Future Direction of National Fusion Research
(Report)

Tentative translation to English
Office of Fusion Energy, Research and Development Bureau, MEXT

January 8, 2003
Working Group on Fusion Research
Special Committee on Basic Issues
Subdivision on Science
Council for Science and Technology

Contents

INTRODUCTION

The major energy sources in the twenty-first century and beyond should satisfy global environmental protection requirements while being closely related to national economy and national security. It is expected that long-term energy sources will be selected based on a national policy from among fission, fusion, and renewable sources such as wind power and photovoltaic power, depending for the time being upon fossil fuels. Fusion research has been actively advanced in the world's major countries since fusion energy has potentially superior characteristics with respect to safety, environmental acceptability, and resource availability. In our country, various fusion systems have been studied in the universities, the National Institute for Fusion Science (hereafter, NIFS), the Japan Atomic Energy Research Institute (hereafter, JAERI), etc., and these studies have produced many scientific results aiming at demonstration of scientific feasibility of a fusion system. This nation's research in this field is excellent—commensurate with that in the EU and the U.S. Advancements in this field will contribute to our nation's science, technology, and academic excellence through various scientific achievements from plasma physics, plasma applications, computer simulation science, cosmic and astronomical plasma physics, superconductivity engineering, material sciences, etc.

The International Thermonuclear Experimental Reactor (hereafter, ITER) Project, which is an international program, is taking a major step to realize fusion energy as a fusion reactor development program by starting intergovernmental negotiations for its construction.

Fusion research requires the long-term integration of physics and engineering. "Developmental research" should identify and follow critical paths to steadily advance fusion research. Simultaneously, "academic research" and education must be maintained and expanded by incorporating the technical skills of interdisciplinary research since the importance of academic research in this field is well recognized for leading to the systematization of physics and engineering and for spinning off technologies in other small science fields. In our country, developmental research has been led by JAERI, while the universities and the interuniversity research institute (NIFS) have conducted academic research. Thus, this research field widely encompasses both academic and developmental research, and publicizing the scientific achievements is important. Therefore, this field should be promoted by national policy as a national frontier science and technology area, taking into account of its broad research basis.

Research activities in plasma physics and reactor engineering in this field have been discussed in the Working Group on Fusion Research (hereafter, the Working Group) to strengthen national fusion research. A plan for centralization and efficient implementation has been formulated that rearranges and integrates the experimental devices that have supported national fusion research activities for many years. This plan requires new research opportunities and continuous training of talented students and researchers in addition to the enhancement of inter-university and inter-institution research at these facilities. The Working Group discussed the future direction of national fusion research considering the following four important points.

1. This report should propose specific plans for centralization and efficient implementation based on an evaluation of the research plan by the research community.
2. This report should propose a realizable program that establishes various

program conditions that respect the autonomy and independence of each research institute, such as each individual university, NIFS, and JAERI, as a corporate organization.

3. Centralized research programs will be established under the consensus of the research community. Core national devices for these programs will be identified as "Centralized Joint Research Devices". Joint research among implementing institutes and the research community will be further promoted using centralized national devices as well as international large devices.

4. The report "On the ITER Program" issued by the Council for Science and Technology Policy on May 29, 2002, and recognized by the Cabinet on May 31, 2002, contains the following mandate, the "National fusion research program should be constructed with an organized coordination with ITER while pursuing centralization and efficient implementation. Here, consideration should be given to the education of talented students and researchers who support fusion research and development, to the research on various plasma confinement systems, and to the development of reduced activation materials."

1. PROGRESS OF DELIBERATIONS

The Working Group was formed to deliberate the future direction of the national fusion program under the Special Committee on Basic Issues of the Subdivision on Science. The Working Group examined ways to establish centralization and efficient implementation among representative researchers in this field.

"Working Group Members" and the "Progress of Deliberations" are shown in Addenda No. 1 and 2, respectively. The Working Group also issued a summary of discussions from the 10^{th} meeting (March 25, 2002), a summary of critical issues from the 12^{th} meeting (July 29, 2002), and a final report from the 18^{th} meeting (Jan. 8, 2003).

2. CENTRALIZATION AND GRAND DESIGN OF FUSION RESEARCH

The Working Group shaped arrangements on centralized research programs, and the national inter-university and inter-institution research structure with a long-term view on the national fusion program.

(1) Necessity of Centralization

An important step is being taken through the ITER program towards research addressing fusion energy production. It is necessary to clarify the priority of future research in the domestic fusion program to deepen the research basis and to enable further development. Considerations are focused on the following four points for the prioritization of such research. This research should:

1. Have a clearer contribution to ITER and stronger international competitiveness,
2. Enrich research programs leading to the wider possibilities of fusion reactors,
3. Enrich research programs leading to universal scientific understanding, and
4. Enrich training programs (education of students, training of young researchers).

The following actions are necessary to develop this field of research effectively and efficiently:

a. Rearrange and integrate existing facilities, and designate "Centralized Joint Research Devices" to enable new research opportunities for the research community,
b. Promote inter-university and inter-institution research, and coordinated

research, and
c. Create research addressing new challenging possibilities.

(2) New Grand Design of Fusion Research

In fusion research addressing the realization of a fusion reactor, integrated research promotion is important for both “developmental research” as represented by ITER and supporting “academic research and the associated education system”. The former is target-oriented research and development in which a specific target of technical research should be attained within a certain period. The latter, especially academic research in the universities, etc., is based on the free thoughts of researchers.

Fusion research should be developed as integrated research having the following two aspects consistent with the government’s basic plan for fusion research and development.

- Developmental research addressing the realization of the fusion reactor with a organized coordination with ITER.
- Academic research addressing systematization of knowledge of this field based on scientific principles.

Figure 1 shows the Grand Design of fusion research as a stratified structure between developmental research and academic research. This figure symbolically shows the systematic need for coordinated promotion among various classes of fusion research. Contributions from each class of the stratified structure are important, especially through the utilization of “Centralized Joint Research Devices”, to realize fusion reactors including ITER.

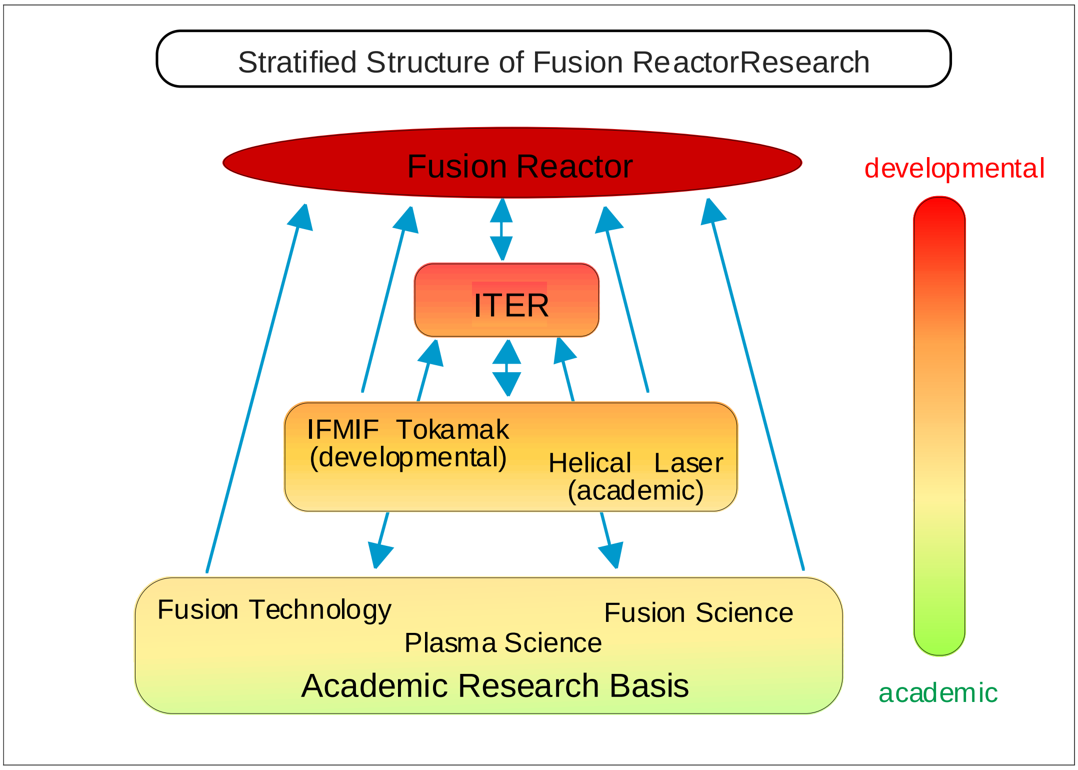

Fig. 1 Stratified Structure of Fusion Research

3. FUSION RESEARCH CENTRALIZATION PLAN

(1) Evaluation of Existing Fusion Research Programs

To evaluate the present research conditions and to decide future programs, different scientific, technological and academic criteria were required according to its organizational structure form. This evaluation activity also provides information to people outside the fusion community. <u>The Working Group conducted a cross-field scientific evaluation independent of individual devices that is based on the research community's peer review of the objectives and significance of existing research programs.</u>

Figure 2 shows the major research bases in our country. The list of existing experimental devices (including computers) is given in Addendum No. 3., “Experimental Facilities and Supercomputers Supporting National Fusion Research”; and the results of the evaluation are described in Addendum No. 4., “Assessments of Existing Fusion Research Programs”. The assessments in Addendum No. 4 were derived from a two-dimensional evaluation shown as vertical and horizontal axes, “experimental devices” and “research fields”, respectively. Although the research results from all programs were highly rated, many aspects of the comments addressed the completion level of the research objectives and future plans. Integrating these evaluation results, the Working Group categorized the achievements and the plans of each program and device in the new Grand Design of fusion research, and summarized the evaluations in the “Future Development” also in Addendum No. 4.

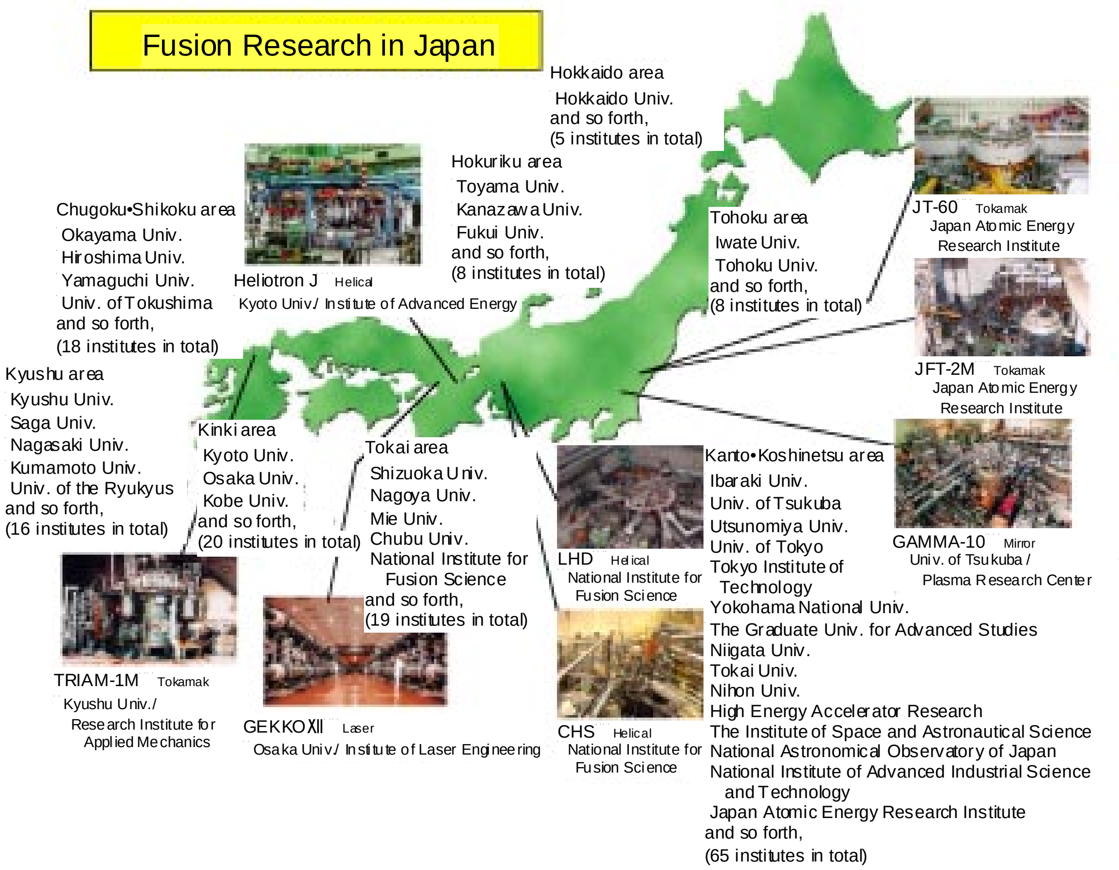

Figure 2 Major research facilities and organizations in our country

(2) Centralized Research Programs

Based on the evaluation results of the existing research programs, the Working Group deliberates a number of proposals as candidate centralized research programs for the coming 10- to 20-year fusion research effort in our country. These candidates are presented in Addendum No. 5., "Evaluation of New Centralized Programs." In considering these centralized programs, the Working Group weighed two critical conditions—the enlargement of the domestic research basis presupposing ITER construction and the establishment of the research plan required to overcome the critical issues for constructing a fusion demonstration reactor within about 30 years. Consequently, it has been concluded that the research programs to be centralized are the tokamak, reactor engineering, and laser fields. Based on the evaluation of the existing programs, helical research (LHD) has been added. Thus, four centralized programs have been determined.

(3) Specific Plan for Centralized Research Programs

1) National Centralized Tokamak Facility Program

For early realization of fusion energy, a centralized national tokamak device is needed to improve the tokamak concept (such as improvement of economical efficiency by demonstration of high-beta, steady-state operation) domestically from an independent standpoint, to maintain world leadership in the ITER activity, and to establish organized coordination with ITER by training a few hundred talented researchers. This device has to be a super-conducting device with break-even-class plasma performance aimed at high-beta values (the normalized beta β_N= 3.5 to 5.5) required for the demonstration reactor with sustained operation longer than 100 seconds under full non-inductive current drive conditions. The device has to provide mobility and flexibility in terms of plasma aspect ratio, plasma shaping control, and feedback control. In implementing this program, joint planning and design of the project between the new JAERI/JNC corporate organization and the national research community is important. It is necessary to position JT-60 as the centralized device for national joint tokamak research, and to continue JT-60 operation until construction of the follow-on national centralized tokamak device. The implementation of the follow-on national centralized tokamak device should be made taking into account the perspective of the ITER project.

2) Fusion Materials Testing Facility Program

Development of materials and blankets is a critical issue for early realization of fusion energy regardless of the plasma confinement system employed. From now, the International Fusion Material Irradiation Facility (hereafter, IFMIF) program being performed by international cooperation under the IEA is especially important to develop candidate structural materials for the first wall for fusion power reactors. This program should confirm the durability of the developed materials against the fusion environment and obtain data on their characteristic properties under neutron irradiation. This program is also expected to contribute greatly to the scientific research required for the efficient development of materials. Therefore, it is necessary to start the Engineering Validation and Engineering Design Activities (hereafter, EVEDA) promptly aiming at performing engineering validation of the important system elements to complete the engineering design needed for construction of these elements. In the implementation of EVEDA, collaboration of the new JAERI/JNC corporate organization, NIFS, and the universities is crucially important.

3) Laser Fast Ignition Program

The laser fast ignition program, FIREX, opens the possibility of fusion energy demonstration with a concept qualitatively different from the magnetic fusion concept by applying the newest laser technology and science in an extreme state. The FIREX first-phase program addresses proof-of-principle experiments for the original fast ignition laser fusion concept by attempting demonstration of plasma heating to the ignition temperature (50 to 100 million degrees Celsius) with the world's highest ultra-intense laser power. This program will contribute not only to enlarging the possibilities for fusion reactors but also to reinforcing our academic basis and maintaining the intellectual property rights of our country. Moreover, by judging its achievements, it may be possible to make the critical decision for the second-phase program directed toward realization of ignition and burn. To make FIREX a joint program for the entire research community, it is necessary to consider the cooperation between an interuniversity research institute and universities.

4) Large Helical Device (LHD) Program

The important role of the LHD program in NIFS as an interuniversity research institute should be noted for the progress in this academic research field while also promoting the three centralized programs mentioned above. The LHD device is a magnetic confinement device addressing fusion reactors with zero net toroidal plasma current. LHD adopts a Heliotron magnetic configuration, which was conceived and developed in our country. It is necessary to continue the academic research on LHD as one of "Centralized Joint Research Devices" to provide a general understanding of toroidal plasmas close to fusion core plasma, to contribute to the ITER project, and to allow cooperation with other new confinement concepts. The research objectives of LHD are described in Addendum No. 6, "Themes of LHD Research."

For implementing a long-term fusion program, it is necessary to cover a wide range of research areas that extend from academic research to developmental research. For this purpose, it is important to publicize academic results continuously and to encourage the development of innovative technology by retaining the wide research basis of fusion science in our country. Towards this goal, it is important to utilize the three centralized programs mentioned above and the existing LHD program as centralized programs for inter-university and inter-institution research.

(4) Priorities of Centralized Programs

Based on the above recommendations, the Working Group suggested the following strategy for the first three centralized programs described.

1) For the early realization of fusion energy, it is necessary to assign a high priority to the construction of the National Centralized Tokamak Facility. This facility will address high-beta, steady-state research in the collision-less plasma regime to resolve the important research issues for the demonstration reactor with organized cooperation with ITER.

2) Development of materials and blankets is a critical issue for the early realization of fusion energy regardless of the plasma confinement system employed. The IFMIF, the core facility of this effort, is fundamental for the research and development of fusion energy. Therefore, it is necessary to promptly begin the Engineering Validation and

Engineering Design Activities (EVEDA). Establishment of a national organizational system is urgently needed for the implementation of EVEDA.

3) It is necessary to start the first phase of the proof-of-principle program of the fast ignition laser fusion concept as an original national project, both to explore the possibility of fusion reactors based on a principle different from magnetic fusion and also to reinforce the academic basis and to maintain the intellectual property rights of our country.

(5) Rearrangement and Integration of Existing Devices

Based on the decisions on centralized programs and evaluation of the existing devices, the future strategy is summarized as follows:

1) As the bases of centralized programs, JT-60 and GEKKO-XII should continue operation until the start of their respective follow-on projects, and should complete their programs at the construction of the new devices.

2) LHD should continue studies towards its initial research goal of achieving a universal understanding of toroidal plasmas by producing high-performance plasmas and by clarifying academic contributions to toroidal systems including ITER as an existing research program.

3) Except the three centralized devices, JT-60, GEKKO-XII, and LHD, the remaining existing devices should complete their programs at their appropriate times. However, any extension proposal associated with a novel research evolution can be a candidate for new research possibilities.

4) In addition to stimulation of joint research using the four centralized programs, it is necessary to construct a research framework that provides challenging opportunities to test original ideas.

4. SCHEMES OF ENHANCED INTER-UNIVERSITY AND INTER-INSTITUTION RESEARCH

Fusion research in Japan has reached a new stage—one that focuses on domestic research with “Centralized Joint Research Devices” and international research with ITER and the Fusion Material Testing Facility. It is necessary to stimulate inter-university and inter-institution research to produce new research opportunities as well as to enhance the centralized programs. Accordingly, some promotion measures for successful inter-university and inter-institution research are necessary to reach the full potential of the research community. This, in particular, implies expanding the budget for the collaborative efforts including accommodation and travel expenses.

Respective roles of NIFS, the universities, and the new JAERI/JNC corporate organization in reinforcing inter-university and inter-institution research are described below.

(1) Roles of NIFS as an Interuniversity Research Institute

NIFS has promoted its original large helical experimental program and the theory and simulation research based on the fundamental principle of academic research on fusion plasma science and its applications. Considering the request for NIFS to reinforce its roles in promoting academic research in the fusion field, it is necessary for NIFS to strengthen coordination and bi-directionality with the universities as an interuniversity research institute, to reconsider the management structure and the covered range of research subjects, etc., and to enhance system designs to enable further activation of research programs.

To use LHD efficiently, it is necessary to strengthen the promotion function of joint research by including system advancement for LHD research in planning and by reforming the role of the joint research committee. It is also necessary to reinforce collaboration with tokamak research in the field of improved confinement and steady-state experiments using its feature of net-current-free plasma being extendable to fusion core plasma condition.

In the area of laser fusion research focused on the proposed fast ignition (FIREX) program, NIFS should collaborate with Osaka University and other institutions, and actively promote research collaboration in this area. In addition to the research collaboration, it is expected that NIFS will play an important role in creating new research opportunities and as a center of basic academic research for fusion by cooperating or collaborating with the universities in pioneering and growing research areas.

Moreover, comprehensive and integrated promotion of reactor engineering research will become more important in the future. The role of NIFS as an interuniversity research institute in the coordination of the wide area of reactor engineering researches in the universities is expected to include international cooperative research in IFMIF in particular as well as blanket engineering, super-conducting coil technology, safety research, advanced reactor design, etc.

(2) Roles of Universities after Reorganization to Corporate Organizations

Research in the universities is aimed at advancing basic academic research, and they play a central role in continuously training researchers who enter the scientific community comprised of thousands of scientists. Consequently, a strong necessity exists to accurately understand the perspective of university research and to introduce measures for its promotion to expand future fusion research. However, the autonomy and independence of the universities should be respected in deciding future individual plans. Particular emphasis should be placed on recognizing the importance of their research policies after they become corporate entities.

In the universities, promotion of academic research and education of students have been recognized as two important tasks. Therefore, it is necessary for the universities to combine students' education with the maintenance of the academic research basis by strengthening cooperation with NIFS as an interuniversity research institute. The universities must also be involved in joint planning and research with JAERI in the fusion research field where systematization and cooperation in the wide research areas of tokamak, helical, and laser fusion as well as reactor engineering, and so forth, are necessary. Active promotion of bi-directional collaboration and joint research is necessary to effectively utilize these research bases.

For a university to provide a bi-directional research basis, it is indispensable for the university to raise its competitiveness and its academic stature by promoting cooperation within itself. The training of new leaders with global research vision should be included in the contemporary education of students.

For these reasons, active promotion of pioneering and creative research in the universities based on strong inter-university and inter-institution research with NIFS and JAERI is necessary.

(3) Roles of the New JAERI/JNC Corporate Organization, Reinforcement of Research Collaboration

JAERI has a mandatory mission from the government to develop a tokamak fusion system centralized on ITER. Under the new corporate organization created by unification with the Japan Nuclear Cycle Development Institute (JNC), it is also entrusted to promote the ITER program, tokamak core plasma development, and reactor engineering in its role as the central fusion organization in our country, as well as to promote professional training and education in the field of fusion research and development.

Using the JT-60 tokamak and other facilities, JAERI is presently striving for research collaboration with the universities and NIFS. Accordingly, it has successfully performed joint experiments on JT-60 between JAERI and the universities by assigning university professionals as leaders of some research task forces. Since such an advanced collaboration framework is indispensable for the national fusion research and development program, long-term training of human resources is required for ITER. Thus, joint research should be promoted by assigning JT-60 as a core national device for joint research. In addition, the JT-60 program should be converted to the National Centralized Tokamak Facility Program considering the perspective of the ITER project.

With regard to reactor engineering, the new JAERI/JNC corporate organization is expected to be the central fusion organization of our country to promote the IFMIF program liaison with the universities as well as to promote the necessary research and development on critical technologies on the blanket, super-conducting coils, heating, and current drive system.

The role of the new corporate organization is further expected as a central institute for fusion research and development in our country following the transformation of the legal status of JAERI to an independent administration agency in 2005. As a consequence, whether before or after the conversion to the National Centralized Tokamak Facility, expediting the establishment of an efficient joint-planning and collaboration framework is strongly advised so that the new corporate organization is able to effectively achieve its assigned mission and to foster human resources continuously.

(4) Enhancement of Inter-university and inter-institution research

As mentioned above, a number of experimental device programs that have been contributing significantly to the progress in plasma physics for many years are going to be reorganized for centralization and efficient implementation. Fusion research will be extended by using larger-scale devices in the area of tokamak, helical, laser fusion research, and reactor engineering research, and by challenging new possibilities. Here, it is extremely important to promote inter-university and inter-institution research activities. The following two policies are to be considered.

1) Enhancement of Bi-directional Collaboration

In order to widen research opportunities under the upcoming reorganization and centralization, bi-directional collaborative research activities utilizing existing research facilities and devices in the universities and research institutes are considered vital. In previous research collaborations, university scientists performed their own research at the interuniversity research institute. However, the opposite movement of scientists is also necessary for the future development of fusion research. Efficient utilization and synergism of resources will allow scientists from joint research institutes to join collaborative research activities at the universities (faculty, university center, research institute, etc.). A new system should be implemented to promote bi-directional research activities.

Practically important issues to promote are participation of scientists from other institutes in pioneering university experiments, a system like the LHD project research collaboration system (a support system that enables the exchange of physicists between universities), augmentation of necessary research funds, and expansion of opportunities and funds for collaborative research in research institutes such as JAERI.

2) Coordinated Research

Specific action items are necessary to promote coordinated research as a form of collaborative activities that enable efficient and broad utilization of large-scale facilities and intellectual and human resources. Detailed consideration of these issues is vital for the encouragement of collaborative research activities.

5. EDUCATION AND TRAINING AFTER CENTRALIZATION

Since fusion research accomplishments require long-term efforts, continuous professional education of young-generation scientists is crucial for successful accomplishment of a large international project such as ITER as well as for playing a leading role in it. After the centralization, reorganization and system redesign should be implemented to provide a competitive environment, and an active exchange and mobilization of researchers to achieve efficient utilization of inter-university and inter-institution research.

Improvement of the research environment for promising young researchers is necessary to enable them to participate in the most advanced research topics. For example, their direct participation in the international and large-scale experiments as well as in cutting-edge and original research using small-scale devices (a strong trait of universities) is important. For professional education, it is important to provide various attractive research opportunities to researchers.

Considering the important high-level professional training and education efforts in the non-university research institutes, a new system to realize such professional training and education is required based on collaboration and exchange between the universities and the research institutes. In the course of student education, the number of students accepting extended research opportunities in other university foundations is expected to increase in the future. A supporting system for such research activities thus will be necessary. From the viewpoint of student education, an adequate and timely support system should be prepared that includes travel budgets, positions in the receiving institutes, research-assistant salaries for graduate students, and accommodations. For the education and training of talented students, it is necessary to utilize the promotion systems of inter-university and inter-institution research, and to offer them the challenge of new possibilities.

6. SUMMARY

The Working Group on Fusion Research has deliberated and issued this report that recommends the national development policy of fusion reactors should make a “paradigm shift” from the previous multi-path strategy to a centralized strategy for fusion research based on necessary contributions from both academic and developmental aspects. The report delineates a new Grand Design for future national fusion research with proposed reorganization and efficient centralization of many experimental devices that have long contributed to fusion research. It strongly urges inter-university and inter-institution research as well as the promotion of research addressing new possibilities and the continuous education.

Considering that the opportunity to study burning plasma is likely to be realized by the ITER project in about ten years, it is necessary to promote fusion research by clarifying the items and subjects that might limit the "critical path" progress to realize a fusion reactor in about thirty years and to pursue advanced follow-on fusion reactors. Therefore, the Working Group evaluated the existing and proposed research plans of the research community. The Working Group has defined four centralized pillars consisting of three future centralized programs, tokamak research (the National Centralized Tokamak Device Program), reactor engineering research (the Fusion Material Test Facility Program), and laser fusion research (the Laser Fast Ignition Program), and has added the existing helical research (the Large Helical Device Program) to these three.

The Working Group defines the following national devices as "Centralized Joint Research Devices"; JT-60 and its follow-on device, the National Centralized Tokamak Device; LHD; and GEKKO-XII and its follow-on device, the Fast Ignition Realization EXperiment. These devices should be used to promote inter-university and inter-institution research as well as joint research with the IFMIF (International Fusion Material Irradiation Facility) by international collaboration in reactor engineering. For JT-60 and GEKKO-XII, it is necessary to complete their planned research prior to construction of the new devices. Except the "Centralized Joint Research Devices", it is concluded that the research projects on existing devices should be completed at their appropriate times. However, proposals of prolongation of device operation associated with a novel research evolution can be a candidate for new research possibilities.

On the other hand, in addition to the centralization to the large-scale devices, it is very important to implement a plan to encourage cutting-edge and original ideas, and to promote education. For the promotion of academic research in our country, it is essential for researchers to have opportunities to pursue research addressing new possibilities through which highly original research can be magnified and the opportunity for education of students and researchers with distinguished talents can be realized. Therefore, for the promotion of these research fields after the centralization, a process is needed to allow the challenge to new possibilities by way of the inter-university and inter-institution research function of interuniversity research institutes, and so forth, which owes responsibility to the research community.

For the centralization of future fusion research and the promotion of the inter-university and inter-institution research proposed in this report, specific issues should be solved by the reflection of governmental policy. Therefore, for continuous communication within the research community and for coordination with the government, it is desirable that a deliberation group similar to this Working Group be established continuously.

ADDENDUM NO. 1

WORKING GROUP MEMBERS

Members

Atsuo Iiyoshi	President of Chubu University
Keiichi Kodaira	President of the Graduate University for Advanced Studies
＊Yasuharu Suematsu	Director, National Institute of Informatics

Specialists

Tokuhiro Obiki	Institute of Advanced Energy, Kyoto University
Makoto Katsurai	Director, High Temperature Plasma Center, University of Tokyo
Mitsuru Kikuchi	Deputy Director, Department of Fusion Plasma Research, JAERI
Masahiro Seki	Director, Department of Fusion Engineering, JAERI
Takayuki Terai	Professor, Graduate School of Engineering, University of Tokyo
Tetsuji Noda	Principal Scientist, Nanomaterials Laboratory, NIMS
Hideki Matsui	Director, Material Testing Reactor Laboratory, IMR, Tohoku University
Shinzaburo Matsuda	Director General, JAERI
Masami Fujiwara	Director General, NIFS
Kiyoshi Yatsu	Director, Plasma Research Center, University of Tsukuba
Tatsuhiko Yamanaka	Director, ILE, Osaka University
Naonori Yoshida	Director, Advanced fusion Research Center, RIAM, Kyushu University
Kuniaki Watanabe	Director, Hydrogen Isotope Research Center, Toyama University

Science Adviser

Osamu Motojima	Director, Department of LHD Project, NIFS

Scientific Research Senior Specialist

Yuichi Ogawa	Professor, High Temperature Plasma Center, University of Tokyo

＊: Chair

ILE : Institute of Laser Engineering
RIAM : Research Institute for Applied Mechanics
JAERI : Japan Atomic Energy Research Institute
NIMS : National Institute for Material Science
IMR : Institute of Material Research
NIFS : National Institute for Fusion Science

ADDENDUM NO. 2

PROGRESS OF DELIBERATIONS

1. Establishment of the Working Group

The Special Committee on Basic Issues of Subdivision on Science under the Council for Science and Technology decided to establish the “Working Group on Fusion Research” on June 6, 2001, for discussions of fusion research under the MEXT (Ministry of Education, Sports, Culture, Science and Technology) centered on the promotion of fusion research in the universities, in NIFS, and with the view of research and development in JAERI.

2. Composition of the Working Group

18 members (Chair, Yasuharu Suematsu, Director, National Institute of Informatics)

3. Progress of the Working Group

1st meeting	July 23, 2001 (Monday)	Discussion on charge
2nd meeting	Nov. 1, 2001 (Thursday)	Discussion on future deliberations
3rd meeting	Nov. 16, 2001 (Friday)	Hearing from Institutes
4th meeting	Nov. 20, 2001 (Tuesday)	Hearing from Institutes
5th meeting	Dec. 10, 2001 (Monday)	Hearing from fusion representatives
6th meeting	Jan. 8, 2002 (Tuesday)	Discussion on the future direction of fusion research
7th meeting	Jan. 25, 2002 (Friday)	Same as above
8th meeting	Feb. 15, 2002 (Friday)	Same as above
9th meeting	Mar. 8, 2002 (Friday)	Same as above
10th meeting	Mar. 25, 2002 (Monday)	Deliberation on “Summary of discussions on the future direction of fusion research”
11th meeting	July 11, 2002 (Thursday)	Discussion on the future direction of fusion research
12th meeting	July 29, 2002 (Monday)	Deliberation on “Summary of points at issue”
13th meeting	Sept. 26, 2002 (Thursday)	Discussion on the future direction of fusion research
14th meeting	Oct. 24, 2002 (Thursday)	Same as above
15th meeting	Nov.14, 2002 (Thursday)	Same as above
16th meeting	Nov. 29, 2002 (Friday)	Deliberation on basic structure of report
17th meeting	Dec.18, 2002 (Wednesday)	Deliberation on draft report
18th meeting	Jan. 8, 2003 (Wednesday)	Deliberation on report

ADDENDUM NO. 3
EXPERIMENTAL FACILITIES AND SUPERCOMPUTERS SUPPORTING NATIONAL FUSION RESEARCH

1. Magnetic Confinement Research

CHS (NIFS)
GAMMA10 (University of Tsukuba)
Heliotron-J (Kyoto University)
JFT-2M (JAERI)
JT-60 (JAERI)
Plasma Experimental Facilities (University of Tokyo)
TPE-RX (AIST)
TRIAM-1M (Kyushu University)

2. Laser Fusion Research

GEKKO XII (Osaka University)
Super-ASHULA (AIST)

3. Reactor engineering Research

Reactor engineering Related Facilities (Material Testing Reactor Laboratory, IMR, Tohoku University)
Reactor engineering Related Devices (NIMS)
Tritium Facilities (Toyama University)
(Reactor engineering researches in JAERI, NIFS, and that in plasma experimental facilities are not included in this investigation.)

4. Supercomputers

NIFS
JAERI

AIST :National Institute of Advanced Industrial Science and Technology

ADDENDUM NO. 4
ASSESSMENTS OF EXISTING FUSION RESEARCH PROGRAMS

1. MAGNETIC FUSION RESEARCH
(1) Assessment of achievements

CHS (National Institute for Fusion Science)
- Obtained many good results as a helical satellite device over the years.
- Contributes to optimize the LHD physics design.

GAMMA-10 (University of Tsukuba)
- Obtained many good results in the area of electric field formation in plasma.

Heliotron-J (Kyoto University)
- A helical device to study the elements of non-planar magnetic axis.

JFT-2M (Japan Atomic Energy Research Institute)
- Obtained many good results as a satellite device of JT-60. JFT-2M has demonstrated compatibility between fusion plasma and ferritic material.

JT-60 (Japan Atomic Energy Research Institute)
- Achieved the break-even conditions of fusion plasma. Many important contributions have provided the necessary database for the ITER program and for advanced tokamak research.

LHD (National Institute for Fusion Science)
- Many contributions to toroidal plasma physics research and steady-state toroidal plasma operation using its super-conducting and net current-less device features.

Plasma experimental facility (Tokyo University)
- Obtained many good results in academic research centered on a variety of ultra-high-beta plasmas.

TPE-RX (National Institute of Advanced Industrial Science and Technology)
- It does not reach the stage of proof-of-principle. But interesting results have been obtained.

TRIAM-1M (Kyushu University)
- Achieved unique contributions to demonstration of steady-state tokamak operation.

(2) Future directions

CHS
- Advanced research on plasma fluctuations, and so forth, together with the role of this satellite machine for LHD should be performed. The results must be assessed scientifically.
- A new emphasis as a national program through cooperation among the universities should be undertaken that would have enough magnitude to make an impact on scientific research.

GAMMA-10
- It is necessary to concentrate on plasma physics to clarify the unresolved confinement mechanism.
- While assessing its scope as university research, a new emphasis as a national program with enough magnitude to make an impact on scientific research should also be undertaken.

Heliotron-J

- The plasma properties under the new configuration should be clarified as soon as possible and the results must be assessed scientifically.
- While assessing its scope as university research, a new emphasis as a national program with enough magnitude to make an impact on scientific research should also be undertaken.

JFT-2M

- Future research should be decided by a check and review on material compatibility experiment and by the sufficiency of the database for the next step high-beta, steady-state tokamak program.

JT-60

- The JT-60 program should be changed to the national centralized tokamak facility (high-beta, steady-state tokamak program), maximizing the JT-60 contribution to ITER while reinforcing research collaboration among the universities and other scientific institutions.
- Regardless of whether before or after the conversion to the next program, its role in fusion research and development in our country should be performed. The joint planning and joint research should be developed among national researchers as a center of advanced tokamak research.

LHD

- As a joint research facility, the universal properties of toroidal plasma should be studied through the production of high performance plasma being extrapolated to fusion core plasma. Academic contributions to toroidal plasmas including ITER should be clarified, as should the concept of a helical reactor.
- Acceptance of the national research group should be promoted further.

Plasma experimental facility (University of Tokyo)

- Academic research with a diversity of plasmas should be attempted in the future.

TPE-RX

- It may be necessary to change its function from that of research development to academic research. It is necessary to review policies that provide academic exchanges among universities and scientific institutions.

TRIAM-1M

- Academic research for steady-state tokamak plasma should be pursued using its features and high-field super-conducting device. The results obtained must be assessed scientifically.
- While assessing its scope as university research, a new emphasis as a national program with enough magnitude to make an impact on scientific research should also be undertaken.

2. LASER FUSION RESEARCH

(1) Assessment of achievements

GEKKO XII (Osaka University)

- Achieved records as a center of laser fusion research and made many contributions to high-temperature & high-density implosion experiments.
- The fast ignition concept was conceived here. Heating to 10 million degrees was verified.

Super-ASHURA (AIST)

- The KrF laser was successfully developed here.

(2) Future directions

GEKKO XII

- The first stage of the proof-of-principle experiment for fast ignition should be started as academic research. For the best use as a joint national utility, it is necessary to reinforce coordination with NIFS.

Super-ASHURA

- The direction of future research should be decided after a review of the potential as a laser driver.
- Mutual collaboration and cooperation with the FIREX program is necessary.

3. RESEARCH RELATED TO REACTOR ENGINEERING

(1) Assessment of achievements

Facilities related to reactor engineering (universities)

- Universities have a high potential in reactor engineering research and have made many contributions in the development of fusion materials, the blanket, and superconductors.

Facilities related to reactor engineering (National Institute for Materials Science)

- This institute has results in developing materials.

Tritium Facility (Toyama University)

- This university plays an important role in tritium research development including tritium safe handling technology.

(2) Future directions

Facilities related to reactor engineering (universities)

- Reinforcement of mutual collaboration and cooperation between JAERI and the universities and between universities to promote ITER and IFMIF is necessary. It is important to clarify this role sharing.
- The institute for material research in Tohoku University at Oarai should be used and expanded to test material properties after neutron irradiation.
- The role of NIFS must be determined, urgently.

Facilities related to reactor engineering (National Institute for Materials Science)

- Reinforcement of mutual collaboration and cooperation on fusion technologies among ITER, JAERI, and the universities is necessary.
- Review of the measures to maintain the research potential in the fusion area is necessary.

Tritium Facility (Toyama University)

- This facility should continue its university research activities. A review of the measures to maintain these activities is necessary.

Note

Analytical study and theoretical research using large scale simulation and its visualize becomes more important for the integral understanding of fusion plasma, and for the systematic development of fusion plasma science and plasma engineering. Therefore, it is very important to upgrade supercomputers and to enhance the joint utilization of these assets among the universities and the research institutes. Since the reviews in the Working Group are mainly for experimental facilities, practical promotion measures for supercomputer systems must be reviewed in the future.

ADDENDUM NO. 5
EVALUATION OF NEW CENTRALIZED PROGRAMS

(1) National Centralized Tokamak Facility Program

- ITER is an experimental reactor with the main purpose of demonstrating fusion burn. For the demonstration fusion power (DEMO) reactor after ITER, it is necessary to implement research on the high-beta, steady-state plasmas in the collision-less regime in parallel with ITER development aiming at improving the economical feasibility of fusion reactors.
- In this research field, JT-60 and the university tokamaks such as WT-3 and TRIAM-1M have been playing central roles as the front-runners in the world fusion research. High-beta, steady-state tokamak research is the critical fusion plasma research area to realize the demonstration fusion power plant within about 30 years. Therefore, under organized coordination with the international cooperation program ITER, it is essential that our country play a leading role in world activities towards this early demonstration of fusion energy by enhancing the tokamak research potential in our country with an advanced tokamak device that can sustain beta values higher than ITER in a quasi-steady state.
- Three proposals having common aspects of high-beta, steady-state research (the JT-60 super-conducting modification proposal, the spherical tokamak proposal, and the TRIAM-1MU proposal) were integrated into the “High-Beta, Steady-State Tokamak Experimental Device” (tentative name) with the main purpose of sustaining high-beta (the normalized beta β_N= 3.5 to 5.5) full non-inductive current drive plasmas for more than about 100 seconds.
- Construction is recommended of the “High-Beta, Steady-State Tokamak Experimental Device” (tentative name) at the Naka Fusion Research Establishment of the new JAERI/JNC corporate organization utilizing the existing research facilities of JT-60, such as the heating systems and the diagnostic systems.
- High-beta, steady-state research is a common research subject among the various toroidal confinement systems. In addition to the “High-Beta, Steady-State Tokamak Experimental Device,” it is also important to establish the academic basis under the coordination among JAERI, NIFS, and the universities by extending high-beta research using the spherical tokamak concept through innovative research in the universities and through international cooperation, and by extending steady-state research using LHD through inter-university and inter-institution research.

(2) International Fusion Materials Irradiation Facility Program

- The development of reactor materials and power generating blankets to endure the high fluence of the 14-MeV neutron irradiation is a critical path in fusion energy development, regardless of the plasma confinement system employed.
- The objective of the material and blanket development is the construction of an engineering database for the development of reactor materials and blankets for and beyond the DEMO. To meet this objective, the immediate construction of the International Fusion Materials Irradiation Facility, IFMIF, is required. This will be the core facility for such materials development under international cooperation.
- Launching the Engineering Validation and Engineering Design Activities (EVEDA), proposed to commence in 2004, is urgently needed.
- A decision on the construction of IFMIF and its implementation system based on the

results of EVEDA in the future is appropriate.

- In parallel with promoting the EVEDA program, it is important to establish bases for the R&D on reactor materials and the blankets.

(3) Laser Fusion Program

- The FIREX first-phase program, which aims at achievement of the high temperature required for fusion ignition with the fast ignition concept, is categorized as being proof-of-principle research. Fast ignition is the laser fusion concept originated in our country; demonstration of fusion ignition and burn could be achieved for the first time during the execution of the FIREX program.
- Our country has been leading the world in laser fusion research by achieving high-density compression as a basic condition for laser fusion and by demonstrating the fast ignition concept. The plasma heating experiment using the peta-watt laser system has reached its goal of 10-million-degree heating set by the Planning and Promotion Subcommittee of the Fusion Council. The results obtained are adequate for this fast ignition research to proceed to the next step.
- Laser fusion research is expected to impact basic science and industrial technology differently than the influence of magnetic confinement research. FIREX should proceed to the first-phase program (goal: to heat the implosion plasma to ignition temperature) as academic research, and then, after judging the first-phase results, reorganize the second-phase program to demonstrate ignition and burn.
- Laser fusion research has been performed by the Institute of Laser Engineering at Osaka University as the central research body. With the reorganization of the universities to corporate entities, it is necessary to study the methods of cooperation with interuniversity research institutes to make FIREX a joint program for the whole research community.

ADDENDUM NO. 6

THEMES OF LHD RESEARCH

- ○ The goals of LHD research are to systematically understand the physical properties of helical plasmas, to establish physical models to predict the plasma behavior with high scientific accuracy, and to clarify the similar and different characteristics between helical and tokamak plasmas in a non-burning plasma at about one hundred million degrees Celsius.
- ○ Five high-priority subjects are:
  1. To demonstrate the reduction of neoclassical transport in the collision-less plasma regime,
  2. To improve plasma confinement by the clarification and control of the anomalous transport mechanism,
  3. To establish physical models defining MHD equilibrium and stability,
  4. To demonstrate good confinement properties of highly energetic particles applicable for alpha-particle confinement, and
  5. To demonstrate the steady-state operation of the divertor; the divertor must be compatible with high-density plasma and have good confinement properties.

- ○ It is necessary to verify the properties of the LHD plasma under the integrated conditions, as well as the individual achievement of the above research subjects to clarify the prospect for a helical system fusion reactor.
- ○ The above research subjects include those that are complementary to tokamak research. For the attainment of the objectives addressing the improvement of plasma performance and the clarification of plasma properties in toroidal plasmas from aspects different from tokamak research, and for contribution to the realization of a future fusion reactor, LHD research should be advanced to achieve plasma performance equal to, or higher than, that from tokamaks.

ADDENDUM NO. 7

GLOSSARY

[Page 2]

International Thermonuclear Experimental Reactor (ITER) Program

ITER is a tokamak-type fusion experimental reactor that addresses the attainment of fusion burning plasma and its long sustainment. It has been promoted as an international cooperation among Japan, the U.S., Europe, and Russia since 1992. The engineering design and technology R&D were performed over a six-year duration. Japan, Europe, Russia, and Canada are now conducting formal intergovernmental negotiations towards its construction.

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Plasma Confinement Systems

Plasma is the fourth state of matter following solid, liquid, and gas. Generally, each form of matter becomes ionized when it is heated to several thousand degrees Celsius; its electrons move freely and it becomes plasma. Within a fusion reactor, high temperature plasma, at more than one hundred million degrees, should be produced and confined without touching any solid material. Two kinds of plasma confinement systems are being investigated—one is a magnetic confinement system, and the other is an inertial (laser) fusion system.

Reduced activation materials

Reduced activation materials are also called low activation materials. High-energy fusion neutrons react with the atoms of the structural materials surrounding reactor plasma to produce radioactive isotopes (RI) with certain probabilities. This process is called "Activation.” A reduced activation property means "low probability of activation" or "short half-life" of the activated RI. The activity is of concern for final disposal of the material unless otherwise noted. "Reduced activation materials" refers to materials with these reduced activation properties.

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Tokamak

A tokamak is a magnetic confinement system with toroidal plasma current. The plasma is stably confined by driving plasma current in a toroidal direction under the strong toroidal magnetic fields with external coils. The current is also used to heat the plasma through the ohmic heating. Russian scientists in the Kurchatov institute invented the tokamak system. Because of its superior confinement property, many experimental devices using this configuration have been constructed and used for research in many institutes throughout the world.

Reactor engineering

A fusion reactor uses core plasma, in which D-T reactions take place, and consists of the components needed to generate and maintain the plasma. These components include the vacuum vessel, blanket, super-conducting magnets, and so on. Reactor engineering is a general term encompassing research and development on these components.

Laser

Inertial fusion is a process whereby a fuel pellet having a few-millimeter radius is compressed by isotropic implosion (adiabatic compression) driven by pulsed high power sources. High temperature plasma having a very high density is formed instantaneously to produce fusion reactions. For this pulsed high-power source, high-power laser systems are mainly used.

Helical (LHD)

A toroidal plasma confinement system using a twisted magnetic field coil is called a helical system. LHD (Large Helical Device) is one of the largest helical devices in the world and is operated at NIFS in Toki City of Gifu prefecture. Construction started in 1990, and experiments began in March 1998. LHD is a Heliotron-type helical system with two helical coils and three pairs of circular coils. The stored magnetic energy of the helical coils is also one of the largest in the world.

High-beta, steady-state operation

The ratio of plasma pressure to magnetic pressure is called the beta (β) value. With higher β values, higher temperatures and higher density plasmas can be confined. With present fusion devices, operation is limited to a few hours at most. However, in the future, it is hoped a reactor will continue its operation for one year in steady-state. Consequently, it is very important for a tokamak reactor to realize steady-state operation with a high β value.

Break-even plasma

The ratio of the thermonuclear power produced to the heating power supplied is called fusion power gain (Q). The break-even condition is defined as a plasma state of Q=1. This condition is closely related to the fusion triple product of plasma temperature, plasma density, and energy confinement time. D-T equivalent fusion power gain $Q_{DT}^{eq}>1$ has been established in JT-60 (Japan) and JET (EU).

Plasma Aspect Ratio

Characteristic parameters of a toroidal magnetic confinement system are the radius of the torus (major radius R) and the fatness of the torus (minor radius a). The ratio of the major radius to the minor radius is called the "aspect ratio" (A=R/a). Typical tokamak devices have an aspect ratio of A~3, while helical devices have an aspect ratio of A=5~7. Recently, a very tight aspect ratio tokamak (A<2) has attracted a great deal of attention and is called spherical tokamak.

Plasma shaping control

Modern tokamaks have a vertically elongated, noncircular, cross–sectional shape. Plasma confinement and stability properties are strongly dependent on this cross-sectional shape. Thus, optimization of cross-sectional shape and its control becomes important.

Feedback control

The current distribution affects confinement and stability of the tokamak plasma, significantly. Using an inductive current drive, the control of the current profile is difficult. However, there are many possibilities for feedback control to obtain an optimum profile for a non-inductive current drive. This is an important subject for future study.

β_N

The upper limit of the beta value in a tokamak has theoretically been shown to be proportional to the plasma current and inversely proportional to the toroidal magnetic field and the minor plasma radius. The normalization parameter for the beta value is called normalized beta (β_N) value. If a higher β_N value is possible, higher performance and more efficient reactor core plasma can be obtained.

Non-inductive current drive

Plasma current should be sustained in a steady-state mode for a tokamak system. In most present tokamak devices, the plasma current is driven inductively, the same way as done in a transformer, and its duration is limited. Non-inductive current drive is necessary to operate a tokamak reactor in a steady-state mode. Plasma current generation by plasma itself is actively utilized with the assist of plasma current generation by neutral beam injection and high-frequency electromagnetic wave injection.

JT-60

A break-even test facility, JAERI Tokamak-60 (JT-60), is located in the Naka Fusion Research Establishment of JAERI. It is one of the largest tokamak devices in the world. JT-60 (Japan), TFTR (US, shutdown), and JET (EU) were called as the Three Large Tokamaks. The maximum plasma temperature achieved in JT-60 was 520 million Kelvin, which is a world record.

Blanket

Fusion core plasma is surrounded by structures called the blanket. The major functions of the blanket are to convert the kinetic energy of the 14-MeV fusion neutrons to thermal energy and to extract this energy from the reactor, to produce tritium fuel resulting from nuclear reactions between neutrons and lithium atoms, and to shield and protect components outside the blanket, such as super-conducting magnets, from fusion neutrons.

Candidate structural materials for the first wall

The first wall is the wall of the fusion device facing the high-temperature, high-density plasma of the fusion reactor core. The first wall is exposed directly to 14-MeV neutrons produced by the nuclear fusion reaction. Therefore, the wall materials are required to have a high resistance to neutron irradiation damage and, in addition, to have low activation properties.

Neutron irradiation

This refers to the exposure of the first-wall structural material to 14-MeV neutrons produced by D-T nuclear reactions in the fusion reactor. The 14-MeV neutrons cause displacement damage to the crystal lattice atoms of the materials and produce He particles accumulation through transmutation reactions with the atoms of the materials.

IFMIF Program

IFMIF is the acronym for International Fusion Materials Irradiation Facility. Structural materials in a D-T fusion reactor are exposed to 14-MeV neutrons produced by the fusion reactions. A plan to build IFMIF is in progress under IEA collaboration. It will clarify the properties of materials under irradiation conditions similar to those of a fusion reactor. The IFMIF will provide neutrons with energies around 14 MeV by bombarding lithium with a deuteron beam.

Engineering Validation and Engineering Design Activity (EVEDA)

This refers to the "Engineering Validation and Engineering Design Activity" (EVEDA) phase in the IFMIF project. The EVEDA is the next phase of activities after the Key Element Technology Phase (KEP) and will be performed as a joint international program under the auspices of the IEA. The EVEDA is oriented to conduct engineering verification of major subsystems as well as to establish the engineering design for construction.

FIREX program

FIREX is an acronym for Fast Ignition Realization Experiment. During its first step, an implosion produces a high-density, low-temperature plasma core, which does not have an ignition hot spot. Next, using a new ignition scheme, a short pulse (picosecond [10^{-12} s]), ultra-high power (petawatt [10^{15} W]) laser beam is injected into the plasma before it expands. The laser beam produces a hot spark, which produces a hot spot ignition condition. This is an advanced scheme to realize high fusion power gain with a smaller laser power compared with previous central ignition schemes.

Ultra-intense laser

This refers to a laser system with an output power of more than a terawatt (10^{12} W) with a pulse length of about a picosecond (10^{-12} s)—now possible because of recent advancements in laser technology.

Heliotron magnetic configuration

The Heliotron concept was one of the helical magnetic confinement configurations originated in Kyoto University. Several machines were developed to optimize this magnetic configuration and became the basis of the currently operating LHD. The Heliotron configuration is composed of two helical coils with current flow in the same direction.

Toroidal plasma with no net toroidal current

In a toroidal magnetic confinement system, poloidal (direction around the plasma minor radius) and toroidal magnetic fields are necessary to confine the plasma. In a tokamak, the poloidal field is produced by toroidal plasma current. In a helical system, the poloidal field is formed with twisted coils. Such a system without net toroidal current is a benefit for a reactor for steady-state operation since it does not require a non-inductive current drive.

Fusion core plasma

Plasma that has parameters near the self-ignition state is referred to as fusion core plasma.

Parameter

Parameter is a general term for physical quantities. For instance, temperature, density, confinement time, etc., are necessary core plasma parameters for a fusion reactor.

Collision-less plasma

Plasma is an aggregation of charged particles, and these particles interact with each other due to Coulomb scattering. This effect decreases as plasma temperature rises. For instance, the mean free path of a particle in a typical fusion reactor is about 10 km; thus a particle can have the probability of traveling freely around a 10m diameter torus a hundred times before having a collision with another particle. High temperature plasma having such a rare collision state is referred to as collision-less plasma.

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GEKKO-XII

GEKKO XII is a 12-beam line laser system for laser fusion research at Osaka University. Constructed in 1983, it was the world's most powerful laser system (laser output of 30 kJ with a laser wavelength of 1 μm). GEKKO XII compressed a fusion fuel pellet to 600 times its solid density and established the principle of laser fusion (high-density compression).

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Non-planar magnetic axis

For toroidal devices, the center of the plasma column is called the magnetic axis. If the magnetic axis is not on one plane, it is called a non-planar magnetic axis. From the point of view of optimization for confinement studies, the study of helical systems with non-planar magnetic axes has become popular.

Ferritic steels

Ferritic steel is a promising iron-based candidate material for reduced activation structural material for the first wall. However, ferritic steel is a ferrous material and exhibits ferromagnetism. The magnetic field for plasma confinement may be affected by this ferromagnetism. Efforts have been devoted to study effects of ferritic steels in plasma experimental facilities.

Ultra-high-beta plasma

Ultra-high-beta value plasma is a plasma that has a beta value from a few tens percent to 100 percent. Such plasma is expected in a high performance fusion reactor or an advanced-fuel reactor. Traditional tokamak or helical systems can sustain only up to 10 percent plasma. As a current carrying toroidal magnetic configuration similar to a tokamak, the Reversed Field Pinch, the Spheromak, Field Reversed Configuration, and more recently the Spherical Tokamak and Internal Conductor System have been studied as new devices to obtain ultra-high-beta plasmas.

Fluctuation study

See Neo-classical transport, Anomalous transport

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KrF laser

KrF laser is a laser system being studied for implosion. It produces UV light (0.25 μm) having higher absorption efficiency than glass lasers. This laser has many advantages such as high system efficiency, high repetition rate, ultra-uniform irradiation, and ultra-short pulse amplification.

Tritium

Tritium is an isotope of hydrogen designated as ^{3}H or T. It is used in a nuclear fusion reactor as a fuel. Rare in nature, it can be produced in a fusion reactor by utilizing the reaction of lithium with neutrons created in the fusion reaction. See Blanket.

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Spherical tokamak

Usually, the aspect ratio of tokamak devices is about three (A~3). A tokamak with a very small aspect ratio (A<2) is called a spherical tokamak. A few tens percent beta value was obtained experimentally in such a device. A spherical tokamak is a concept to improve tokamak performance.

14-MeV neutron

D-T fusion reactions generate 3.5-MeV alpha particles and 14-MeV fast neutrons. The alpha particles contribute to the plasma heating, while the neutrons that bombard the first wall and the blankets enclosing plasma generate thermal energy in the blanket and produce tritium through their reactions with lithium. In addition, the 14-MeV neutrons induce radioactivity in these structures.

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Petawatt laser

An ultra-high power laser in the petawatt (10^{15} watts) range is called a petawatt laser. It has a very short pulse length (picosecond, 10^{-12} s) and produces a hot spark when it irradiates ultra-high-density, low-temperature plasma. The hot spark produces a hot spot in the plasma, which leads to ignition in the fast ignition scenario.

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Neoclassical transport, Anomalous transport

Transport processes in plasma are produced by Coulomb collisions between charged particles. Transport that mainly obeys this mechanism is referred to as “Classical Transport.” Collisional transport that includes the effects of inhomogeneous magnetic fields is called “Neoclassical Transport.” On the other hand, electromagnetic fluctuations induced by plasma motion itself also affect plasma transport which is called fluctuation-induced transport. Fluctuation-induced transport is often called “Anomalous Transport” because its origin and characteristics presently are not well understood.

MHD equilibrium

Plasma behaves as an electromagnetic fluid (magneto-hydrodynamic, MHD), macroscopically. The condition of this force-balanced state is called “MHD equilibrium” and is expressed under the MHD equation system with fluid equations and Maxwell equations.

α Particle, high energy particle

Alpha particles (helium nuclei), each with energy of 3.5 MeV, are produced by the D-T fusion reaction and are used to heat the core plasma to around 10 keV. On the other hand, a high-energy particle beam with energy range of a few hundred keV is also used to heat the plasma to 10 keV. These α particles and high-energy particles must be confined long enough (about 1 sec) to fully heat the plasma.

Divertor function

In a toroidal magnetic confinement system, heat and particles diffused from the core plasma must be removed. A divertor performs this function. In toroidal magnetic confinement devices, the magnetic configuration between the plasma and first wall is modified to form a divertor regime where heat and particles are exhausted.

ATTACHMENT : Future Direction of National Fusion Research (Synopsis)

January 8, 2003, Working Group on Fusion Research, Special Committee on Basic Issues, Subdivision on Science, Council for Science and Technology

INTRODUCTION

- ○ Fusion research has been actively advanced in the world's major countries since fusion energy has potentially superior characteristics with respect to safety, environmental acceptability, and resource availability. In our country, various fusion systems have been studied in the universities, NIFS and JAERI, and so forth, and these studies have produced many scientific results aiming at the demonstration of the scientific feasibility of a fusion system.
- ○ Fusion research requires long-term integration of physics and engineering. "Developmental research" should identify and follow critical paths to steadily advance fusion research. Simultaneously, the "academic research" and education must be maintained and expanded by incorporating the technical skills of interdisciplinary research since the importance of academic research in this field is well recognized by producing the systematization of physics and engineering and by spinning off technologies in other small science fields.
- ○ The Working Group has proposed a plan for centralization and efficient implementation through rearrangement and integration of experimental devices that have supported national fusion research activities for many years. Creation of new research opportunities and the continuous training of talented students and researchers in addition to the enhancement of inter-university and inter-institution research are important in this plan.

1. CENTRALIZATION AND GRAND DESIGN OF FUSION RESEARCH

- ○ The Working Group's considerations are focused on the following four points for the prioritization of such research. This research should: 1) Have a clearer contribution to ITER and stronger international competitiveness, 2) Enrich research programs leading to a wider possibility of fusion reactors, 3) Enrich research programs leading to universal scientific understanding, and 4) Enrich training programs (education of students, training of young researchers).
- ○ The following actions are necessary to develop this field of research effectively and efficiently: a. Rearrange and integrate existing facilities and designate "Centralized Joint Research Devices" to enable new research opportunities for the research community, b. Promote inter-university and inter-institution research, and coordinated research, and c. Create research addressing new challenging possibilities.
- ○ Fusion research should be developed as integrated research having the following two aspects consistent with the government's basic plan of fusion research and development: 1) Developmental research addressing the fusion reactor with organized coordination with ITER, and 2) Academic research addressing systematization of knowledge of this field based on scientific principles.

2. FUSION RESEARCH CENTRALIZATION PLAN

- ○ To formulate the new strategy of fusion research, the Working Group has conducted a cross-field scientific evaluation independent from individual devices based on the research community's peer review of the research objectives and the significance of existing research programs.

- ○ Based on the evaluation results of the existing research programs, the Working Group deliberates a number of proposals as candidate centralized research programs in the next 10- to 20-year fusion research effort in our country.
- ○ Consequently, it has been concluded that the research programs to be centralized are the tokamak, reactor engineering, and laser fields. Based on the evaluation of existing programs, helical research (LHD) has been added. Thus, four centralized programs have been determined.

• Specific Plan of Centralized Programs

- ○ High priority should be assigned to the construction of the National Centralized Tokamak Facility, which will address high-beta, steady-state research in the collision-less plasma regime.
- ○ The International Fusion Material Irradiation Facility (IFMIF) program is fundamental for the research and development of fusion energy. Therefore, it is necessary to promptly start the Engineering Validation and Engineering Design Activities (EVEDA). Establishment of a national organizational system is urgently needed for the implementation of EVEDA.
- ○ It is necessary to start the first-phase proof-of-principle program of the fast ignition laser fusion concept to reinforce the academic basis and to maintain the associated intellectual property rights of our country.
- ○ It is necessary to continue the academic research of the existing LHD to provide a general understanding of toroidal plasmas, to contribute to the ITER project, and to interact with other devices that are exploring innovative confinement concepts.

• Rearrangement and Integration of Existing Devices

- ○ JT-60 and GEKKO-XII should continue their operation until the commencement of their follow-on projects. They should then complete their programs at the construction of the new devices.
- ○ LHD should continue studies towards its initial research goal to clarify the academic contribution to toroidal systems, including ITER.
- ○ Except JT-60, GEKKO-XII, and LHD, the existing devices should complete their programs at their appropriate times. However, any extension proposal associated with a novel research evolution can be a candidate for new research possibilities.
- ○ In addition to stimulation of joint research using the four centralized programs, it is necessary to construct research framework that provides challenging opportunities to test new ideas, and to take actions to realize it.

3. SCHEMES OF ENHANCED INTER-UNIVERSITY AND INTER-INSTITUTION RESEARCH

- ○ As an interuniversity research institute, it is necessary for NIFS to strengthen coordination and bi-directionality with universities, to reconsider the management structure and the covered range of research subjects, etc., and to enhance system designs which will enable further stimulation of research programs.
- ○ After the universities are reorganized to corporate organizations, a strong necessity exists to accurately grasp the perspective of university research and to introduce measures for its promotion to expand future fusion research.
- ○ As for the role and the reinforcement of research collaboration in the new JAERI/JNC corporate organization, it is entrusted to promote the ITER program, tokamak core plasma development, and reactor engineering as the central fusion

organization in our country, as well as to expedite the establishment of an efficient joint-planning and collaboration framework, and to promote professional training and education in the field of fusion research and development.

- A number of experimental devices that have been contributing significantly to the progress in plasma physics for many years are going to be reorganized for centralization and efficient implementation. Fusion research will be extended further by focusing on larger-scale devices in the areas of tokamak, helical, and laser fusion research, and in reactor engineering, and by exploring new challenging possibilities. Under these situations, it is extremely important to promote actively inter-university and inter-institution research activities as well as bi-directional collaboration and coordinated research.

4. EDUCATION AND TRAINING AFTER CENTRALIZATION

- After the centralization of programs, reorganization and system redesign should be implemented to provide a competitive environment and an active exchange and mobilization of researchers for the optimization of research and education under the efficient utilization of inter-university and inter-institution research system.
- It is important to provide various attractive research opportunities to many researchers for education and training.

5. SUMMARY

- This report delineates a new Grand Design for future national fusion research with the proposed reorganization and efficient centralization of many experimental devices that have long contributed to fusion research. It strongly urges inter-university and inter-institution research as well as the promotion of research addressing new possibilities, and the continuous education and training of talented students and researchers.
- Four centralized programs are identified. They are the three intensified areas of (1) tokamak research (the National Centralized Tokamak Device Program), (2) reactor engineering research (Fusion Material Test Facility Program), and (3) laser fusion research (Laser Fast Ignition Program), with the addition of (4) the existing helical fusion research (Large Helical Device Program).
- The national devices JT-60 and its follow-on device (the National Centralized Tokamak Device), LHD, GEKKO-XII and its follow-on device (FIREX) are defined as “Centralized Joint Research Devices”. Inter-university and inter-institution research should aggressively be promoted with these devices together with international collaboration in reactor engineering using the IFMIF.
- Except the “Centralized Joint Research Devices,” it is concluded that the research projects on existing devices should be completed at their appropriate times. However, proposals of prolongation of device operation associated with a novel research evolution can be a candidate for new research possibilities.
- For the promotion of academic research in our country, it is essential for researchers to have opportunities to pursue research addressing new possibilities through which highly original research can be magnified and the opportunity for education of distinguished students and researchers can be realized. Therefore, a process is needed to allow the challenge of new possibilities by way of the inter-university and inter-institution research function of interuniversity research institutes, and so forth, which is responsible to the research community.

○ To maintain communication within the research community and with the government, it is desirable that a deliberation organization like this Working Group be established continuously.