the displacement damage during irradiation strongly affects the irradiation response of the materials. Spectral tailoring irradiation technique to adjust thermal neutron flux level to achieve He/dpa ratio typical of fusion neutron environment has been developed (This technique is only applicable for nickel containing materials). The results by the spectral tailoring experiment delivers irradiation response of the austenitic alloys with improved accuracy.

Results clearly shows that He/dpa ratio for fusion environment accelerates the microstructural evolution during irradiation. Results also exhibited that Japanese and US PCA have superior resistance to irradiation induced microstructural change compared to commercial austenitic alloys. Effect of He/dpa on tensile properties below 400C is not strong, and this indicates PCAs have acceptable performences in the fusion neutron environment.

(iv) Fracture toughness

Although fracture toughness is an important properties for the structural application, limited data of the irradiation effect were available. Irradiation to 3 dpa caused strong reduction of fracture toughness. The degradation tends to saturate with neutron dose. Although the reduction by irradiation is large, the residual fracture toughness level is not small, and the level evaluated to be high enough as a structural materials for the blanket.

(v) Irradiation assisted stress corrosion cracking (IASCC)

Because He/dpa ratio affects microstructural evolution including irradiation induced segregation, effect of neutron spectra on IASCC need to be evaluated. Evaluation of the susceptibility to stress corrosion cracking is rather complicated for the nature of the phenomenon. EPR (electochemical potentiokinetic reactivation) method and SSRT (sow strain rate tensile) test were applied for the evaluation of irradiated specimens.

Comparing with the result on the specimens irradiated in FBR, result clearly shows that He/dpa ratio for fusion condition accelerated degradation. This also implies the importance of the effect of He/dpa for the evaluation of the IASCC susceptibility of LWR core component where He/dpa ratio stringly depend on the position.

- Low activation ferritic/martensitic steel

During phase II JAERI and ORNL (including the out side activities of the Collaboration) carried out irradiation experiments on ferritic/martensitic steels with chromium (Cr) content levels of ranging from 2.25 to 12 percent. Results indicated Cr content strongly affects irradiation hardening, and the hardening exhibits minimal at 7-9 Cr. Taking these things into account; the knowledge and experiences about microstructural stability, strength at high temperatures and also for the low residual activities, JAERI designed F82H with NKK corporation and ORNL made several of 9Cr-W-V-Ta heats. Those alloys irradiated at temperatures from 200 to 600C to the damage levels of 60 dpa, and exhibited good resistance for irradiation over

- In situ testing

Electrical and thermal conductivities of ceramic materials are tend to be affected not only accumulated damage level but also dose rate during irradiation. Techniques for the in situ testing of thermal and electrical conductivities of ceramic materials have been, therefore developed. As preliminary results, the degradation of thermal conductivity decreases rapidly with dose and saturates during the early stage of irradiation.

CHAPTER 7 Annex IV Program – Fusion Fuel-

7.1 DOE/JAERI TSTA (Tritium Systems Test Assembly)

Annex IV was signed on June 11, 1987 for a five-year period (Phases 1 and 2). It was amended in 1992 (Phase 3), in 1994 (Phase 4), in 1997 (Phase 5) and in 1998 (Phase 6). Phase 6 is a three-year program, which is now under way until June 10, 2001.

The objective of this program in Phases 1, 2 and 3 was to evaluate the joint operation and experiments on fusion-fuel technology with Tritium Systems Test Assembly (TSTA) at the Los Alamos National Laboratory (LANL), Los Alamos, New Mexico. It was successful in meeting all of its technical objectives. During this period until 1994, fusion-fuel processing

technology was successfully demonstrated through the operation of the TSTA fusion-fuel processing loop system in which the processing rate reached up to one-fifth of that estimated in a fusion experimental reactor. The JAERI-developed Fuel Clean-up System (JFCU) was installed in the TSTA system and reliable processing was demonstrated by the successful 25-day continuous operation of this U.S.-Japan combined system. It was also verified that this system could process various non-steady state input coming from a pulsed tokamak operation with enough flexibility.

Beginning in 1994, safety technology of fusion fuel was emphasized, and the activities in Phases 4 and 5 were focused to enhance safety of the fusion-fuel system. During the period from 1994 to 1998, actual tritium migration behavior in a large room was successfully investigated by releasing 37 GBq {1 curie} of tritium to the 3000 m3 TSTA main cell. Using the Tritium Plasma Experiment apparatus, a powerful tritium plasma source, tritium retention studies on plasma facing materials of a fusion reactor were performed and valuable data was obtained. Through successful decommissioning of the JFCU, experience of decommissioning and decontamination of tritium-contaminated components was gained. In this period, radioactive reaction studies with tritium were performed at JAERI's Tritium Process Laboratory and unique data was obtained.

The Annex was further amended in 1998 to emphasize and extend tritium safety technology including new activities to understand tritium behavior in a tokamak. During the period from 1998 until 2001, the collaborative program was expanded to include both TSTA and the Tokamak Fusion Test Reactor (TFTR) at the Princeton Plasma Physics Laboratory (PPPL). Research of off-normal events in the fuel system and tritium inventory control studies on process components are underway at TSTA. At PPPL, research of tritium distribution in the TFTR vacuum vessel, analysis of tritium behavior during TFTR deuterium-tritium operation, research and development for decontamination and decommissioning of TFTR and basic research on advanced radioactive liquid waste treatment techniques are continuing. Characterization studies on materials exposed to tritium are in progress both at TSTA and TFTR. A significant amount of useful data is being obtained from all of these efforts.

Technology for Fusion Fuel Processing (Annex III and Annex IV)

- Developed and demonstrated, at the Tritium Systems Test Assembly (TSTA) facility, the full fuel handling and processing system and technology for next step fusion devices. This includes demonstrating the ability to handle large quantities of tritium safely and response of the system to off normal occurrences.

- Developed and tested a number of tritium analytical techniques and environmental and personnel protective systems for tritium handling. In addition, increased the fusion scientific database in the area of tritium materials interaction and qualified equipment and components for tritium service in the fusion program.

- Performed tritium release experiments, within the TSTA building, to determine how tritium could migrate to the environment in the event of a release.

- Developed database on decontaminating and decommissioning fusion systems, such as the JFCU and the Tokamak Fusion Test Reactor (TFTR), for use in the design of future fusion facilities.

CHAPTER 8 Completed Annex Projects (Associated with DOE/JAERI)

8.1 DOE/JAERI FUSION BLANKET NEUTRONICS (ANNEX II)

Introduction:

This Collaborative Program officially started on October 24, 1984, for three years as Annex II to the Implementing Arrangement between JAERI and USDOE on Cooperation in Fusion Research and Development. The collaboration was extended for another three years starting from October 23, 1987 to cover other aspects of the collaboration (see below) and the third (and final) renewal was made in October 1990. The program was officially concluded by the end of October, 1993. Technical meetings followed by Steering Committee meetings were held annually to discuss progress and annual reports were submitted to the U.S./Japan Coordinating Committee on Fusion Energy (CCFE).

The collaboration was in the form of a mutual and equitable participation from both sides in carrying out more than 20 integral experiments on mockups of various configurations that simulate the engineering features of fusion blankets that include a first wall, neutron multiplier, coolant channels, heterogeneity, armor layer, large openings, etc. Both point 14 MeV source and a simulated line source were used to generate the representative neutron source which was tailored to have as much simulation to the energy and angular distribution of neutrons emitted from plasma in a fusion reactor. The Fusion Neutron Source (FNS) Facility at JAERI was used to perform these experiments. Each experiment was carefully pre-analyzed to ensure optimal arrangement and experimentalists from both sides participated in performing the experiments and processing the experimental database in a usable form. The U.S. and JAERI performed, independently, the post analysis of these experiments using state-of-the-art computational tools and nuclear databases available in the U.S. and Japan.

Objectives and Phases of the Program:

The main objectives of the Program have been: (a) to establish new experimental techniques for performing fusion neutronics integral experiments, (b) to provide experimental data for evaluating the accuracy of basic nuclear data and calculational methods for fusion system design, (c) to provide estimates of uncertainties in the calculation of tritium breeding, nuclear heating, and induced radioactivity and decay heat, (d) to provide feedback for future nuclear data measurements and evaluations and calculational method improvements, and (e) to provide guidelines for fusion system designers, particularly the magnitude of safety factors required to compensate for quantified uncertainties.

Phase I of the program included experiments that were performed in an open geometry where test assemblies were loaded in the experimental cavity in the wall between two large rooms. Li2O blocks were used to form the breeding zone. Combination of first wall (316SS) and beryllium in various configurations (front layer, sandwiched layer, etc) were utilized. In Phase II, the experiments were performed in a closed geometry where the test assembly was placed at one end of a rectangular enclosure made of Li2CO3 and the D-T neutron source was placed inside the cavity. Several experiments with FW, and beryllium in various arrangements (e.g., as a liner) were also carried out to study the multiplication effect of beryllium and the prediction capability of present codes and databases. This phase also focused on studying the heterogeneity effect of coolant channels on tritium breeding rates (TPR) and nuclear and decay heating. In Phase III, a novel approach to generate a simulated line source was applied where an annular test assembly with inner square cavity was moved periodically back and forth relative to a stationary point source and, hence, a simulated line source was created. Several experiments on Li2O and Li2CO3 breeding materials were performed in this phase which also included a neutron streaming from a large opening on one side of the assembly and its impact on TBR and neutron spectrum inside the test assembly.

Major Accomplishments

This 10-year program was an exemplary international collaboration, which produced a wealth of experimental data on TBR, in-system neutron spectrum, and nuclear heating and decay radioactivity. Analysis of the experiments were performed using 3-D Monte Carlo and 2-D discrete ordinates codes and the latest nuclear data libraries in the U.S. and Japan. Significant differences among measurement techniques and calculational methods were found. To assure a 90% confidence level for tritium breeding calculations not to exceed measurements, designers should use a safety factor > 1.1 to 1.2, depending on the calculational method. The radioactivity measurements were performed for more than 20 materials with the focus on gamma emitters with half-lives < 5 yr. The ratio of the calculated-to-experimental (C/E) values ranged between 0.5 and 1.5, but it deviates greatly from unity for some materials. Most of the discrepancies were attributed directly to deficiencies in the activation libraries, particularly errors in cross sections for certain reactions. The microcalorimetric technique was vastly improved through the program. It allowed measurements of the total nuclear heating with a temperature rise as low as 1 _K/s. The C/E ratio for nuclear heating deviated from unity by as much as 70% for some materials but only a few percent for others.

The main findings from this Collaborative Program have been published in several scholarly journals and discussed in various workshops and international meetings on fusion neutronics.The most comprehensive discussion of these findings and accomplishments have been documented in 16 manuscripts that appeared in a special issue of the Fusion Technology Journal as Volume 28, No. 1&2, 1995.

8.2 DOE/JAERI FUEL CLEANUP COMPONENTS FOR THE TRITIUM SYSTEMS TEST ASSEMBLY (ANNEX III)

In 1986, Annex III was signed between DOE and JAERI for the development of improved components for the fuel cleanup system (FCU) for the Tritium Systems Test Assembly (TSTA) facility at the Los Alamos National Laboratory (LANL). The purpose of the FCU is to separate out the hydrogen isotopes from all impurities that may be found in the exhaust coming from the plasma or breeding blanket. The major objective of the Collaborative Program was to test with tritium at TSTA two process-ready components, the palladium diffuser and the ceramic electrolysis cell. These components were designed and manufactured by JAERI. Both of these components were critical parts of a new FCU design that JAERI was developing for future fusion experimental devices. The tests at TSTA were very successful. Eventually, these two components became the key parts of the JAERI FCU, which was also tested successfully as part of Annex IV.

8.3 DOE/JAERI SUPERCONDUCTING POLOIDAL COIL TECHNOLOGY (ANNEX V)

In 1988, Annex-V was signed between DOE and JAERI for the development of supeconducting poloidal coils. The implementing institutes are the Massachusetts Institute of Technology (MIT) in the U.S. and JAERI in Japan. The major goal of the program was to develop superconducting pulsed coils that could be charged up to 7T and 20MJ in one second by using newly developed Nb3Sn pulsed superconductors. The U.S. coil was called “US-DPC” and the Japanese coil was called “DPC-EX.” Both coils were tested one by one by using the Demo Poloidal Coil Test Facility at JAERI’s Naka Fusion Research Establishment. The facility also included a pair of NbTi backup coils, 1.2-kW forced-cooled cryogenic system and the high power supply of the JT-60 to charge the coil swiftly. The newly developed coils achieved a pulsed charging up to 7T within the range of 0.5 to 3.0 seconds and established a new technology of using Nb3Sn coil as a large pulsed coil for fusion by 1992.

8.4 DOE/JAERI FEL HEATING AND CURRENT DRIVE ON MTX (ANNEX VI)

The Japan-U.S. Collaborative Program for Annex VI was established in May 1988. Under this Annex, the Microwave Tokamak Experiment (MTX) was carried out to evaluate the application of high power, pulsed microwaves to plasma heating under the collaboration between JAERI and LLNL. The microwaves generated by the FEL were injected into the tokamak and the hot electrons generated were observed in the summer of 1992. JAERI provided the key components to conduct the experiments, including the mirrors to transform FEL microwaves to the appropriate modes, calorimeter to measure the microwave power and the various diagnostic systems to verify the hot electron generation.

8.5 DOE/JAERI NEW TUBE TEST WITH JT-60 ICRF SYSTEM (ANNEX VII)

The new U.S. tetrode tube X2274 was tested with the JT-60 ICRF system and demonstrated 1.5 MW for 5 seconds at 130 MHz, which was a world record at that time (1988-1992).

8.6 DOE/JAERI Collaborative Program on the Testing of a Negative Ion Source for Neutral Beam Injectors (ANNEX VIII)

Annex VII was singed between DOE and JAERI in December 1988 for the development of a high current negative ion source for neutral beam injectors. A 'volume type' negative ion source developed by JAERI was transported to Lawrence Berkeley Laboratory (LBL) and tested both in hydrogen and deuterium operation. High current density negative ions of 10.4mA/cm2 H- and 8.4mA/cm2 D- were successfully produced with an arc discharge power of 40kW. It was found that the isotope effect for the deuterium negative ion current was about 0.8 of the hydrogen negative ion current. To obtain the high D- current density, it was important to optimize the magnetic filter strength of the volume negative ion source. Electrons accompanying with the negative ions were effectively suppressed by biasing the plasma grid positively with respect to the anode. The ion source was sent back to JAERI in 1989.

8.7 DOE/JAERI THOMSON SCATTERING SYSTEM FOR JFT-2M (ANNEX X)

The U.S. DOE and JAERI signed Annex X on October 25, 1989, for a collaborative program on the JFT-2M TV Thomson Scattering System. In May-July1991, the TVTS fabrication was carried out on JFT-2M in collaboration with PPPL. In February 1992, the first measurement of the Thomson scattered light was done and the TVTS hardware worked routinely since May 1992.

8.8 DOE/JAERI NEGATIVE ION SOURCES AND ACCELERATORS FOR NEUTRAL BEAM INJECTORS (ANNEX XI)

A high current source using multiple merging beams was developed by Japan and was incorporated into the neutral beam accelerator system which was tested at the Lawrence Berkeley National Laboratory (LBNL) in Berkeley, California. Japan needed to develop a 500 keV source for use on JT-60 and the U.S. wanted to develop 1.3 MeV source for the multilateral ITER project. Although the collaboration successfully demonstrated high current operation of neutral beams with energy up to 200 keV, the ITER Director announced that neutral beams might not be used on ITER. The U.S. initiated the cancellation of Annex XI.

U.S.-JAPAN FUSION RESEARCH COOPERATION