Tentative Translation

A Roadmap toward Fusion DEMO Reactor (first report)

July 24, 2018
Science and Technology Committee on Fusion Energy
Subdivision on R&D Planning and Evaluation
Council for Science and Technology

The vision for developing a fusion reactor must be presented clearly and be acceptable not only to the fusion science community but also to society. To this end, the Science and Technology Committee on Fusion Energy formulated "Japan's Policy to promote fusion R&D for a fusion DEMO reactor" from December 2017 to present:

(1) Strategy necessary to develop a fusion DEMO reactor
(2) Basic concepts required for the DEMO reactor and development plans to resolve technological issues
(3) Views on transitioning to the DEMO phase

Also, in December of this same year the committee decided to compose an action plan for solving each technological issue in developing the DEMO reactor to enable effective follow-up and timely confirmation of the status of the R&D framework.

Currently, we are considering a roadmap toward the construction of the Fusion DEMO Reactor (hereinafter referred to as the "roadmap") and subsequent commercialization of fusion energy. At the same time, it is necessary to identify early the issues specified in the action plan, which should be addressed on a priority basis within the limited resources. In this effort, we reviewed the roadmap from the viewpoints of ① the importance and urgency of development and ② international collaboration, both of which are particularly important in identifying issues. We have compiled the results as the first report.

This report also includes policies for reinforcing the all-Japan framework of industry, academia, and government in DEMO R&D, especially policies for strengthening collaboration with universities.

To accomplish the research and development described in this roadmap, it is also essential to train and secure human resources continuously over a long term. Policies and other measures required for this were summarized in the "Training and securing of human resources for the promotion of fusion energy developments" formulated by this committee on March 28, 2018 (see the reference), which must be promoted jointly by industry, academia and government, in parallel with research and development.

1. Viewpoints in Creating the Roadmap

This roadmap is organized to clarify particularly important milestones in development, from the viewpoint of indicating ① the importance and urgency of development. From the viewpoint of ② international collaboration, development is also classified which development should be carried out through international collaboration or domestically by Japan. Basic concepts in ① and ② are as follows:

① Importance and urgency of development

Although the development issues specified in the action plan must all be addressed in order to construct a DEMO reactor, particularly important milestones and their related research have been classified as follows:

(1) Urgent issues, together with their milestones, that must be addressed immediately to accomplish items of the check and review (items to confirm the progress toward the DEMO design) described in the "Japan's Policy to promote fusion R&D for a fusion DEMO reactor"

* Check and review is scheduled to be conducted as follows:

- 1st intermediate check and review: Around 2020
- 2nd intermediate check and review: Within a few years after 2025

(2) Issues that require timely budget allocations so that construction and design can be started early enough for check and review and for the decision to transition, together with their milestones.

(3) Strategic issues, together with their milestones, that are important in terms of the connection between issues.

Regarding the issues classified as those that must be addressed early based on above (1) to (3) above, it has been decided which issues should be resolved by the domestic program or through international collaboration based on the perspectives described in ② below:

② International collaboration

Among the development issues specified in the action plan, those that should be addressed through international collaboration have been classified as follows:

(1) Issues for which Japan has advanced R&D bases as a result of research and development until now and can play a leading role for other countries.

(2) Issues that are likely to be resolved more effectively through international collaboration due to complementarity with domestic research and development.

(3) Issues that are difficult to resolve solely by Japan due to limited resources.

2. Views on Formulating the Roadmap

The exhibit shows the roadmap formulated by identifying issues based on the viewpoints shown in 1. above. The following describes the views on each item listed in the roadmap:

① ITER Project (managed by international collaboration)

The ITER Project is now underway to construct an experimental reactor, ITER, by seven Members – Japan, the European Union (EU), Russia, the United States, South Korea, China and India - in order to demonstrate the scientific and technological feasibility of fusion energy, with an aim to start its operation in 2025 (approved at the ITER Council meeting in June 2016). By taking advantage of world-leading R&D bases, Japan is now engaged in the manufacturing of superconducting coils and other ITER components under international procurement allocation.

The ITER Project, which is now in the construction phase, is a project that should be advanced with the highest priority. The first important milestone is the first plasma in 2025, followed by the most important milestone in fusion research, "deuterium-tritium (DT) burning and ignition." Toward this scheduled milestone, it is necessary to initiate plasma control tests. To realize the DEMO, it is necessary to achieve the way for long plasma burning by initiate burn control and engineering tests after the DT burning and ignition. Preceding research with JT-60SA is important for achieving technical targets for ITER. In addition to establishing a framework for reflecting the achievements into development for ITER, Japan is required to contribute to the ITER research plan, using the related R&D bases in the country.

After the late 2020s, when the ITER Project will enter the operation phase, it will become possible to research and develop core plasmas for the DEMO and test blanket modules at full scale. In order not to miss this opportunity, DEMO-related R&D must be accelerated through the steady implementation of the necessary preceding research.

② Broader Approach activities: phase II (managed by international collaboration)

As an international collaboration project with Europe, Japan has been engaged in Broader Approach (BA) activities to establish a technological base required for the

DEMO by complementing and supporting the ITER Project.

Under the BA activities up to March 2020, the International Fusion Energy Research Center (IFERC) has been established in Aomori Prefecture as an international research and development center for fusion DEMO. Other achievements will include completion of a prototype accelerator required for the International Fusion Materials Irradiation Facility (IFMIF) in Aomori Prefecture and a world top class advanced superconducting tokamak device, JT-60SA, in Ibaraki Prefecture. Based on the results obtained through BA activities so far, Japan is entering a new stage for generating a wider range of research outcomes, using a prepared research environment.

These activities are recognized as a good practice of international collaboration also in Europe. With activities after April 2020 defined as BA phase II, Japan and EU are currently considering an implementation plan. Specific actions expected to be carried out jointly by Japan and EU include the following:

IFERC: DEMO design activities and R&D, computational simulation, and preparation for remote experiment

IFMIF/EVEDA: Sophistication of the prototype accelerator toward long-term continuous operation, and concept design of fusion neutron sources based on past activities

JT-60SA: Development of operation scenarios for ITER and DEMO, and enhancement of devices

These actions play major roles as design and development activities toward the realization of the DEMO. It is necessary, most of all, to complete the construction of JT-60SA by March 2020 and achieve the first plasma to shift to the initial research phase. Then, through the integrated research phase for collaborative research to achieve technical targets for ITER and complementary research for ITER to realize the DEMO, it is important to proceed to the extended research phase that aims for sustaining high-performance steady-state plasma for a long time to validate the steady-state operation.

As JT-60SA is also included in Japan's national centralized tokamak program, it is important for the researcher community in Japan to establish and conduct a research plan that uses JT-60SA, jointly with the National Institutes for Quantum and Radiological Science and Technology, the implementation body of the program.

③ Fusion neutron source (managed also through international collaboration)

In order to realize in-vessel components in a DEMO under high-energy neutron irradiation that no human beings have ever experienced, it is necessary to develop required materials, including design criteria. To this end, development and verification under a high-energy neutron irradiation environment is required, which in turn requires development of neutron sources and facilities for post-irradiation examination. At present, Japan is being engaged in the concept design of neutron sources in the IFMIF/EVEDA, which is underway as part of BA activities, in collaboration with Europe.

In Japan, the advanced fusion neutron source (A-FNS) is under consideration based on the past achievements of the IFMIF/EVEDA, with the National Institutes for Quantum and Radiological Science and Technology as a core player. Also in Europe, an implementation body (F4E) has started considering the feasibility of the European DEMO oriented neutron source (IFMIF/DONES), with the assumption that its facility will be located in Spain or Croatia. From the perspective of steady and effective DEMO development, it is desirable to materialize the construction of A-FNS by taking advantage of the experiences and results obtained in the IFMIF/EVEDA, which has been promoted in Rokkasho Village, while seeking for international cooperation.

In the first intermediate check and review, it will be decided whether to promote the construction of A-FNS, for which design R&D will be conducted. After the decision is made, prototype accelerator technologies for neutron sources will be demonstrated as the IFMIF/EVEDA, in line with engineering design of A-FNS. Based on these results, the second intermediate check and review will be required to decide upon the transition to the construction of A-FNS, necessitating smooth advancement to construction design and actual construction. Around 2030, fusion neutron irradiation test will be initiated in order to acquire initial irradiation data on, for example, materials required for deciding the construction of a DEMO.

④ DEMO R&D

(1) DEMO design activities (managed also through international collaboration)

DEMO design has been promoted by organizing the Joint Special Design Team for Fusion DEMO as an all-Japan framework. Jointly with Europe, Japan is also tackling problems that must be solved for the DEMO design as part of the IFERC project under BA activities.

While Japan continues to make the DEMO design more effective on common research issues through international collaboration under BA activities, independent activities will be carried out on design of Japan's tokamak DEMO. The first intermediate check and review will decide whether to start concept design and elemental technology development, based on the past achievements of BA and other activities. The second intermediate check and review will set up the DEMO concept and decide whether to start engineering design and full-scale technology development. Based on the progress of DEMO design and the decision made in the second intermediate check and review, the DEMO engineering design and technology development phase will make a decision on the construction of facilities for development test of full-scale superconducting coils and facilities for developing remote maintenance technologies to be adopted for the Japanese DEMO. In light of the results of JT-60SA and ITER, it is also necessary to develop heating/current drive systems that are applicable to the DEMO reactor.

(2) Development of integrated plant simulator for DEMO

Use of computers in the field of fusion has been promoted through BA and other activities, and has generated results in, for example, simulation for physical interpretation of the results from existing experimental devices.

In the future, it will be necessary to promote development of integrated plant simulator for DEMO by incorporating various knowledge, including experimental knowledge on burning plasmas and those in the latest computational science, with an aim to expand the range in which the DEMO can be controlled and operated more effectively. To achieve this goal, it is important to secure computational resources dedicated to fusion in line with the advancement of computational technologies.

(3) Safety research and tritium handling technologies

While fusion reactors are inherently safe, as demonstrated in their characteristic where fusion reaction stops promptly when the fuel supply is stopped, safety technologies are required for their design and development, such as the handling of their fuel, tritium.

Safety research must be conducted in a way to retain the intrinsic safety of fusion. In view of accumulating data, it is important to study the DEMO safety through steady promotion of verification and validation (V&V) in an early stage.

Technologies for handling a large amount of tritium must be accumulated as domestic technologies, by utilizing ITER's knowledge as well, knowing the fact that ITER is constructed in France. The second intermediate check and review will make a decision on the construction of facilities for developing technologies for handling a large amount of tritium required for fuel system development.

(4) Reactor engineering and related foundation research

Regarding material development including design criteria and development of measurement/control units and divertors, reactor engineering research will be promoted by giving priority to more important items in deciding application to the DEMO.

The first intermediate check and review will decide on the installation of high-density divertor test facilities. The second intermediate check and review will make a decision based on divertor-related data obtained from JT-60SA, large helical device, and high-density divertor test facility. According to the decision, it will be determined whether to install a divertor heat-load test facility at the same location where A-FNS is constructed.

Based on the results of (1) to (4), it is necessary to acquire prospective social acceptability and economic feasibility in the commercialization stage to complete DEMO engineering design in consistency with technological development.

On the other hand, there also exist advanced basic research issues to be tackled, mainly by universities. Under these circumstances, reactor engineering foundation research will be promoted with the priority on items that require early formulation of a reactor engineering research base.

⑤ Blanket technologies

The blanket is an important device that accepts neutrons generated from a fusion reaction in the reactor and converts them into power generation energy as heat while enabling self-sufficiency in tritium fuel for the fusion reaction.

A test blanket module (TBM) system will be developed through safety demonstration and engineering tests required for loading the ITER TBM on ITER (including development and validation of cooling, tritium recycle, and remote maintenance systems). Apart from installing TBM No. 1 onto ITER to demonstrate the soundness, the performance of functional materials such as tritium and neutron breeders will be verified in TBM No. 2 after DT burning and ignition to validate tritium recycle. The results of TBM system development including engineering tests will be incorporated to proceed with engineering design development for the DEMO blanket.

⑥ Research on large helical devices

The National Institute for Fusion Science has been studying realization of high-performance plasma and confinement of stable, high-temperature, high-density plasmas through experiments such as deuterium experiment using a large helical device. The helical-type system has demonstrated a high performance next to that of the tokamak-type system, which has been adopted for ITER and JT-60SA. In deuterium experiment, the system has made outstanding achievements, such as an ion temperature of 120 million degrees, one of the most important plasma conditions for realizing fusion, achieved in July 2017. With future advancement from academic research to development research also anticipated, research on large helical devices will continuously be promoted from various academic perspectives.

This research will contribute to DEMO R&D by resolving technological issues common to fusion reactors.

⑦ Research on high-power lasers

The ongoing research on laser-type fusion by the Institute of Laser Engineering, Osaka University is included in Japan's national centralized program, together with tokamak and helical fusion. Currently, strategies for promoting academically matured research are under consideration by utilizing large experimental laser devices such as GEKKO XII and LFEX to accumulate data and knowledge. High-power laser technologies are used to generate extreme situations of a high energy density for substances. For the "high-energy density science" that uses this environment, wide applications are expected, including generation of new materials and research on planetary interior, as well as in the field of fusion.

In the future, research on high-power lasers will be promoted by taking into account its academic expansion to fields other than fusion, future advancement from academic research to development research, and contribution to the DEMO development described above.

⑧ Social relations activities

For fusion energy to become the public's energy source of choice, it is necessary to share information and engage in continuous dialogue with society. In order to carry out strategic outreach activities, it is necessary to set up an outreach headquarters for overall management of social relations activities across the country to foster public understanding.

⑨ Transition to the fourth phase

Through steady implementation of the above activities, the check and review in the 2030s will make a decision on transition to the DEMO construction phase, the "fourth phase of fusion research and development." The attached roadmap toward fusion DEMO reactor shows the examples of targets to achieve at that point. One of the particularly important judgment conditions for transitioning to the fourth phase is enhancement of public understanding toward commercialization of the fusion reactor through expanded social relations activities.

3. Closer Relations with Universities to Strengthen the DEMO R&D Framework

In realizing the action plan, it is needless to say that contributions from universities are required in reactor engineering basic research and other related fields. The "Training and securing of personnel for the promotion of fusion energy developments" formulated by the Science and Technology Committee on Fusion Energy on March 28, 2018 reiterated the importance of universities in securing personnel required for DEMO R&D.

In order to encourage universities to autonomously and independently conduct great activities, it is necessary to build a new framework for universities that organizes collaborative research toward the DEMO, apart from the existing framework in which the National Institutes for Quantum and Radiological Science and Technology is playing a central role.

In building this framework, it is desirable to establish an institution that will play its core role. In terms of fusion, the core institution is required to have ① achievements of summarizing collaborative research conducted autonomously and independently by universities, ② ample achievements in human development through research, and ③ comprehensive abilities that cover all aspects of the most advanced large fusion equipment in the world from design to construction and operation. The institution is also required to be able to use these abilities in DEMO design.

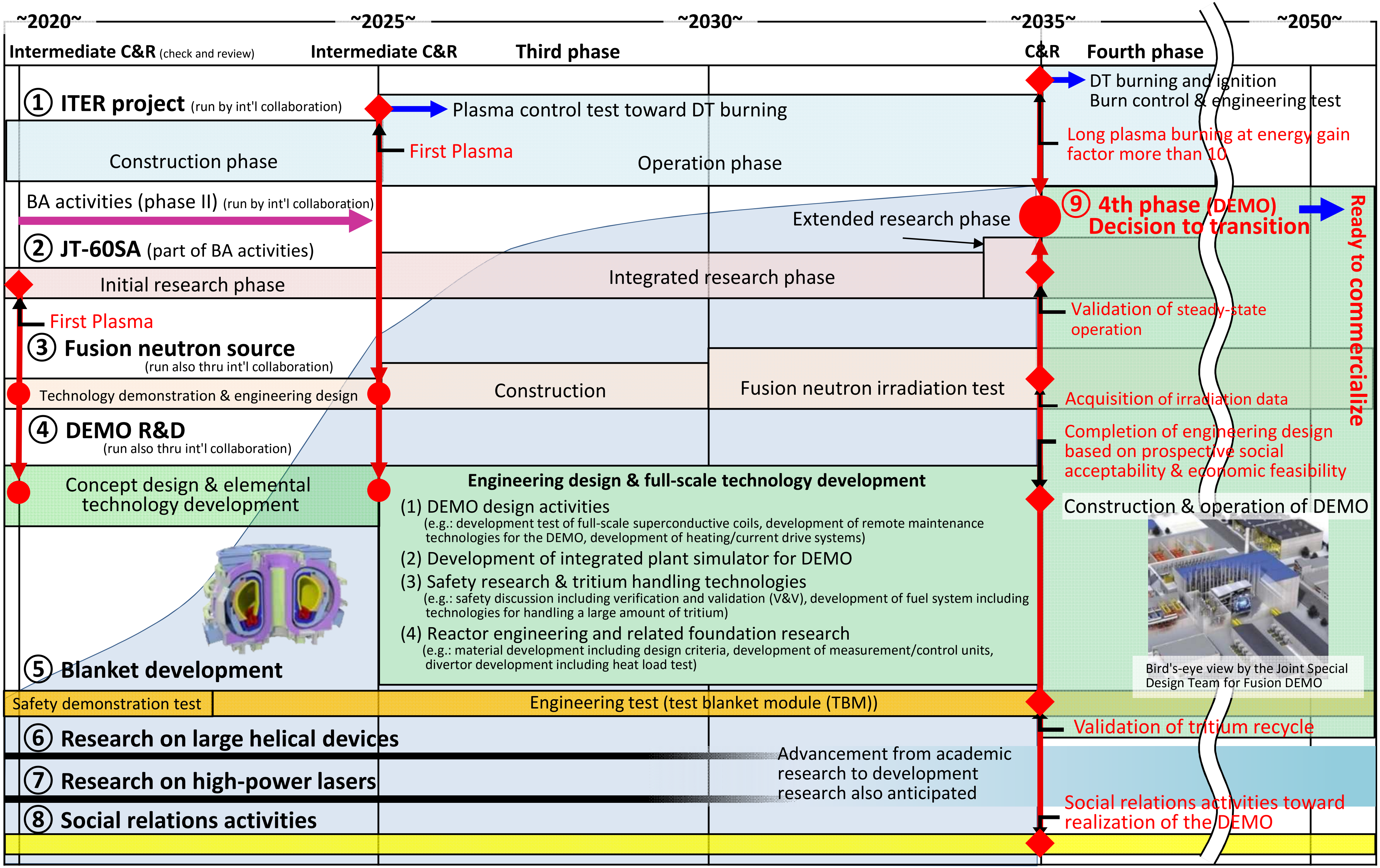
In view of the above requirements, the National Institute for Fusion Science is most suitable as the core institution, and it is necessary to further enhance the consideration of the framework with the institute at the center.

On the other hand, the Joint Special Design Team for Fusion DEMO, which was established through collaboration by industry, academia and government to build the DEMO concept, will play a key role in building an all-Japan framework including collaboration with universities. It will also be considered how to strengthen the team's framework, for which a basic approach will be summarized by the end of this calendar year.

Exhibit

A Roadmap toward Fusion DEMO Reactor

Legend
- ◆ When to achieve the target
- ● When to decide transition to the next phase
- Figure of activities required
- ↰ Target to achieve



Reference

Training and securing of personnel for the promotion of fusion energy developments

March 28, 2018
Science and Technology Committee on Fusion Energy
Subdivision on R&D Planning and Evaluation
Council for Science and Technology

Introduction

Consistent, long-term R&D will be needed to achieve fusion energy, necessitating the training and recruitment of personnel who will continue to work on such a project for the long period of time. As the fusion DEMO reactor is an important step indispensable for achieving fusion energy, this proposal summarizes issues in training and securing personal needed for early transition to the DEMO phase, as well as required measures and actions. Based on this proposal, the fusion research and development community is expected to consider and take specific actions for human resource development in respective organizations. For the outside of the community, this proposal shows the direction for conducting outreach activities in the future, which will be indispensable to attract human resources and for fusion energy to be selected by society. Another aim of this proposal is to publicize outside the community that human resources trained in the field of nuclear fusion are valuable also in other fields, by offering direction in developing highly skilled professionals who are capable of becoming global leaders through research and education of nuclear fusion, which is a field of “comprehensive” engineering. This proposal also intends to promote "knowledge circulation" by increasing the mobility of such highly skilled professionals within and outside the community.

1. Background of This Proposal

For research and development of the fusion demonstration power station (DEMO) in Japan, the "Future Fusion Research and Development Strategy" [1] formulated by the Atomic Energy Commission's Advisory Committee on Nuclear Fusion in October 2005 serves as the basic guidelines. On December 18, 2017, the "Japan's Policy to promote R&D for a fusion DEMO reactor" [2] was formulated by the Science and Technology Committee on Fusion Energy, which reflected the latest status in research and development. These documents indicate the importance of human resource development.

Two previous documents, the "Report on the Technological Feasibility of Fusion Energy and Basic Research to Support the Project" [3] (May 17, 2000, Sub-committee on Development Strategy, Advisory Committee on Nuclear Fusion, Atomic Energy

Commission) and the "Future Fusion Research in Japan" [4] (January 8, 2003, Working Group on Fusion Research, Special Committee on Basic Issues, Subdivision on Science, Council for Science and Technology) also presented analysis of key human resources in fusion research and development, including ITER, as well as measures for securing them and evaluation of the prospect, under the background of each period. In 2007, when the ITER Organization was established and broader approach (BA) activities were started, measures for the ITER Project[1-1] and BA activities[1-2] were summarized as the "National Policy of Nuclear Fusion Research Including ITER Project and BA Activities" [5] (June 27, 2007, Working Group on Fusion Research, Committee on Research and Development in Atomic Energy, Subdivision on R&D Planning and Evaluation, Council for Science and Technology), including how to build a promotion framework in Japan and how to promote programs with domestic priority. The document showed the necessity of human resources with wide academic and technical knowledge and the importance of further enhancement of domestic research and human resource development through the enhancement. Consideration on human resource development was deepened further in the "Training and securing of personnel required for promoting fusion research" [6] (July 2008, Working Group on Fusion Research), which classified issues into short-term and mid- to long-term and summarized actions to be taken.

In the fusion research and development community, the Fusion Network surveyed trends in fusion research in universities in 2006 and 2016, and reported the results as the "Questionnaire and results on human resource development in the nuclear fusion field" (hereinafter referred to as the "questionnaire on HR development" or simply "questionnaire") [7], including the numbers of students and teachers as well as the reality in research and education. On the significance and role of academic research in the "ITER era," the Japan Society of Plasma Science and Nuclear Fusion Research summarized the "Academic research for advancing nuclear fusion (publicity)" [8] in 2007, which described the roles of academic associations for human resource development. In June 2008, the Working Group on the Roadmap Development and Related Issues was set up under the ITER・BA Technical Promotion Committee of the Fusion Energy Forum upon a request from the Research & Development Bureau, MEXT. With regard to developing and securing human resources for promoting the ITER Project, BA activities and tokamak DEMO reactor, the number of personnel and the age distribution in each research field at that time were surveyed and analyzed, as well as the number of personnel required in the future. The results and a plan for securing personnel were summarized in the "Report on Human Resource Planning for Development of Tokamak-type DEMO" [9].

Since the "Training and securing of personnel required for promoting fusion research" was formulated in 2008, the ITER Project and BA activities have been promoted steadily, but at the same time, new issues have also surfaced. In June 2015, the Joint Special Design Team for Fusion DEMO was established with the objective to advance the building of a technological base for developing the DEMO through an all-Japan framework of industry, academia and government, and DEMO design activities began in full swing in this framework, which requires new human resources and an implementation body. The questionnaire on HR development conducted in February 2016 compared fusion research in universities, which is a starting point for such human resource development, with the results of the questionnaire in FY 2006. In addition to proposal of cross-university education programs, the results of the questionnaire in 2016 offered warnings against decreasing rates of advance to doctoral programs, aging teachers, and decreasing weight given to fusion research in universities. Under these backgrounds, the Science and Technology Committee on Fusion Energy decided, after examining the latest R&D situation and demands, that issues and actions to be taken should be summarized with regard to developing and securing human resources, which led to the formation of a team to draft a proposal. In preparing the proposal, the drafting team conducted, in collaboration with the Taskforce on DEMO Comprehensive Strategy, an evaluation of the number of personnel necessary for advancing DEMO R&D according to the action plan. The team also conducted a survey for universities, research institutes, and industry on the current numbers of teachers, researchers, engineers, and students in fusion research and development, together with their research fields and age distribution. After recognizing the number of personnel that should be developed and secured in the future, the team considered required measures.

2. Fusion Energy Development and Its Required Personnel

2.1. Development of the DEMO

- The common objective set for the entire fusion science and development community is to resolve technological issues that must be addressed to realize a tokamak reactor, which is the most advanced type of DEMO at the current stage of development.
- With the ITER Project and BA activities as the main pillars for resolving technological issues shown in the action plan and building the technical base for the DEMO, it is necessary to promote research and development comprehensively through an all-Japan framework.
- For acceleration of research and development and advancement of technologies, academic research, which reduces the achievements of development research to elements and systematizes and generalizes them as academic entities, is important, in parallel with development research. It is also required to promote integration of development research and academic research and build a "system for knowledge

circulation" that will improve the reliability of reactor design.

2.2. Required Personnel

- A fusion reactor is a huge and complicated system that organically integrates various technologies, and thus requires advanced and extensive technologies. Personnel who will engage in designing such a system in a core institution and lead a project with a wide perspective are required to have the basic ability to develop individual techniques, high expertise in problem solving, and the skill to apply those in a practical manner. This means human resources are required from a wide range of fields. Establishment of a fusion reactor system also requires a broad perspective capable of taking in the big picture and the ability to integrate various individual techniques.
- The ITER Project and BA activities are both under way as international projects, and there are many other frameworks of international collaboration as well. DEMO reactor development is also expected to be promoted partly through international collaboration. Personnel in universities, research institutes and industry are expected to have leadership on international projects and the ability to work creatively in international co-creation.
- For nuclear fusion to become the public's energy of choice, it is necessary to secure personnel capable of enlightening society through outreach activities. To explain to society at large in an easy-to-understand manner, dialog ability is required, including science technology and risk communication, as well as humanities and social sciences knowledge needed for precise analysis of the social situation.

While the above abilities are required for development of fusion energy, such as future construction of a DEMO, they are also needed in today's industries, which are becoming more complicated and internationalized. Communication ability is also indispensable for development in teams. In this regard, fusion energy development can be positioned as a platform for developing highly skilled professionals, who will be supplied widely in society.

2.3 Professional Development Today

- As indicated in the estimate by the Taskforce on DEMO Comprehensive Strategy, implementation of the action plan requires several times more personnel than the total number of the current fusion researchers, including those engaged in academic, helical system, and laser system research. A large disparity also exists in industry between the number of personnel that will be required and the number currently focusing their efforts on fusion energy development [10].

- The questionnaires on HR development conducted in 2006 and 2016 reported that the total number of doctoral students currently engaged in plasma research is on a flat or slightly downward trend, although that of master's students is increasing. In comparison with the number of master's students, rates of advance to doctoral programs decreased to one in 10 in the 2016 survey, from one in 6 to 7 in 2006.
- The questionnaires also investigated trends in fusion research in universities, which showed a decline in the weight given to fusion research within overall plasma research in research laboratories and groups in 2016, compared to that in 2006. In 2016, the percentage of research laboratories and groups whose weight is lower than 20% increased to about 30%. While the number of papers published in journals has leveled off at 500 to 600 per year, the percentage of those in the nuclear fusion field continued to drop also in 2016, and the percentage was lower than 60% in some years. On the other hand, papers in plasma application are increasing, which shows trends of a decline in the weight given to fusion research within overall plasma research at universities and a shift to research in other fields.
- In professional development in industry, on-the-job training (OJT) will play a central role, where technologies will be developed and experiences gained through construction of actual nuclear fusion facilities. Engineers involved in construction of LHD[2-1] and JT-60SA[2-2] or technological development for ITER are expected to pass developed technologies down to the next generation for use in on the job training through construction of new devices and R&D for the DEMO. Professional development in industry will be supported by orders to be placed continuously from large device projects.
- In industry, professionals have already been utilized mutually between similar fields, including the field of atomic energy. As its extension, it may be possible to develop, in a cooperative manner, human resources with potential for engagement in fusion energy development.
- Apart from being a "quasi-host country" for the ITER Project, Japan has gained latest technologies and experiences in manufacturing, assembly and operation of large experimental fusion devices such as LHD and JT-60SA. As a country indispensable for ITER assembly, Japan is expected to make great contributions internationally. Although ITER is the largest platform for developing professionals for the DEMO, the percentage of Japanese staff in the ITER Organization has remained as low as at about **3**%.
- In order for many professionals to participate in fusion research and development,

it is necessary to present a roadmap that shows a long-term vision. The roadmap will make it easy to plan participation and personnel development/securing for fusion research and development by industry.

In view of the above human resources required for fusion energy development, the current environment surrounding professional development cannot be said to be well-prepared. Hereafter, issues in preparing the human resource development environment are described in Chapter 3, followed by specific actions in Chapter 4.

3. Preferable Environment for Human Resource Development and Related Issues

- In order to promote DEMO development based on a long-term plan, the environment should be conducive for the training of such personnel, who will be involved in the developments in the fusion field, as well as for the securing and further training such personnel.
  - ➢ Universities and graduate schools are expected to develop students majoring in the nuclear fusion and related fields and offer such talent to the academic world, research institutes, and industry, among others. A particularly important standpoint for universities and graduate schools is to develop human resources who will play a vital role in various fields in the future, while forming wide knowledge and further promoting academic research, which is a source of innovation. They are also expected to offer programs that will interest students and encourage them to continue on to higher education, thereby increasing the number of doctoral candidates. To this end, it is necessary to maintain and bolster an environment for basic fusion research in universities.
  - ➢ International research and development such as the ITER Project and BA activities, which are under way as national projects, are needed to partner with domestic academic research and technological research and development, including those in the private sector. It is necessary to develop such partnerships as a system for knowledge circulation. These activities are an extremely important platform also in terms of human resource development, and should effectively and strategically be leveraged completely by universities, research institutes and industry.
  - ➢ In order to increase human resources involved in nuclear research and development and to achieve a continuous and steady supply of such resources, it is important to promptly set up an outreach headquarters shown in the action plan, and strategically provide fusion energy information. It is also required to inspire interest in fusion R&D and promote understanding of its importance among all ages, including children. This will lead to the

securing of potential human resources who will engage in fusion research in the future, acceleration of the flow of human resources from other fields, and spin-off to other fields, all of which are important in maintaining and expanding the community, as well. This is an issue common to the entire community, and specific actions need to be taken together with industry, academia, and government, centering on the outreach headquarters at the center.

- Issues in preparing the above environment for developing and securing human resources are as follows:
    i. Graduate school education: Building graduate education programs for learning a broad and varied range of specialization in order to lead DEMO reactor development and cooperation between industry and academia in order to gain experience with manufacturing and system integration. This is because the DEMO reactor development is an example of "comprehensive" engineering, which requires integration of various technologies. Graduate school education is a starting point for human resource development. and the environment for basic research must be maintained and bolstered.
    ii. Personnel mobility: Creating broad personnel mobility among industry and academia, including the ITER Organization, and establishing attractive career paths, from the viewpoint of creating a system for knowledge circulation
    iii. Outreach: Social partnership work, including outreach, from the viewpoint of recruiting work-ready personnel and securing future personnel

4. Specific Actions Expected for Resolving Issues

Based on the classification of the above i. to iii. into smaller issues, the following describes specific actions expected to be taken to resolve those issues: Issues to be addressed urgently and those to be addressed in the long term, though early kick off is required, are marked "(Urgent)" and "(Long-term)," respectively. Implementation bodies are also described for each issue.

i. Graduate school education:

i-1. (Urgent) Professional, interdisciplinary graduate school education, through flexible curricula and other systems, that is not limited to a single major or university but involves the entire country. Collaborative framework of industry in system engineering and other fields.

Specific actions:

- **Build a comprehensive fusion education system through intercollegiate partnerships (by universities)**

While world-class, well-known researchers are found in universities in Japan, those universities are distributed nation-wide, resulting in fusion research and education generally conducted in a relatively small scale in each university. Even under such circumstances, many human resources have been produced, as each university has provided unique research and education by utilizing their advantages. Because DEMO, however, is a comprehensive field, future human resources that will lead its development will be required to view fusion technologies from a comprehensive perspective. To provide graduate school education fundamental to such wide knowledge, it is expected to build a high-quality, comprehensive fusion education system that will be supported by the collaboration of researchers nation-wide, while maintaining the advantages and uniqueness of each university.

- **Combine graduate school education with large devices domestically and internationally (by universities, research institutes, and JADA)**

Collaboration is expected to be promoted between universities and large devices both in Japan and abroad, including ITER abroad as well as LHD, JT-60SA, and GEKKO XII[4-1] in Japan. The NIFS has already established the inter-university researcher system[4-2] and the graduate school affiliates system[4-3], while the Institute of Laser Engineering, Osaka University has already set up systems required as an inter-university and collaborative research center. These systems are expected to be reviewed or expanded to ensure more effective use as necessary. The QST has implemented systems for accepting joint research, interns, and students of partner graduate schools. Through these systems, an environment should be established for further flexible acceptance of graduate students. Large devices as mentioned above provide opportunities for valuable experiences such as shared use and acceptance of interns. Using means such as joint research networks, it is expected to promote a system, throughout the country, for building a solid collaboration framework without boundaries between universities and research institutes. As the ITER Project offers internship systems separately for undergraduate, master's and doctoral students, their active use should be encouraged by regularly informing university and graduate students of them.

Engagement in research and development outside a student's academic affiliation not only offers increase in expertise and availability of valuable facilities. Discussion and negotiation with many people, that leads to acquiring necessary skills, for example, the ability to understand others, judgment of the surrounding situation, the ability to coordinate and negotiate, and how to facilitate discussion, to become a leader in an organization: the ability to understand others, judgment of the surrounding situation, the ability to coordinate and negotiate, and how to facilitate discussion. Experiences in overseas organizations while young are also expected to foster global perspectives.

- **DEMO R&D collaborating with graduate school education and development of young scientists in universities (by country, research institutes, and universities)**

  At present, DEMO reactor design is under way with the Joint Special Design Team for Fusion DEMO as a central member. Collaborative researches are also conducted. Since collaborative research offers a great opportunity for graduate students and young researchers in universities to engage in DEMO reactor design, its funding and other implementation systems should be revised flexibly to increase applications from universities and to make collaborative research more effective and efficient. In order to encourage participation from universities, attention is required to setting of themes which lead to evaluation in universities and budget implementation systems. What should be evaluated in universities may also need to be reviewed in universities.

- **Graduate school education linked to industry (by universities and industry)**

  Engineers with experiences in manufacturing in companies are expected to cooperate in graduate school education and build frameworks that will be beneficial also to companies. More specifically, it is desirable, in promoting DEMO design, to employ engineers and retired members with ample field experiences from manufacturers through cross-appointment and other systems. It is also expected to establish curricula for graduate students to learn system engineering from the point of view of manufacturers, including processes for large plants from design to construction, and development of individual elemental technologies and their integration technologies. This opportunity may prompt graduate students, through lectures and exercises, to understand business in manufacturer and enter the industrial world after earning doctorates. This may offer job opportunities through supporting consideration of career paths or mutual interaction. To employ human resources in universities from industry, employment patterns should take their respective circumstances into account for continuous collaboration. A flexible system design is preferable.

- **Plan workshops for students and young researchers (by academia, universities, and research institutes)**

  Opportunities to generate to the learning of a wide variety of topics, including exercises, using various workshops for students, such as summer school by the Japan Society of Plasma Science and Nuclear Fusion Research, summer program to become a student by the Graduate University for Advanced Studies, Frontiers in Plasma Science by the NIFS, and plasma workshop for young scientists by the QST are expected. In these programs, academic associations to which researchers in various fields belong play a major role. Apart from enhancing collaboration in existing activities, with academic associations playing a central role, constructive integration of such activities are expected to be necessary while revitalizing student education throughout the country by academic associations.

- **Create opportunities to match corporations and graduate students (by academia, universities, research institutes, and industry)**

  To increase the number of students who go on to doctoral programs in nuclear fusion, it is important that holders of doctoral degrees in nuclear fusion will be able to serve not only in this field but also in other wider fields, including industry. In order for those holders to be employed by companies, matching between the two is the most important. At present, however, there are very few opportunities to look for such matching. To solve this problem, academic associations and the Fusion Energy Forum are expected to provide opportunities to match companies and students. With academic associations playing a central role, they are also expected to plan internships at companies manufacturing components for ITER or JT-60SA. This will also provide a valuable opportunity for learning actual research and development in companies.

i-2. (Long-term) Establishing a framework for the stable supply of human resources through graduate school education under collaboration among universities, research institutes, and industry is needed. In addition to large devices in research institutes within and outside Japan, the ITER Project and BA activities should also be utilized. A comprehensive exit strategy is necessary so that students who have specialized in fusion energy will be able to play active roles in the fusion energy field, either in research institutes or in industry. The strategy also needs to enable such resources to serve in other fields as well in order to advance general science technologies in Japan, by taking advantage of experiences in fusion research as comprehensive engineering.

Specific actions:

- **Promote cross-sectoral graduate school education (by universities, research institutes, and industry)**

  It is important to create an atmosphere wherever graduate students can engage in research, according to their interests and themes, in a cross-sectoral manner, including the private sector. By increasing choices, it is also necessary to make nuclear fusion more readily selected as the theme of education and research for graduate students. To this end, it is necessary to increase practical examples and achieve results.

- **Set a curriculum that envisions the incorporation of other disciplines (by universities)**

  As plant construction for a fusion DEMO reactor requires a variety of human resources, each individual is expected to have not only specific specialist skills but also a wide range of abilities. It is desired to set a curriculum which takes into account that graduates will serve not only in academia or fusion-related departments in manufacturers but also in other fields.

ii. Personnel mobility:

ii-1. (Urgent) Increase in the number of Japanese professional staff in the ITER Organization

Specific actions:

- **Establish a system of dispatch based on a hierarchy (by country and research institutes)**

  It is necessary to design a variety of frameworks for a wide range of human resources, from graduate students to seniors, to participate in the ITER Project in the short term and in the long term, which should be mainly led by QST and NIFS. In this design, it is important to set up different strategies for each hierarchy of graduate students, young researchers, mid-level researchers, seniors, and retired members. Here, the design should take into account that different human resources will be required in the construction and operation phases. Participation into the ITER Project should be encouraged by utilizing the most of the systems currently in place by the ITER Organization, including internships for graduate students, postdoctoral fellowships for young researchers, ITER Project Associate[4-4] for mid-level researchers, and ITER Scientist Fellow[4-5] for seniors. Those who participated in the project should also be encouraged to apply to the ITER Organization for staff employment. From the viewpoint of securing a wide variety of human resources who will lead the construction of ITER, utilization of experienced human resources in manufacturers should also be considered, including retired researchers and engineers.

- **Flexible placement system that includes maintaining the person's former position in Japan (by country, research institutes, and industry)**

  In considering the above system of placement, measures must be taken to avoid disadvantages to human resources to be placed and their organizations. Engineers in manufacturers with ample experience, especially in plant design and construction, are necessary for the current ITER Project, which is now in the construction phase. Due to fixed-term employment at the ITER Organization , flexible and varied systems should be designed to facilitate participation by engineers, such as maintaining their positions in their organizations in Japan during the term. Consideration of career paths after the expiration of the term is important also in efficiently utilizing valuable knowledge and experience obtained through ITER in fusion research and development in Japan, including DEMO reactor design.

- **Effective promotion to recruit ITER Organization employees (by JADA)**

  As effective publication and promotion are necessary to take advantage of work-ready personnel in other fields, recruitment of ITER staff should be announced widely in Japan in a way to attract the attention of many people.

ii-2. (Urgent) Promotion of participation in BA and DEMO design activities by universities, NIFS, and industry

Specific actions:

- **Establish a cross-appointment system (by universities, research institutes**

and QST)

By actively utilizing a cross-appointment system[4-6] and concluding agreements, the mobility of researchers and engineers should be increased between organizations inside and outside Japan to promote participation in BA and DEMO design activities. Since even different reactor types have much in common in their design, it is necessary to build a collaboration framework that will facilitate participation in the Special Team by industry and academia to effectively utilize human resources through an all-Japan framework.

- **Get more corporations to join the Special Team (by country and QST)**

  Before constructing a DEMO reactor, a prospect of an appropriate economic feasibility after the commercialization must be presented. This requires a DEMO reactor to be designed with realistic costs in mind, by seeking direct contribution from engineers in heavy electrical/industrial machinery manufacturers and fully reflecting their experience and knowledge. To achieve this goal, it is necessary to increase the number of companies joining the Special Team.

ii-3. (Long-term) Promotion of mobility between nuclear fusion and other fields

Specific actions:

- **Link related areas of research with related projects (by academia, universities, and research institutes)**

  Human resources with new perspectives can be developed and secured if professionals who have acquired advanced technologies and experience or those with spin-off effects through fusion research and development are connected to other fields. One of the opportunities for such connections is a joint session with related fields set up in an annual academic meeting, which is expected to lead to a framework for mobilizing human resources between different fields. Academic associations, which aim at sustainable development and expansion of the community, are considered as an important place for specialists in nuclear fusion and other fields to communicate and discuss. Roles expected for academic associations also include publicizing information for collaboration and technology advancement.

  More specifically, the atomic energy field, in particular, has many points in common, including radiation and safety standard establishment. Interaction with these fields is expected to encourage experienced or work-ready personnel to enter the nuclear fusion field. Collaborative research with related fields or large projects should also be promoted, which will prompt engagement in fusion research by wider fields.

ii-4. (Long-term) Presentation of varied career paths

Specific actions:

- **<u>Conduct a follow-up investigation of career track (by academia, universities, research institutes, and industry)</u>**

  When individuals select their careers, the career tracks of forerunners are likely to be used as important criteria for the selection. Enhancement of the mobility of human resources through the urgent actions shown above is expected to produce varied career tracks. The selection of a career will be facilitated by conducting a follow-up investigation of career tracks and presenting them as a database. Although the Fusion Network played a central role in the former questionnaires on HR development, this investigation is expected to be conducted in collaboration with academic associations, as they own their databases of students, researchers, and engineers.

iii. Outreach:

iii-1. (Urgent) Deployment of strategic outreach activities

Specific actions:

- **<u>Set up an outreach headquarters and draft a plan to promote its activities (by country, research institutes, and universities)</u>**

  It is necessary to integrate outreach activities, which have conventionally been conducted individually by universities and research institutes, and establish an outreach headquarters. The headquarter conducts outreach activities related to the entire fusion research and development and drafts an activity promotion plan. In collaboration with related organizations and academic associations, the headquarters is expected to publicize the advancement of fusion research, including those in Japan and ITER, widely to society through its unique planning. For future outreach activities, it is important to learn the broad needs in society and respond to them in a sincere and sensitive manner. This requires bilateral information exchange and communication with society; our researchers inform society of the significance of fusion energy research and development widely and understand what society expects from nuclear fusion. In drafting a promotion plan, outreach activities suitable today should be taken into account, including the use of SNS and other options.

iii-2. (Long-term) Increasing the number of potential human resources to engage in fusion research and development in the future through outreach activities to evoke interests and mutual understanding widely in society

Specific actions:

- **<u>Train and secure personnel to promote outreach activities (by research institutes and universities)</u>**

  Graduate school education is expected to provide opportunities for students to be exposed to humanities and social sciences by intensive and special seminars, so that they will acquire a wide perspective and learn to interact with the general public and understand the significance of research and development.

  Some universities have offered scientific communication programs that are open to outsiders as well. By utilizing these programs as necessary, human resources who will be capable of leading outreach activities should be developed among personnel in research institutes and universities. Apart from development within related organizations, securing human resources from outside should also be considered, for example, by using advertising agencies and employing professionally-educated human resources such as science communicators. Interaction with the fields of the humanities and the social sciences is also expected at academic meetings and workshops to deepen mutual understanding through exchange of information.

- **<u>Manage outreach activities (by country, research institutes, universities, and academia)</u>**

  Based on the drafted promotion plan, outreach activities are expected to be promoted through enriched contents that will interest broader generations. To sustain these activities, a system must be established to fairly evaluate staff engaging in their promotion.

  Further revitalization of individual PR activities is also expected at universities, technical colleges, and high schools, especially in super science high schools (SSHs), as these organizations are likely to provide future human resources in nuclear fusion.

  Participation in outreach activities by university and graduate students, as well as their talks regarding nuclear fusion and their respective research, will be extremely effective in urging high school and university students to select to study nuclear fusion in universities and graduate schools. In this regard, outreach activities are expected to be conducted in collaboration with university and graduate students, as well.

- **Lobby to get fusion energy into textbooks and supplementary educational materials (by universities, research institutes and academia)**

  In order for nuclear fusion to be elected upon selection of universities or assignment to laboratories, lobbying activities should be conducted with an aim for fusion energy to be included in textbooks and supplementary educational materials used in elementary to higher education.

Sources:
[1] "Future Fusion Research and Development Strategy (in Japanese)" (Atomic Energy Commission's Advisory Committee on Nuclear Fusion, October 2005)
http://www.aec.go.jp/jicst/NC/senmon/kakuyugo2/siryo/kettei/houkoku051026/index.htm
[2] "Japan's Policy to promote R&D for a fusion DEMO reactor" (Science and Technology Committee on Fusion Energy, December 18, 2017)
http://www.mext.go.jp/b_menu/shingi/gijyutu/gijyutu2/074/houkoku/1400117.htm
[3] "Report on the Technological Feasibility of Fusion Energy and Basic Research to Support the Project (in Japanese)" (Sub-committee on Development Strategy, Advisory Committee on Nuclear Fusion, Atomic Energy Commission, May 17, 2000)
http://www.aec.go.jp/jicst/NC/senmon/old/kakuyugo/siryo/siryo136/siryo2.htm
[4] "Future Fusion Research in Japan (in Japanese)" (Working Group on Fusion Research, Special Committee on Basic Issues, Subdivision on Science, Council for Science and Technology, January 8, 2003)
http://www.mext.go.jp/b_menu/shingi/gijyutu/gijyutu4/toushin/1213875.htm
[5] "National Policy of Nuclear Fusion Research Including ITER Project and BA Activities (in Japanese)" (Working Group on Fusion Research, June 27, 2007)
http://www.mext.go.jp/b_menu/shingi/gijyutu/gijyutu2/017/gaiyou/1286888.htm
[6] "Training and securing of personnel required for promoting fusion research (in Japanese)" (Working Group on Fusion Research, July, 2008)
http://www.mext.go.jp/b_menu/shingi/gijyutu/gijyutu2/017/gaiyou/1286893.htm
[7] "Questionnaire and results on human resource development in the nuclear fusion field (in Japanese)" (Fusion Network)
2006: http://f-net.nifs.ac.jp/061226.pdf
2016: http://f-net.nifs.ac.jp/20160408_001.pdf
[8] "Academic research for advancing nuclear fusion (publicity) (in Japanese)" (Japan Society of Plasma Science and Nuclear Fusion Research, June 8, 2007)
http://www.jspf.or.jp/news/file/appeal07.pdf
[9] "Report on Human Resource Planning for Development of Tokamak-type DEMO Reactor (in Japanese)" (Fusion Energy Forum, 2008)
http://www.fusion.qst.go.jp/fusion-energy-forum/files/member/iter_ba/4_jinzai.pdf
[10] "Comparison of the number of personnel required for DEMO development in the future and that of the current personnel (in Japanese)"
http://www.mext.go.jp/b_menu/shingi/gijyutu/gijyutu2/074/shiryo/__icsFiles/afieldfile/2017/12/28/1399735_008.pdf

Glossary

[1-1] ITER Project

The ITER Project aims to demonstrate the scientific and technical feasibility of fusion energy and will begin operations in 2025 (approved at the ITER Council meeting in June 2016). The council of this large international project is comprised of seven members – Japan, the European Union (EU), Russia, the United States, South Korea, China, and India. Under this project, each member is assigned to manufacture specific devices and deliver them to the ITER Organization, which will in turn integrate them to construct the experimental fusion reactor ITER. Project construction is currently underway in Saint-Paul-lez-Durance, France.

[1-2] BA Activities

Abbreviation of broader approach activities. In 2007, Japan and the EU signed the BA agreement in which they agreed to complement and support the ITER Project while also starting advanced research and development projects for establishing the technical base required for the DEMO reactor as part of the BA activities. BA activities include the International Fusion Energy Research Center (IFERC) project, the Engineering Validation and Engineering Design Activities for the International Fusion Materials Irradiation Facility (IFMIF/EVEDA) project, and the Satellite Tokamak (JT-60SA) Program project (the former two in Rokkasho Village, Aomori Prefecture and the last one in Naka city, Ibaraki Prefecture).
* The official name is the "Agreement between the Government of Japan and the European Atomic Energy Community for the Joint Implementation of the Broader Approach Activities in the Field of Fusion Energy Research."

[2-1] LHD

Large Helical Device. A helical-type experimental device for superconducting plasma confinement at the National Institute for Fusion Science, National Institutes of Natural Sciences. On LHD, stable, high-temperature, and high-density plasma confinement research is conducted from a viewpoint of broad based academic research to build a helical-type fusion reactor in the future.

[2-2] JT-60SA

JT-60SA is the superconducting tokamak device being built by the Naka Fusion Institute, Fusion Energy Research and Development Directorate, National Institutes for Quantum and Radiological Science and Technology. It is a joint project of Japan's national centralized tokamak program and the Satellite Tokamak Program managed by Japan and the EU as part of the BA activities to complement and support the ITER Project.

[4-1] GEKKO XII
A large experimental laser system in the Institute of Laser Engineering, Osaka University. Since its completion in 1983, laser fusion research, including Fast Ignition featuring a higher efficiency than conventional methods, has been conducted, as well as high-energy physical research.

[4-2] Inter-university Researcher System
A system for providing research guidance for Japanese and foreign graduate students on specific research subjects for a certain period of time under referral from their graduate schools.

[4-3] Graduate School Affiliates System
A system for sending laboratory employees to universities to give intensive and other lectures based on the academic exchange agreement.

[4-4] ITER Project Associate
An ITER system for accepting a wide range of professionals from participating members, with a general term of 4 years or shorter.

[4-5] ITER Scientist Fellow
An ITER system for recruiting and appointing specialists of specific themes after obtaining the agreement of the ITER Organization and member countries.

[4-6] Cross-appointment System
A system for employing researchers or experts in two or more organizations. This can include universities, public research institutes, or companies, allowing them to engage in research and development and education according to their role in the respective organization under a certain level of effort management.

Note: The descriptions in the glossary above have been produced in reference to the following websites except for the item with a specific source:
- ATOMICA
- The Japan Society of Plasma Science and Nuclear Fusion Research
- Ministry of Economy, Trade and Industry

- National Institute for Fusion Science
- National Institutes for Quantum and Radiological Science and Technology
- Institute of Laser Engineering, Osaka University