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Development of Strategic Establishment of Technology Bases for a Fusion DEMO Reactor in Japan

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Abstract

The strategic establishment of technology bases required for the development of a fusion demonstration reactor (DEMO) has been discussed by joint endeavors throughout the Japanese fusion community. The mission of Fusion DEMO is to demonstrate the technological and economic feasibility of fusion energy. The basic concept of Fusion DEMO has been identified and the structure of technological issues to ensure the feasibility of this DEMO concept has been examined. The Joint-Core Team consisting of experts from the Japanese fusion community including industry has pointed out that DEMO should be aimed at steady power generation beyond several hundred thousand kilowatts, availability which must be extensible to commercialization, and overall tritium breeding sufficient to achieve fuel-cycle self-sufficiency. The necessary technological issues and activities have been sorted out along with 11 identified elements of DEMO, such as superconducting coils, blanket, divertor, and others. These will be arranged within a time line to lead to the Japanese fusion roadmap.

Keywords

DEMO, reactor design, transition condition, ITER, roadmap, technological issue

1. Introduction

Japanese fusion research and development is now in the phase targeting the achievement of self-ignition and long-pulse burn via the ITER project, along with the establishment of the technology base required for the development of a “DEMONstration fusion reactor” (hereafter referred to as “DEMO”). The goal of this phase is to show the scientific and technological feasibility of fusion energy. The phase after ITER aims at technological demonstration and confirmation of the economic feasibility of fusion energy with the DEMO project as its core. A national framework to implement these processes has been discussed by the Atomic Energy Commission [1] and the scientific council of the Ministry of Education, Culture, Sports, Science and Technology (hereafter referred to as “MEXT”), as well as by the Japanese fusion community. Along with ensuring the progress of the ITER project, it is increasingly important to develop a strategic roadmap that clarifies the technology, which should be secured, maintained, and developed in Japan or under international cooperation; to share this roadmap among industry, government, and academia, and to activate a framework for implementation throughout Japan. Global activities such as “Fusion Electricity, A roadmap to the realization of fusion energy” in Europe [2], CFETR [3] in China, and initiation of the DEMO program workshop [4] by IAEA also stimulates formulation of strategic roadmap towards DEMO in Japan. In 2013, the Working Group on Fusion Research under the council of the MEXT noted that in order to proceed with this task, establishment of the organizational approach to develop a strategy for DEMO with integrated viewpoints is important. This organizational approach will be the core engine for the establishment of technology bases for the development of DEMO. Subsequently, the Working Group on Fusion Research requested that the National Institute for Fusion Science (hereafter referred to as “NIFS”) and the Fusion Research and Development Directorate, the Japan Atomic Energy Agency (hereafter referred to as “JAEA”), which are implementing bodies of large projects, to take the leading roles in forming the Joint-Core Team for the establishment of technology bases required for the development of DEMO.

The terms of reference of this Joint-Core Team defined by the Working Group on Fusion Research are as follows:

1. Mission

To develop strategy for the establishment of technology bases required for the development of DEMO by taking into account the progress of the ITER project, the BA (Broader Approach) activities and academic research such as on the Large Helical Device (LHD), and standing on the consensus in the Japanese fusion community.

2. Issues

- 1) Concept definition of DEMO premised for investigation
- 2) Activities requiring resource commitment and their goals (research activities, investigation activities)
- 3) Scientific and technological review of work for the above mentioned activities

The Working Group on Fusion Research expected that the Joint-Core Team would lead detailed discussion about the strategy for the establishment of technology bases together with the Japanese fusion community, and that prioritized scientific and technological issues would be incorporated into international projects such as the ITER project and the BA activities, and academic research programs, and that consequently all endeavors are coordinated to organize a framework for implementation throughout Japan toward the establishment of technology bases.

The Joint-Core Team has reviewed the analyses in “Future Fusion Research and Development Strategy” (hereafter referred to as “Future Fusion R&D”) [1] determined by the Atomic Energy Commission’s Advisory Committee on Nuclear Fusion in October 2005 and other reports to date and has taken into account the most recent scientific and technological achievements and prospects. The Joint-Core Team then compiled two reports, “Basic Concept of DEMO and Structure of Technological Issues” [5] and “Chart of Establishment of Technology Bases for DEMO” [6], on strategy and tactics for the establishment of technology bases required for the development of DEMO. This article overviews these two reports.

2. On the Concept of DEMO Premised for Investigation

2-1. Change of Energy Situation and Social Requirement

Since 2005 when the Atomic Energy Commission issued the “Future Fusion R&D” [1], there have been three major events that have affected fusion research and development significantly. Those are the economic downturn precipitated by the Lehman Brothers bankruptcy in 2008, the experience of the shortage of electric power after the Great East Japan Earthquake in 2011, and the collapse of the nuclear safety myth due to the accident at the Tokyo Electric Power Company Fukushima Daiichi Nuclear Power Station in 2011.

Although economic recession and shortage of electric power are temporary phenomena and indeed are in recovery, the change in general public attitude will be maintained for a long time. Japanese people have recognized, with pain, that they can prioritize reduction of CO₂ only under the conditions of a good economy and sufficient available reserves of electric power.

The fundamental revision of atomic energy policy and the long-term suspension of all nuclear power stations have reminded the Japanese people of the reality that Japan does not yet have an alternative technology to replace fossil fuels even though Japan does not have a major domestic energy resource. While an increase renewable energy is fully expected, its limits are being recognized. Therefore, serious consideration for the security of domestic energy reinforces the importance of fusion research and development consistent with general public opinion, which recognizes that technological innovation is a Japanese resource.

The Strategic Energy Plan decided by the Cabinet on 11 April 2014 [7] states that dependence on nuclear power generation should be reduced to the extent possible by promoting energy conservation, and introducing renewable energy and improved thermal power stations. These circumstances bring focus onto the issue of how fusion energy is positioned in order to facilitate the paradigm shift to fusion energy via high-efficiency thermal power from the base-load by nuclear power. In this case, what is required for fusion energy would be its capability and attractiveness to replace thermal power generation, and the establishment of complementary relations with renewable energy.

It is necessary to assess seriously the effect of the collapse of the nuclear safety myth and a loss of national trust in science and technology and to take appropriate measures when justifying DEMO, which directly connected to the realization of fusion energy. It is known that a fusion reactor has intrinsic safety features, such as no possibility of re-criticality and runaway. In addition, the potential hazard of tritium, which is radioactive matter, in a fusion reactor is smaller by three orders of magnitude than the potential hazard of iodine 131 equivalent in a fission reactor. It should be noted that construction of DEMO in Japan would be difficult unless the design of DEMO shows safety beyond that of a nuclear power station. The direction of fusion research and development should aim at commercialization consistent with social demand by taking advantage of its safety.

2-2. Fundamental Strategy

A critical goal in the promotion of research and development of fusion energy is the acquisition of both economic and social rationality competitive with other power generation, based upon the fundamental condition of scientific and technological feasibility, allowing it to be commercialized. It is also necessary to establish a design that takes advantage of intrinsic properties of high safety and minimal environmental impact throughout the plant life cycle from construction to decommissioning.

With regard to the *Transition Conditions* of fusion R&D phases, the roadmap which defines milestones in the research and development for DEMO should be elaborated following the anticipated time of the *Intermediate Check and Review (C&R)* around 2020 and the *Changeover* toward the *Next Phase Program* around 2027, both of which are described in the “Future Fusion R&D.”

2-3. Development Strategy

Fusion energy will have to have economic competitiveness including *externality* among diversified energy resources. This means that DEMO is required to demonstrate safety and operational reliability. Thus, a strategy to gain the support of public opinion with regard to acceptance of DEMO in addition to its economic potential is necessary. To enable construction of DEMO, a design which satisfies social needs and acceptance is required, as well as the resolution of issues and technological integration. This reinforces the necessity of a DEMO design team assembled with broad and diversified talents.

The plan to define milestones toward its goal in the operational development phase of DEMO is

important in order to resolve issues for commercialization. In planning the goal of DEMO, it is necessary to define the technological issues required to fulfill the *Transition Conditions* towards the *Next Phase Program* and to approach those issues through the organized framework for implementation throughout Japan, in parallel with the ITER project.

Implementation of the ITER project, which is an experimental reactor, is the central pillar in the activity to establish the technology bases of DEMO. Therefore, all R&D programs in parallel with the ITER project should consider synergy with it. In addition to reflecting achievements in the ITER project, it is quite important to accumulate data, which will contribute to the resolution of technological issues for DEMO. For example, an R&D program aiming at reduction of the construction cost of DEMO will be planned by making full use of the experience of the construction of ITER.

The first concept to be considered for DEMO is a tokamak, which exhibits the most advanced development. In order to promote acceleration and issue resolution by innovation and to build more comprehensively on the state of progress of fusion R&D at the *Changeover* to the *Next Phase Program*, complementary and alternative concepts would be explored, for example, helical systems or laser fusion. Further, diversified R&D approaches of innovative concepts with potential for breakthrough should be managed in good balance and in a strategically linked manner.

2-4. Basic Concept Required for DEMO

In view of the status of energy and social circumstances since the Great East Japan Earthquake, the Japanese fusion community is requested to produce the plan to develop DEMO endowed with safety which society requires and to show confidence in the commercialization of fusion energy by the middle of the 21st century. The purpose of DEMO is to indicate the prospect for achieving economic and social feasibility of fusion energy that is competitive with other energy resources.

The “Future Fusion R&D” stated that a tokamak DEMO is presumed to have dimensions similar to ITER and a generating capacity of 1 million kilowatts. From the view of the presently available technology bases and their future prospects, this definition should be revisited in the planning of the roadmap with defined milestones aimed at steady and stable power generation beyond several hundred thousand kilowatts, availability extensible to commercialization, and overall tritium breeding to fulfil self-sufficiency of fuels.

The operational development of DEMO should be planned by classifying the commissioning phase, the power-generation demonstration phase, and the demonstration of economic feasibility phase, with milestones defined at each phase. Targets, such as demonstration of power generation by the system equivalent to a commercial reactor, demonstration of high energy gain factor, long-pulse and long-term operation which can be extrapolated to a commercial reactor, and development and demonstration of advanced technology to improve economic performance, should be achieved in each corresponding phase.

The target of “overall tritium breeding ratio (TBR) beyond 1 is required” documented in the “Future Fusion R&D” must be achieved. What “overall” means here should be discussed in detail and clarified.

Controllability of plasma, such as heat and particle control, and disruption avoidance should be established in order to reduce excessive load on plasma facing components and to enable stable burning in the long term. By realizing a maintenance scenario which can be extended to a commercial reactor, DEMO, in its final phase, should be aimed at demonstration of availability sufficient for commercialization.

Flexible design of reactor-core components is required in order to resolve issues such as the high-performance blanket and the improvement of divertor capability needed for commercialization. Although the divertor and the blanket would be based upon technology developed in the ITER project and the ITER-TBM (Test Blanket Module) will be employed in the early phase of DEMO, careful attention should be paid to performance extension by improvement of long life-time and high-efficiency energy conversion based upon new knowledge obtained during the operation of DEMO. Component development should be planned based upon the technological specification of heat and particle flux on the divertor, and neutron and heat flux on the first wall of the blanket. Assurance of safety to suppress exposure of the public as well as the workers in a DEMO plant to “As Low As Reasonably Achievable” (ALARA) is necessary.

The construction cost of DEMO should be at an acceptable level from the view of subsequent commercialization.

2-5. Points of View for Changeover to DEMO Phase and Assessment of Transition Conditions

It is relevant to elaborate the plan of technological development with the presumption of the review of *Transition Conditions* around 2027 when the fusion burning with deuterium and tritium (DT burning) fuels will be demonstrated in ITER. Here, it is necessary to embody the contents and criteria of judgement by close examination of C&R items (planned) indicated in “Future Fusion R&D” (see Table I). In particular the results of energy gain, long-pulse operation, and demonstration of blanket function, etc., obtained in the ITER project, are critical elements directly connected to the assessment of the *Transition Conditions* to the DEMO phase. On the other hand, revision and update of this table is inevitable due to the progress of the ITER project. Therefore, it is necessary to investigate the appropriateness and the timeline of these critical elements by revisiting the original point of these criteria.

In that case, the *Intermediate C&R*, which is the milestone before the assessment of *Transition Conditions* for the *Phase Changeover*, becomes more important than ever. The “Future Fusion R&D” report stated, “This milestone is presumed around ten years after the establishment of the ITER Organization.” The assessment of achievements of construction and development in the ITER project

is crucial at the *Intermediate C&R*. While the examination in this present analysis endorses the view that the draft targets at the *Intermediate C&R* described in the “Future Fusion R&D” are appropriate, the date presumed was to be around 2020. Accumulation of technological experience and knowledge through construction of ITER, development of material related to DEMO, and maturity of conceptual design of DEMO will be reviewed, and performance at this interim assessment should convince stakeholders the fulfilment of *Transition Conditions* in time. Full-scale engineering R&D towards construction of DEMO will be launched by the success in the *Changeover* to the *Next Phase Program*. In the case that commercialization of fusion energy is aimed for the middle of the 21st century, the start of engineering R&D at the properly extended level in the preparation term before the assessment of the *Transition Conditions* should be promoted for early realization of DEMO. Therefore further embodiment of targets and their assessment for the *Intermediate C&R* should be prepared sufficiently to trigger this extended engineering R&D.

The significance of the statement, “In deciding the *Changeover* to DEMO phase, it is important to gain the prospects for its commercialization and to receive participation by private sectors, as well as to understand the overall progress of fusion research and development including other methods,” in the “Future Fusion R&D” will be explored and embodied in succession.

3. Technological Issues of Elements of DEMO

Based upon comprehensive analyses, technological elements for DEMO are sorted into the following 11 categories:

- (1) Superconducting Coils
- (2) Blanket
- (3) Divertor
- (4) Heating and Current Drive Systems
- (5) Theory and Numerical Simulation Research
- (6) Reactor Plasma Research
- (7) Fuel Systems
- (8) Material Development and Establishment of Codes and Standards
- (9) Safety of DEMO and Safety Research
- (10) Availability and Maintainability
- (11) Diagnostics and Control Systems

Each element has been analyzed in order to clarify the process for demonstrating the technological feasibility of DEMO and to develop the roadmap with a timeline and implementing entities.

Analysis has been done in line with the following procedure.

- 1) To analyze issues from the points of rearrangement, extraction of a core issue, prioritization, and

clarification of the reason of prioritization, etc. Then, to show the structure (tree) of technological issues in each element in view of the timeline with the *Intermediate Check and Review (C&R)* and the assessment of the *Transition Conditions* presumed around 2020 and 2027, respectively.

- 2) To define for each, a package consisting of “Concern” which prevents development/evolution, in other words, necessary conditions to move forward to the next stage, “Defined Issue” in order to resolve concern, and “Implementing Body/Platform” which is charged with Defined Issue.
- 3) This package consisting of these three elements can be understood as a project. It is necessary to sort out the linkage between these packages and to align these packages with each other logically.
- 4) To document the presently ongoing projects such as the ITER project and the BA activities as well in the form of the above mentioned packages.
- 5) To pursue the “main stream” approach in order to ensure sufficient feasibility and to contrast the “side stream” which plays a complementary role and is expected to innovate breakthroughs.
- 6) To show the interaction between the projects described by the packages and the interface with other elements and the DEMO design.
- 7) To show implementing bodies/platforms corresponding to each defined issue. The ITER project and the BA activities including JT-60SA are the core of the presently ongoing projects.

The following items are indicated based upon the above mentioned analysis of the structure of technological issues, aligned R&D with defined milestones, and plans of research bodies grappling with issues and required facilities.

- 1) What is required before the *Intermediate C&R*?
- 2) What is required after the *Intermediate C&R* and before the assessment of *Transition Conditions* (driving the content mentioned as “Promotion to start the enterprise of engineering R&D in accordance of the assessment at the *Intermediate C&R*” in section 2.5)?
- 3) Urgent issues
- 4) Points of note

3-1. Superconducting Coils

- 1) Issues
 - (a) Improvement of strength of structural material. Strengthening of the conductor and its electrical insulation against high mechanical stress.
 - (b) Improvement of critical current density (J_c) and mechanical strength of the superconductor strand. Improvement of the mechanical strength of the coil as a whole system. Mitigation of degradation of J_c caused by the residual strain due to the difference of thermal contraction between the strand and the conduit of the CIC conductor and/or by the bending stress at mutual contact points of

strands in the twisted cable.

- (c) Nb₃Sn: Improvement of the structure of the CIC conductor or development of an innovative conductor in order to mitigate the degradation of J_c due to the large electromagnetic force. Investigation of measures for reduction of AC loss and stability improvement, and a scheme of cooling for the coil.
- (d) Nb₃Al: Further lengthening of the strand and the reduction of the cost of the strand. Improvement of the current rating of the conductor.
- (e) ReBCO: Further lengthening of the strand and the reduction of the cost of the strand. Minimization in amount of silver used. Other issues include structure of the conductor and the scheme for twisting to enlarge current rating, mechanical reinforcement, cooling scheme, quench protection, reduction of AC loss, and technology of joints and winding.
- (f) Full-scale conductor test facility, which can provide the field conditions required for DEMO, must be prepared. Establishment of a conductor test method which can evaluate the degradation of performance due to electromagnetic force.
- (g) Development of innovative superconducting materials and investigation to enable assessment of their practical utilization and mass production.

2) Extraction of Core Issues and Necessary Tasks to Resolve These Issues

Construction of ITER and of JT-60SA are now in progress. Both of these devices are large superconducting coil systems which will move beyond preceding machines and demonstrate the significant progress in mass production of high performance strands and conductors, and in the manufacturing of huge coils from conventional technologies. It is extremely important to accomplish manufacturing of the components and construction of the system, and to reflect the lessons learned through this process in the design of DEMO.

What are necessary tasks before the *Intermediate C&R* ?

- ① It is necessary to reconsider and clarify the specification requirements for the superconducting coil system in harmony with the overall DEMO design.
- ② Pre-conceptual design of the superconducting coil system based upon the above requirements is required.
- ③ It is necessary to review the issues based upon the outcomes of the pre-conceptual design and decide the R&D strategy for the superconducting coil system.

What are necessary tasks after the *Intermediate C&R* and before the assessment of the *Transition Conditions* ?

- ① It is necessary to implement actions to accomplish the targets for J_c of the Nb₃Sn strand, high strength structural materials development, insulation materials development, and conductor performance improvement which are defined in the R&D strategy
- ② The conceptual design of the superconducting coil system is necessary.

- ③ Final selection of materials based upon the outcomes of the conceptual design and material development is necessary.

Urgent issues

- ① The DEMO design team should be properly organized and strengthened. A design group for the superconducting coil system should be created within the DEMO design team, and pre-conceptual design activity for superconducting coils should be initiated.

Points of note

- ① In order to review the technology issues described in the above and to decide on the R&D strategy, prospects in the development of structural materials, superconducting materials, and other materials are necessary as input information. In particular, with regard to the Nb₃Sn conductor, production for ITER is in progress and verification of performance is under way. Data to be used for technological assessment of DEMO should be collected from evaluation of the margin in the ITER design through a kind of performance limit test in addition to those tests to confirm the performance specified for ITER. And it is necessary to pay attention to flexibility in the planning so as to enable feedback to the design of DEMO from the consequences of engineering R&D and the experience of assembly and the initial operation of ITER
- ② Existing facilities should be upgraded in an appropriate timely manner in order to test conductors and coils in higher magnetic field.
- ③ It may not be easy to secure engineering staff in the design group for the superconducting coil system while manufacturing of the ITER coil and the construction of JT-60SA are proceeding in parallel. Staff should be increased step by step and a scheme should be planned to make the best use of human resources, including from universities.
- ④ Nb₃Sn is a current prime candidate for the superconducting material. Nb₃Al shows superior performance at higher strain and is tolerable for use in a higher stress condition. High temperature superconducting material (ReBCO) has a potential of higher J_c at higher magnetic field, higher mechanical strength, and better cooling stability. These two alternative candidates should be developed in parallel with Nb₃Sn not only for adoption in DEMO but also for the prospect of further performance improvement that is favorable for a commercial reactor. Collaboration with their development for purposes other than fusion, including industrial application should be taken into account.
- ⑤ The structure of the issues is based upon design concepts in the present DEMO study in BA. Additional technological issues will be encountered if an innovative magnetic field configuration such as Super-X diverter is introduced.

3-2. Blanket

1) Issues

- (a) Expansion of basic/reference data for structural materials, tritium-breeding materials, and neutron multiplication materials.
- (b) Demonstration of integrated functions of blanket system in full fusion environment.
- (c) Demonstration of overall tritium self-sufficiency in DEMO and efficient suppression of tritium permeation.
- (d) Development of concepts of remote handling maintenance, plant safety, and standards/criteria harmonized with the overall DEMO design.
- (e) For advanced blanket concepts, solutions of issues specific to each concept are required.

2) Extraction of Core Issues and Necessary Tasks to Resolve These Issues

Since the issues of the extension of data as well as overall demonstration of function have been identified, quantification of targets is important. With regard to advanced blanket concepts, relation with technological issues and the development plan of a water-cooled solid-breeder blanket should be well planned.

What are necessary tasks before the *Intermediate C&R* ?

With regard to a water-cooled solid-breeder concept as the prime candidate:

- ① It is necessary to review functional test facilities for ITER-TBM and the DEMO blanket and development plan, and to package them in a project.
- ② Through the activities described above, it is necessary to complete the technological bases of the blanket system including design and manufacturing technology of blanket, tritium handling, and neutron measurement, etc.
- ③ Fabrication of the ITER-TBM should be completed.

With regard to advanced blanket concepts:

- ④ By proceeding from the R&D on elemental technologies to integrated tests using coolant circulation loop systems simulating reactor conditions, the simultaneous demonstration of plural functions and phenomena and the acquisition of fundamental design data should be promoted.
- ⑤ Since the design investigation and the R&D on heat exchange and power generation methods are considered insufficient, reinforcement of the activities is required.

What are necessary tasks after the *Intermediate C&R* and before the assessment of the *Transition Conditions* ?

With regard to a water-cooled solid-breeder concept as the prime candidate:

- ① It is necessary to compile basic data in order to analyze results of ITER-TBM experiments. Additionally, it is necessary to confirm tritium breeding and recovery functions by different facilities from ITER to complement the limitation in ITER (e.g., pulsed operation).
- ② It is necessary to demonstrate tritium breeding and recovery functions, and removal of heat and power generation in a low-fluence DT experiment on ITER.

- ③ It is necessary to get a prospect of the soundness of the blanket in the DEMO environment through irradiation tests in addition to the ITER-TBM experiments.
- ④ It is necessary to review the target definition of DEMO-TBM and the development plan, to organize programs, to select a concept of DEMO-TBM, and to conduct scheduled development.

With regard to advanced blanket concepts:

- ⑤ Identification of issues, feedback regarding blanket conceptual designs, and evolution of R&D must be promoted by separate examination of technologies and designs for each of blanket fabrication technology, dissimilar material welding, coolant flow through complicated channels, and transfer and recovery of hydrogen and heat etc. by use of small test devices.
- ⑥ Various blanket concepts are proposed and R&D activities of each concept are being developed. Concepts to be prioritized in DEMO-TBM R&D activities should be selected by comparison of preliminary proposed DEMO-TBM designs with heat exchange based upon involvement of acquired fundamental design data and developed technologies.

Urgent issues

With regard to a water-cooled solid-breeder concept as the prime candidate:

- ① Firstly, specification of DEMO should be clarified, and then corresponding requirements for the blanket system should be defined.
- ② Collaboration among universities, research institutes, and industries for the ITER-TBM development and comprehensive performance test should be strengthened.
- ③ Guidelines regarding pressure resistance capability of the blanket container should be clarified in the early stage of the development because they are related to the guidelines to secure plant safety and have a great impact on the structure of the blanket container.
- ④ To enhance activities described above, the DEMO design team should be strengthened. It is necessary that a team charged in development of elemental technologies participate in design activity.

With regard to advanced blanket concepts:

- ⑤ Enhancement of activities for design investigation and comparison of candidate blanket concepts and heat exchange methods is required for the prioritization in the DEMO-TBM R&D.

Points of note

- ① It is necessary to pay careful attention to the relationship between the target of “Demonstration of burn control” and the target of “Demonstration of power generation in blanket” defined in *Transition Conditions* to the DEMO phase. In particular, it should be noted that plasma burning time affects demonstration of the functional test of the blanket.

3-3. Divertor

1) Issues

- (a) Magnetic configurations and plasma operation (in particular, detachment) which reconcile the heat load and pumping capability
- (b) Materials development, which takes into account the tritium inventory and material degradation due to the heat load, particle load and neutron load
- (c) Heat removal design for steady-state high heat flux
- (d) Identification of the boundary plasma conditions and establishment of the burning plasma operation scenario that are compatible with the soundness and the maintainability of the divertor components

2) Extraction of the Core Issues and Necessary Tasks to Resolve These Issues

In order to realize a heat balance at the divertor, both (1) reduction of heat flux from the burning plasma, and (2) improvement of the heat removal characteristics of the divertor components under the neutron irradiation conditions, are necessary. Furthermore, in order to realize a particle balance in the plasma vacuum vessel, (3) securing particle controllability (exhaust of the fuel and impurity) is required. Since these issues have a contradictory dependence with each other, it is necessary to find a consistent compromise.

What are necessary tasks before the *Intermediate C&R* ?

- ① It is necessary to address the review of the fusion output specification to match a heat flux which enables a heat balance at the divertor.
- ② It is necessary to clarify physical phenomena to govern the operational conditions of the divertor, namely, the width of the scrape off layer (SOL), elementary processes of plasma wall interactions (PWI), and other issues.
- ③ It is necessary to formulate a modeling to describe the detachment discharges and to conduct verification and validation of the model by the experiments in the existing devices in order to secure an extrapolating reliability for DEMO.
- ④ It is necessary to develop high-heat conducting materials, which can maintain the material performance and lifetime even under the heavy neutron irradiation conditions. Since the material properties have an impact on the fundamental basis of the reactor design, including the maintenance cycle, it is necessary to select the candidate materials at an early stage.
- ⑤ Copper alloys are first candidates for the high-heat conducting materials from the viewpoint of the very high thermal conductivity. However, determining the characteristics of the neutron irradiation tolerance is an urgent issue. Since there is very limited research activity related to this field, it is necessary to launch a research and development program.
- ⑥ The design of the pump remains insufficient, despite the fact that the secure particles exhaust property is one of the most essential functions for particle control of a burning plasma. It is

necessary to clarify usage conditions of the pumps and to launch a research and development program.

What are necessary tasks after the *Intermediate C&R* and before the assessment of the *Transition Conditions* ?

- ① It is necessary to propose a divertor configuration and the operating scenario to realize simultaneously both particle control property and heat removal property by advancing the optimization of the divertor configuration in reactor design study, and then to prove the feasibility of the developed scenarios in JT-60SA and other plasma devices.
- ② In order to secure the extrapolated reliability of the detachment discharge scenario, it is necessary to develop a comprehensive simulation study in addition to the theoretical modeling of the elemental processes of the divertor.
- ③ It is necessary to develop the pumps, which can be operated under the reactor conditions.

Urgent issues

- ① It is an extremely important issue to secure the heat and particle controllability at the divertor, in order to satisfy the required performance of DEMO. Since the divertor design has a great impact not only on the in-vessel components but also on the overall system design of DEMO including coil arrangement, it is necessary to pursue this issue as early as possible. Therefore, the following are urgent issues concerning divertor design, optimization of the divertor configuration, modeling of the detachment discharge, and study of the comprehensive integrated simulation of detachment discharge including core plasma.
- ② Specifications of the pumps have not been clarified yet. In order to launch the research and development program, it is necessary to initiate a conceptual design of the pumps as early as possible. This issue will have a major impact on the divertor design.
- ③ In order to deal with high-heat flux to the divertor properly, it is reasonable to use copper alloys with high thermal conductivity. On the other hand, available copper alloys do not have sufficient material properties against the neutron irradiation, and it is foreseen that the divertor components will have to be replaced frequently. In order to reduce the exchange frequency of the divertor components and to realize the acceptable availability factor of DEMO, it is an urgent issue to understand and to improve the properties of the tolerance to neutron irradiation.

Points of note

- ① Not only pursuing the performances of the constituent materials, but also overall assessment of the divertor component is required to select the candidate materials for DEMO.
- ② Development of an innovative divertor cooling system is fundamentally important towards achieving highly efficient energy production in DEMO.

3-4. Heating and Current Drive Systems

1) Issues

- (a) Continuous reliable operation over one year (steady state, high system efficiency, neutron irradiation-resistance).
- (b) Neutral Beam Injector (NBI): development of the radio frequency (RF: Radio Frequency) ion source, technological development of beam acceleration (1-2MeV) and development of photo-neutralizer.
- (c) Electron Cyclotron resonant Heating (ECH): development of the fast variable frequency gyrotron (170-220GHz), development of the mirror-less waveguide-injector-type launcher system.
- (d) Establishment of remote maintenance method.

2) Extraction of Core Issues and Necessary Tasks to Resolve These Issues

Since the heating and current drive systems for DEMO are an extension of ITER technologies, steady progress in the ITER project is critically important, and accumulation of operating experience in ITER and JT-60SA also is important. Core issues in the technological development for DEMO are improvement of system efficiency and steady-state operation, and the minimization of the occupied volume to ensure sufficient TBR.

What are necessary tasks before the *Intermediate C&R*?

- ① It is necessary to get a prospect for development of NBI and ECH systems in ITER towards extended development to enable these systems which are foreseeable from ITER technologies for DEMO.
- ② It is necessary to clarify the roles and the power ratio of NBI and ECH in DEMO, and to develop their R&D plans by focusing on the technological specifications of the heating and current drive systems.

What are necessary tasks after the *Intermediate C&R* and before the assessment of the *Transition Conditions*?

- ① It is necessary to establish the beam focusing technology required for installing the neutron shield structure in the beam line in order to avoid performance degradation of the ion source by neutron streaming from the beam line.
- ② It is necessary to develop the high-efficiency neutralizer for improvement of the efficiency of NBI.
- ③ It is necessary to develop the electrode material with low work function for establishment of the Cs-free ion source which enables steady-state operation.
- ④ It is necessary to develop the multiple-stage energy recovery technology for improvement of the efficiency of the gyrotron for ECH.
- ⑤ It is necessary to develop the mirror-less waveguide-injector-type launcher and technology for fast variable frequency for minimizing the occupied volume of in-vessel components to secure the

breeding blanket space in order to avoid degradation of the total TBR.

- ⑥ It is necessary to develop the gyrotron with higher frequency consistent with the DEMO design since the magnetic field of DEMO is higher than that of ITER.

Urgent issues

- ① The R&D in ITER should be advanced steadily and the R&D plan for DEMO should be developed by defining the roles of NBI and ECH required for DEMO and their technological specification as technological targets.

Points of note

- ① The mock-up test facility for DEMO NBI should be ready around the time of the assessment of *Transition Conditions*. It is necessary to establish planning and a framework including the decision whether the test facility is newly constructed in Japan or an international project by extending the ITER NBTF (in Padova, Italy).
- ② The neutron irradiation test facility for the equipment of NBI and ECH systems is necessary.

3-5. Theory and Numerical Simulation Research

1) Issues

- (a) Understanding of physical mechanisms for transport barrier, density limit, beta limit etc.
- (b) Development of an integrated fusion plasma simulation code which is internationally competitive and highly reliable, and dedicated validation of its prediction capability based upon comparisons with experimental results.
- (c) Development of a system code for a fusion reactor taking account of spatial profiles of various physical parameters in fusion plasmas and their temporal evolutions due to transport phenomena and instabilities.
- (d) Development of an integrated reactor engineering code including an integrated blanket analysis and a material analysis.
- (e) Development of a simulator integrating items described in (b)-(d).
- (f) Secure logistics providing for large-scale computer resources, effective cooperation among a large number of researchers in Japan, and training for young scientists who are charged in research and development of DEMO.

2) Extraction of Core Issues and Necessary Tasks to Resolve These Issues

It is necessary to develop and improve the simulation model which can reproduce systematically whole phenomena. It is important to promote research activities systematically from two sides: improvement of accuracy for each component code and systematic code management.

What are necessary tasks before the *Intermediate C&R*?

- ① It is necessary to develop an integrated fusion plasma simulation code which is able to predict fusion plasma performance by treating systematically core, edge, scrape-off layer, and divertor plasmas based upon fusion plasma performance obtained in fusion experimental devices.
- ② It is necessary to develop a basic engineering code combined with thermal analysis, electromagnetic force analysis, stress analysis, neutronics analysis, etc., which enables a plant simulation compatible with a fusion plasma simulation.

What are necessary tasks after the *Intermediate C&R* and before the assessment of *Transition Conditions*?

- ① It is necessary to develop a burning fusion plasma simulation code which enables prediction of ITER plasma performance by extending an integrated fusion plasma simulation code.
- ② It is necessary to develop a base code for DEMO which enables prediction of the basic behaviour of an energy plant consistent with a burning fusion plasma simulation by extending basic engineering codes.
- ③ It is necessary to develop a simulator for real time control consistent with the above codes.

Urgent issues

- ① It is necessary to clarify sharing of roles for JAEA, NIFS, and universities, and to define concrete milestones which are consistent with the roadmap towards DEMO.
- ② It is necessary to examine measures to secure computer resources after the BA activities.
- ③ It is necessary to examine strategic measures to secure personnel resources.

Points of note

- ① It is necessary to conduct development involving sufficient cooperation between fusion plasma simulation development and fusion plasma research, between plant simulation development and the DEMO design activity, and between control simulator development, and diagnostics and control research.
- ② It is necessary to emphasize cost saving and process shortening by adapting a technique to substitute with computer simulations for engineering R&D as an important strategy in theory and numerical simulation research.

3-6. Reactor Plasma Research

1) Issues

- (a) Advancement of plasma design for a tokamak DEMO (highly integrated reactor performance, reduction of divertor heat flux, establishment of control technique)
- (b) Improvement of performance of steady-state plasma by using both LHD (Large Helical Device at NIFS) and JT-60SA (compatibility between high performance plasma and reduced heat load on the first wall)

- (c) Integration of reactor plasma technology and reactor engineering (divertor test, PWI, matching test of blanket and plasma, test of plasma control device)
- (d) Acceleration of training of personnel to exert leadership in the international arena.

1-2) Measures and Management Systems Required for Resolution

- (a) Need organized measure by integrating ITER, JT-60SA, and theoretical modeling. With regard to improvement of divertor configuration, cooperate with overseas devices.
- (b) Promote research on steady-state plasma with high performance close to the fusion condition in the deuterium experiment in LHD, and contribute to resolution of the issues expected in ITER and DEMO through systematic study of toroidal plasmas.
- (c) Implement many of the integrated tests of reactor plasma technology and reactor engineering under high neutron irradiation environment in ITER. Carry out tests of innovative ideas and tests which are difficult in ITER due to device constraints, in JT-60SA and LHD.
- (d) Establish a framework of JT-60SA experiment so that the domestic research community team can exert international initiative and leadership. Need a system of management and human affairs enabling researchers from universities and others to attend ITER and JT-60SA experiments with long-period or resident stay. Secure human resources steadily from a long-range perspective.

2) Extraction of Core Issues and Necessary Tasks to Resolve These Issues

It is necessary for Reactor Plasma Research to grapple with resolution of the DEMO issues by advancing supportive and complementary researches in JT-60SA steadily as both a domestic core device and a satellite tokamak, by strengthening cooperation with domestic and international facilities, and by optimizing the use of the achievements in ITER towards DEMO. In particular, it is important to ensure device soundness by demonstrating reduction of divertor heat load and pulsed heat load due to ELM and control techniques of disruption as well as the prospect for control technology for steady fusion output by demonstrating high-beta steady state operation, high density with high confinement, and particle control technique.

What are necessary tasks before the *Intermediate C&R*?

- ① It is necessary to advance development of physics models and improvement of performance prediction codes in order to assess feasible integrated reactor plasma performance. In particular, viewpoints of compatibility between the steady high performance plasma and the reduced heat load on the first wall are important.
- ② It is necessary to advance development of the DEMO physics database in order to improve the extrapolating capability of the reactor plasma performance to DEMO by extending the ITER physics database based upon research progress of experiments, theory, and simulation.
- ③ It is necessary to focus the reactor plasma parameters through advancement and establishment of convincing reactor plasma design by considering compatibility between the target of DEMO and the constraints of reactor engineering.

- ④ It is necessary to reflect the approach to resolving the DEMO issues in research plans of ITER and JT-60SA.
- ⑤ It is necessary to initiate development of the database by utilizing domestic plasma experiments and divertor testing devices in order to extend basic data of tungsten materials related to plasma-wall interaction

What are necessary tasks after the *Intermediate C&R* and before the assessment of *Transition Conditions*?

- ① It is necessary to demonstrate the high-beta steady-state operation with over no-wall beta limit under the condition without in-vessel control coils, which are unable to be installed inside the vacuum vessel in DEMO.
- ② It is necessary to demonstrate high density and high confinement operation by clarifying physics mechanisms of confinement degradation appearing in the high-density regime.
- ③ It is necessary to demonstrate high radiation loss operation and detachment operation towards reduction of divertor heat load, and particle control technique for refueling and helium ash exhaust.
- ④ It is necessary to demonstrate small or no ELM operation, which does not damage the soundness of the divertor, in order to reduce pulsed heat load by ELMs.
- ⑤ It is necessary to demonstrate control technique for substantial mitigation at the occurrence of disruption because disruption is a critical issue that threatens device soundness.
- ⑥ It is necessary to demonstrate burning plasma with $Q=10$ in ITER in order to acquire the control technique of burning plasma.
- ⑦ Based upon resolution of these issues, it is consequently necessary to show the prospects for control techniques of steady fusion output and for ensuring device soundness.

Urgent issues

- ① Need to develop ITER and JT-60SA research plans reflecting the DEMO physics design, and to extend database towards DEMO by utilizing ITPA and domestic and abroad devices before JT-60SA becomes operational.
- ② Need to establish now the system which enables human resource development and participation of researchers from universities and others for their long-period or resident stay in order to participate in the experiments of ITER and JT-60SA in a framework of implementation throughout Japan.

Points of note

- ① Need to clarify the content of the item “demonstration of burning control in self-ignition regime” in the *Transition Conditions*.
- ② Need to strategically organize the exchange and mobility of human resources in order to strengthen relationships of feedback and feed-forward between the DEMO design and experiments in ITER and JT-60SA.

- ③ Need to actively promote ITER remote experiments in order to extend the participating researchers and to nurture young researchers through the operation of the ITER Remote Experimentation Centre (REC) prepared by BA activities, to accumulate data of ITER and other tokamaks strategically in REC to utilize optimize development and validation of theoretical simulation and the integrated code, and plasma modeling research by making full use of the accumulated data.
- ④ Need to urgently develop (mobilize) young researchers (under thirty) in charge of DEMO in the future under a situation where there is no large tokamak experiment in Japan until 2019.
- ⑤ It is important to show the prospect for plasma control technique based upon the technologies available and feasible in DEMO.
- ⑥ Measures for the issues originating in high-beta in tokamak in Japan are only available on JT-60SA. Need to accelerate the activities in JT-60SA to increase heating power and to prepare diagnostics in solidarity with domestic plasma experimental devices in order to show the prospect to resolve these issues in JT-60SA in advance of the high beta experiment in ITER.
- ⑦ Need to carry out the LHD deuterium experiments with upgraded heating power and the extended pulse length early in order to clarify the issues in long pulse property of large heat flux on divertor, and then need to reflect them in the DEMO conceptual design.
- ⑧ Need to upgrade to tungsten divertor in JT-60SA at an appropriate time based upon the experimental results on tungsten divertor in ITER and other devices in order to develop control technique of detachment consistent with the DEMO design under the tungsten divertor envisaged in DEMO.
- ⑨ Need to organize the framework to optimize intrinsic advantage of each domestic plasma experimental device such as LHD, GAMMA10 (Tsukuba University), QUEST (Kyushu University), and others in order to compile the basic data for the DEMO design with regard to plasma wall interaction including tungsten as a common objective.
- ⑩ Need to promote development of control simulator applicable in the early phase of JT-60SA operation in cooperation with universities and others, and to examine demonstration test of the simulator in ITER in order to establish practical and reliable control technique and control logic.

3-7. Fuel Systems

1) Issues

- (a) Establishment of handling technology for large amounts and high concentrated tritium and heat medium containing tritium, material accountancy, and securing initial loading of tritium. Furthermore, development of large-scale technologies to deal with these issues.
- (b) Development of large scale technologies for handling waste liquid and the detritiation system from solid waste.
- (c) Programmatic resolution of safety issues including tritium handling consistent with research and development of the blanket and the divertor.
- (d) It is indispensable for tritium breeding to secure lithium 6 for initial loading to blankets and

continuous reloading depending on the operational condition. From the viewpoint of securing logistics, the technology should be nationalized. In order to establish technology for separation and collection of lithium, technological development for scale-up through the selection process and development of a plant is necessary.

2) Extraction of Core Issues and Necessary Tasks to Resolve These Issues

ITER is the first plant to establish an actual fuel system including tritium handling, and provides the guidelines for subsequent research and development. Therefore, development of the equipment for ITER and accumulation of the tritium handling technology in ITER should be done with highest priority.

What are necessary tasks before the *Intermediate C&R*?

- ① It is necessary to define the fuelling scenario in DEMO and to clarify specifications of the fuel cycle system taking into account fuel inventory.
- ② It is necessary to develop components of the fuel cycle system such as impurity removal and isotope separation, and to establish the component technologies.
- ③ It is necessary to demonstrate the detritiation system and the accumulation of experience for tritium accountancy, and to establish safe handling technology.
- ④ It is necessary to obtain base data for tritium handling such as tritium material interactions.

What are necessary tasks after the *Intermediate C&R* and before the assessment of *Transition Conditions*?

- ① It is necessary to start the DT operation in ITER and to verify the fuelling scenario by maintaining the burning condition for a long duration.
- ② It is necessary to demonstrate that the components of the fuel cycle system work according to their specifications in ITER.
- ③ It is necessary to demonstrate that the detritiation system works according to the specifications and to accumulate operation experience with accurate tritium accountancy in ITER.
- ④ It is necessary to verify that the equipment treating tritium works according to the specifications in ITER.
- ⑤ It is necessary to obtain prospects of the technology for securing lithium 6, which is used for tritium breeding.
- ⑥ It is necessary to obtain prospects of the technology for securing the initial loading of tritium or alternative measures.

Urgent issues

- ① It is necessary to decide specifications of the fuel cycle system consistent with the fuelling scenario in DEMO in order to establish the concept of the fuel system required in DEMO.
- ② It is necessary to estimate fuel inventory in DEMO, which influences significantly the fuelling

scenario, based upon analyses of the existing experimental data.

Points of note

- ① It is important to complete the Japanese commitment to the ITER project through the procurement of the detritiation systems and promote activities to accumulate the technologies for the fuel cycle system required in DEMO by utilizing ITER.
- ② With regard to handling and securing tritium and lithium 6, not only establishment of the technology in Japan but also implementation of research and development under an international framework are required.

3-8. Material Development and Establishment of Codes and Standards

1) Issues

- (a) Towards establishment of codes and standards for fusion reactor structural materials, a basic safety policy in the fusion reactor and related structural design criteria must be determined with further understanding of materials characterization and the degradation mechanisms.
- (b) Alternative and compound approaches not relying solely upon the early realization of IFMIF (International Fusion Material Irradiation Facility) should be examined and conducted in order to acquire a fusion neutron irradiation database required for the pre-conceptual design activities of DEMO.
- (c) Establishment of testing standards is required for Small Specimen Testing Technologies (SSTTs), which are the basis for compiling the irradiation data.
- (d) Active and prolonged participation of industries is essential to enable practical use of structural materials because their development requires a long period of time.

2) Extraction of Core Issues and Necessary Tasks to Resolve These Issues

Establishment of the material standards of reduced-activation ferritic steel, which is a baseline material for the blanket of DEMO fusion reactor, requires material characterization and an understanding of the degradation mechanisms. This process should be based upon the basic policy to ensure safety in the design activity and the corresponding concepts of structural design codes and standards. The material standards should be considered, including the fusion neutron irradiation effect, which is represented by transmutation. Methodology to utilize the irradiation data derived from small specimens used in past experiments, future IFMIF experiments, and other experiments should be established as a testing standard.

With regard to the fusion neutron irradiation effect, alternative and compound approaches such as the construction of a new fusion neutron source which is able to verify effects of the helium transmutation and the effective utilization of the existing fission reactors should be examined and undertaken not relying solely upon the IFMIF or the early realization of an intensive fusion neutron

source with neutron spectrum and flux equivalent for the IFMIF.

What are necessary tasks before the *Intermediate C&R*?

- ① It is necessary to establish mass-production technologies for the reduced-activation ferritic steel.
- ② It is necessary to establish blanket structure fabrication technologies.
- ③ It is necessary to initiate preparatory activities for materials standardization in academic societies and other related communities.
- ④ It is necessary to obtain 80 dpa irradiation data by using fission reactors.
- ⑤ It is necessary to establish the reliability of small specimen evaluation data.

What are necessary tasks after the *Intermediate C&R* and before the assessment of the *Transition Conditions*?

- ① It is necessary to clarify demands upon the structural materials for DEMO.
- ② It is necessary to present technological specifications of blanket structural materials for DEMO.
- ③ It is necessary to obtain data regarding joining/coating, effects of electromagnetic force, compatibility with coolants, and the irradiation effect on these properties.
- ④ It is necessary to develop understanding of the effect of the helium transmutation using fusion neutron sources.
- ⑤ It is necessary to standardize SSTTs.

Urgent issues

- ① Clarification of a material database which must be acquired in order to develop the structural material standards through dialogue with related academic societies and the DEMO reactor design team.
- ② Irradiation plans using fusion neutron irradiation sources or existing irradiation facilities should be proposed in order to develop codes and standards for the structural material to be used as the prime candidate for the DEMO blanket.
- ③ For items which cannot be evaluated in the irradiation plan, it is necessary to clarify a methodology for compensating with simulation and modelling.

Points of note

- ① With regard to advanced materials, investigation of how they may be utilized through discussion with the DEMO reactor design team and compilation of a material database should be carried out in order to judge their applicability at the assessment of the *Transition Conditions*.
- ② Since the High Flux Isotope Reactor (HFIR) at the Oak Ridge National Laboratory, in the United States, is the only available fission neutron irradiation facility for high dose experiments, early re-start of domestic reactors such as JMTR and JOYO is hoped for.
- ③ Material development requires a long period of time. Long-term and active participation of

industries is essential for the steady development of practical materials.

3-9. Safety of DEMO and Safety Research

1) Issues

- (a) Assessment of safety and environmental effect of tritium based upon the understandings of engineering safety of a fusion plant.
- (b) Quantification of environmental behavior of tritium and its biological effects, safety management and securing of public acceptance in keeping with the fact that tritium is released to the environment even under normal operation.
- (c) Establishment of a framework according to Japan's characteristic conditions for safety research about abnormal plant behavior and appropriate measures.

2) Extraction of Core Issues and Necessary Tasks to Resolve These Issues

The problem in the assessment of safety is due to the breakup of the examination team after the invitation activity of ITER and stagnation of major activities. It is important to re-launch the activity as a project. The examination team for safety should be organized to promote a wide range of support from industry, government, and academia including other fields.

What are necessary tasks before the *Intermediate C&R*?

- ① It is necessary to review plans and the schedule of compilation of material data, development of computer simulation codes for safety analysis, and facilities required for verification and validation tests and to package them in a project

What are necessary after the *Intermediate C&R* and before the assessment of the *Transition Conditions* ?

- ① It is necessary to arrange the safety requirement standard and the corresponding guidelines of the safety design of DEMO. The examination should be reasonably implemented taking account of intrinsic safety features of a fusion reactor as well as existing regulations and standards/criteria.
- ② It is necessary to conduct preliminary examination of formulation of regulations and licensing process.
- ③ It is necessary to assess social acceptance of DEMO plant

Urgent issues

- ① It is necessary to enhance safety studies and compilation of material data and to strengthen justification of a pre-conceptual design.
- ② It is necessary to clarify firstly the specifications required for DEMO and then the corresponding requirements to elements.
- ③ For the above activity, a framework for pre-conceptual design including examination of safety

should be organized.

Points of note

- ① An organized framework of a team should be attractive and significant to participating researchers from different fields.
- ② The examination team working for ITER invitation was dismissed.
- ③ Absence of a project of safety examination leads to difficulty of support from industry.
- ④ While experts for safety are limited, their demand is great in other fields.

3-10. Availability and Maintainability

1) Issues

- (a) Understanding of whole view of availability and maintainability, including economy, RAMI (Reliability, Availability, Maintainability, Inspectability), safety, etc. Making a proposal of “a certain economy” considering prospects of a maintenance method, the approaches for ensuring reliability (concept of quality assurance, redundancy, and safety margin), inspectability, and risks of unscheduled shutdowns.
- (b) Lifetime prediction of in-vessel components and showing the direction of efforts for lifetime extension.
- (c) Establishment of a comprehensive maintenance concept including a maintenance method, reactor structure, reactor building, and hot cell. Development of radiation resistant devices and system integration.

2) Extraction of Core Issues and Necessary Tasks to Resolve These Issues

The maintenance method concept in a DEMO should be determined at the first step in the DEMO design since it is related closely with the reactor structure, development and design of devices, and equipment, and also with burning plasma control. For review and prioritization of R&D items and targets of maintenance technology after the BA activities, investigation of components to be maintained, required technology, and procedures should be done by promoting the detailed reactor design. Since the present technological assessment expects that the replacement frequency of divertors will be highest and will thus determine the periodic maintenance cycle, prediction of the lifetime of divertors is required to forecast economic viability.

With regard to R&D activities, it is necessary to construct a new large-scale R&D facility for maintenance technology and develop remote handling technology for large-scale components. It is also required to develop radiation resistant materials and devices by utilizing existing irradiation facilities.

What are necessary tasks before the *Intermediate C&R*?

- ① With regard to the selection of the reactor structure and maintenance method taking into account consistency with plasma control and component designs, and safety, it is necessary to compose a corresponding proposal quickly by the DEMO design team since it affects various R&D elements.
- ② Subsequently investigate and select specific maintenance technology and working procedures by involving results of detailed investigation and design for maintenance in ITER, and also technology in fission reactors. Based upon this involvement, R&D items newly required for DEMO can be clarified. At the intermediate C&R, it is necessary to show results of feasibility review taking technology base into account in addition to proposals of a maintenance method, technology, and working procedures.

What are necessary tasks after the *Intermediate C&R* and before the assessment of the *Transition Conditions*?

- ① With regard to R&D of remote maintenance technology newly required for a DEMO, it is necessary to construct a new development facility for large-scale maintenance and promote the development by involving achievements of maintenance technology obtained in ITER and remote robot technologies in industry.
- ② With regard to radiation resistant functional materials and devices for sophisticated and efficient remote maintenance, it is necessary to carry out development aiming for integrated dose of 200 MGy based upon the results up to 100 MGy obtained during ITER-EDA.
- ③ At the assessment of the *Transition Conditions* presumed around 2027, it will be necessary to show the prospect of availability based upon a periodic replacement cycle predicted from the lifetime of plasma facing components, and also on detailed investigation and optimization of maintenance processes involving the latest R&D results. This must include examination of causes for unscheduled shutdown based upon a database of failure rates of equipment and devices accumulated in ITER, JT-60SA, etc., and their inspection and measures.
- ④ It is necessary to define standards for disposal, reuse, and clearance of fusion reactor materials to show perspective of the back end including a disposal building, storage site, burial method, etc., of radioactive waste.

Urgent issues

- ① Strengthening of a framework for implementation of the DEMO design is necessary to compose a proposal of a maintenance concept early.
- ② Strengthening of development of the DEMO divertor system and studies on lifetime prediction from both viewpoints of component development and plasma control is necessary.

Points of note

- ① It is expected that the standard for disposal and reuse of radioactive waste will be established

autonomously by JAEA, industry, universities, etc., based upon the procedure to establish the standard of a fission reactor before the assessment of the *Transition Conditions* and the final authorization of the standard by Nuclear Regulation Authority etc. will be done after the assessment of the *Transition Conditions*.

3-11. Diagnostics and Control Systems

1) Issues

- (a) Development of the integrated and consistent plasma scenario including heat load control, helium exhaust capability, and core and edge plasmas.
- (b) Development of an operating scenario for edge plasma consistent with erosion, embrittlement, and maintenance of divertor components.
- (c) Development of the integrated reactor system simulator for the design of diagnostics and the control system for DEMO.
- (d) Establishment of practical and reliable control techniques and control logic.

2) Extraction of Core Issue and Necessary Tasks to Resolve These Issues

It is important to focus clusters of essential and applicable diagnostics based upon performance and operating results of diagnostics developed and prepared for ITER because of various constraints due to high irradiation field in DEMO. In particular, it is necessary to show the prospect of the DEMO relevant diagnostics through the development of essential diagnostics for burning control and radiation-proofed components, and improvement of accuracy of equilibrium control by magnetic measurements as well as to develop the real time operation control simulator.

What are necessary tasks before the *Intermediate C&R*?

- ① It is necessary to focus diagnostics to be applicable to DEMO and definitely needed for operation control.
- ② It is necessary to accumulate data of plasma response property for the use of model validation since highly precise modeling including temporal evolution of plasma is necessary for development of operational control simulator.
- ③ It is necessary to define the operation standard point and surrounding allowable operating regime by clarifying the operating margin against the limits and operational control range of detached plasma.
- ④ Based upon measures in the above mentioned issues, it is necessary to define the target performance of diagnostics and to reflect it in research plans of ITER and JT-60SA.

What are necessary tasks after the *Intermediate C&R* and before the assessment of *Transition Conditions*?

- ① It is necessary to develop diagnostics and their analysis codes in ITER, JT-60SA, and LHD in order to achieve their performances required for control

- ② It is necessary to develop radiation-proofed components in parallel with evaluation of the lifetime of diagnostics in the irradiation test facility.
- ③ It is necessary to show the prospects for accuracy of equilibrium control under the DEMO relevant electro-magnetic condition by using the data measured with magnetics which are placed far from plasma or close to structural material where influence of eddy current should be large as in JT-60SA.
- ④ It is necessary to develop the real time operational control simulator in order to build control logic under the DEMO condition where available diagnostics are restricted and to demonstrate its function in JT-60SA and ITER.

Urgent issues

- ① Organize and strengthen the examination activity for diagnostics and control systems consisting of experts from core plasma, theory and simulation, diagnostics, and actuators

Points of note

- ① Strong cooperation with Reactor Plasma Research and Theory and Numerical Simulation Research for development of the real time operational control simulator is essential.

3-12. Newly Required Facilities and Platforms

As shown in the previous sections, which analysed the technological issues of 11 elements of DEMO, some issues can be dealt with by presently available programs or their expansion and improvement. On the other hand, activities to resolve some issues have not been initiated yet because corresponding frameworks/platforms do not yet exist. Newly required facilities, etc., are summarised in the following.

- Test facility of large-scale superconducting coils which fulfills the specification of DEMO (Test facility of superconducting conductor and coils with around 16 T)
- Facility related to blanket (development of ITER-TBM, post irradiation examination, development of waste disposal technology)
- Test facility of real-scale performance of NBI (including expansion of ITER NBTF)
- Supercomputer resource
- Handling facility for large quantities of tritium
- Lithium plant (collection and purification facility)
- Intensive fusion neutron source, fusion neutron source (including expansion of IFMIF/EVEDA)
- Facility for development of large-scale component maintenance

With regard to newly required facilities, full use should be made of available infrastructure beginning with facilities prepared in the presently ongoing programs such as the BA activities, and also expanded.

Figure 1 shows the summary of newly required facilities together with on-going projects such as ITER in the timeline. In particular, it is necessary to develop the BA site in Rokkasho as the central core base for development of DEMO and to organize a framework for implementation throughout Japan by clarifying the roles together with the BA site in Naka, NIFS, and universities and reinforcing cooperation.

4. Points of Reactor Design Activity

What is required in the DEMO design activity is to show the concept which is feasible by reliable extension of the present technology bases and fulfills social requests. Here DEMO is only one-step from ITER to commercialization, which is prospected in the middle of the 21st century.

In order to show the economic feasibility of fusion energy by DEMO, DEMO is required to pursue superior performance for high-efficiency energy production by improvement of components in addition to accumulation of operating experience in order to prove reliability as an energy production system (i.e. to guarantee availability extensible to commercialization, reduction of unplanned downtime ratio, etc.). Therefore, design should be flexible so as to enable refinement of components and test for improved performance in service. Furthermore, the estimate of the cost of a commercial reactor should be incorporated into the DEMO design, and it should include not only the cost of construction and operation but also the back-end cost of decommissioning and disposal of waste.

The DEMO design should secure a self-consistent design involving material, productivity, workability, assembly precision, maintainability, inspectionability, and refinement to project to industrialization in the future. Therefore, close collaborative work with industries in significant scale is necessary in the early phase of the DEMO design. Furthermore, continuous and phased commitment of industries in long-term prospect is required, and it is quite important to take measures to facilitate this.

With regard to the level of completion by the *Intermediate C&R*, it is required that the overall target of DEMO will be decided and that technological examination to guarantee overall consistency of the system and the prospect of real fabrication will be completed.

- Decision of overall target of DEMO
- Basic design of DEMO concept
- Addressing of development request to reactor plasma and engineering (operating scenario, structural material, divertor material, configuration of blanket, maintenance system, etc.)

5. International Cooperation and Collaboration

It has to be noted that budgetary and human resources, and R&D and production bases in Japan are

insufficient to conduct all the R&D for DEMO alone. Therefore, it is indispensable to plan strategic international cooperation by considering resources, technological maturity level in Japan, and complementarity to other countries/party.

The most important point is application of achievement and accomplishment in the ITER project. By making full use of this opportunity, it is important to promote accumulation and acquirement of useful data to resolve technological issues of DEMO by working closely with other committing countries/party. Approaches to lead the initiative not only in the construction/commissioning phase but also in the experiment phase in ITER is primarily important for this point. Achievement and accomplishment in the ITER project, including management aspects, will lead to international cooperation in the development of DEMO.

International cooperation programs are pronounced in technological investigations targeted to assess a DEMO design and to endorse feasibility of real component fabrication. It is necessary to select what is appropriate to be conducted under the international framework first. Based upon analysis of complementarity to domestic activities, the procedure, the time line, the implementing body, and cooperation with domestic activities should be well defined in international cooperation programs.

Specifically, the following remarks are particularly important among the statements about international cooperation described in Chapter 3.

- The effective extension from the presently ongoing projects should be promoted for facilities of fusion neutron source and intensive fusion neutron source for material development, and a large-real-scale test facility for development of heating and current-drive system.
- Since the fission neutron irradiation facility is not available in Japan now and its test has to depend on the HFIR in the United States, restart of research reactors of Joyo and JMTR is expected, and the bilateral cooperation with the United States should be maintained.
- Since a large-scale tokamak experiment will not be available in Japan until the start of operation of JT-60SA in 2019, cooperation with tokamak experiments abroad and simulation, specifically regarding the detachment operating scenario and the tungsten issue, which are related to development of the divertor, is indispensable. In order to facilitate this, special care should be paid to proactive commitment to ITPA and related implementing agreements of the International Energy Agency, etc.
- Since a variety of concepts of TBM in ITER depending on contributing countries and party will be tested, good cooperative relations should be established so that achievement by other countries/party will be reflected in the DEMO design appropriately.

6. Development of Grand Strategy towards Future Establishment of Technological Bases for DEMO

In accordance with the request of the Working Group on Fusion Research under the council in the MEXT, the Joint-Core Team has worked on development of strategic establishment of technology

bases required for development of DEMO by taking into account the progress of the ITER project, the BA activities, and academic research such as on the Large Helical Device (LHD). In particular, the concept of DEMO premised for investigation and activities to ensure the feasibility of this DEMO concept have been examined.

The purpose of DEMO is to show the prospect for economic and social rationality of fusion energy competitive with other energy resources. In order to prepare for commercialization, DEMO should be aimed at steady and stable power generation beyond several hundred thousand kilowatts, availability which must be extended to commercialization, and overall tritium breeding to fulfil self-sufficiency of fuels. And the roadmap towards DEMO with defined milestones should be elaborated. In DEMO itself, the operational development phase of DEMO before reaching the targets should be planned by classifying the commissioning phase, the power-generation-demonstration phase, and the demonstration of economic feasibility phase, and defining a milestone at each phase. Targets such as demonstration of power generation by the system equivalent to a commercial reactor, demonstration of high energy gain factor, long-pulse and long-term operation which can be extrapolated to a commercial reactor, and development and demonstration of advanced technology to improve economic performance should be defined and achieved in each phase.

Required technological activities of 11 elements of DEMO have been sorted out with attention to development of the roadmap. Each element has been analyzed in order to clarify the procedure to demonstrate the technological feasibility of DEMO, which is the most fundamental mission, and to develop the roadmap with the timeline and implementing bodies. Here *Intermediate C&R* and the assessment of *Transition Conditions*, which have been defined in the “Future Fusion R&D,” are presumed around 2020 and 2027, respectively. Then, in view of the timeline, the structure (tree) of technological issues in each element and approach to resolve these issues are identified. While some issues can be dealt with by the presently ongoing projects and existing implementing bodies/platforms or their expansion/reinforcement, there still remain issues which are not yet dealt with because of the lack of corresponding projects and implementing bodies. Based upon the analysis of the structure of technological issues, aligned R&D programs with defined milestones, and plans of research bodies grappling with issues and required facilities, the following are identified; 1) What is required before the *Intermediate C&R*; 2) What is required after the *Intermediate C&R* and before the assessment of the *Transition Conditions* (driving the content mentioned as “Promotion to start the enterprise of engineering R&D in accordance of the assessment at the *Intermediate C&R*” in Section 2.5); 3) Urgent issues; and 4) Points of note.

All related research and development programs are organized in the Chart of Establishment of Technological Bases for DEMO around the development of the design of DEMO as the primary axis with attention paid to required evidence to support the maturity of the design of DEMO and consistency in the timeline. Complete picture of this chart is available in Ref. and two elements of “Reactor System Design” and “Material Development and Establishment of Codes and Standards” are shown as examples in Fig.2 and Fig.3, respectively. Technological tasks are arranged in up to 4 levels

and 205 tasks are defined in total. These configuration has been carefully considered for the subsequent development of Working Breakdown Structure.

It should be noted that the progress of the ITER project will have a great impact on timing and criteria at the *Transition Conditions*. In particular, based upon common recognition about when and how much the results of energy gain, long-pulse operation, and demonstration of blanket function, etc., will be obtained in the ITER project, timing and criteria at the *Transition Conditions* should be discussed in formulation of the roadmap.

The problem recognition common in all 11 elements is the dilemma between design of DEMO and R&D for each technological issue. In short, it is nothing but changing the situation from an unfavorable situation in which a target of technological R&D cannot be defined because the design is not fixed and that the design cannot be fixed because the prospect of technological R&D is unclear, to a favorable situation in which the progress of both sides accelerates each other synergistically. Development of DEMO is arranged so as to bring together all related technology from a position of integration. Therefore, in a broad sense, the DEMO design activity is requested to manage the overall development plan with the definition of the target of each technology and assessment of technological maturity, and to play a role not only to promote and boost secure progress of the main stream options but also to promote innovative technological developments for breakthrough. In order to establish this DEMO design activity which covers planning, management, and coordination of the R&D plan required for engineering development for DEMO, a strategic framework for implementation throughout Japan should be organized in addition to reinforcement of the present activity for DEMO design by fusion experts. This framework should work for effective PDCA cycle, in particular, Check and Action, and organize activity including coordination with other fields and academic societies to resolve issues.

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Table I Check and Review Items in Future Fusion R&D (draft) from “Future Fusion R&D,” The Atomic Energy Commission’s Advisory Committee on Nuclear Fusion, October 2005 [1]

Issues	Performance goal by check and review in the interim phase	Transition conditions to the DEMO phase
1. Demonstration of burn control in self-heating regime using the experimental reactor	<ul style="list-style-type: none"> Lay out plans for achieving the technological goals of ITER 	<ul style="list-style-type: none"> Demonstration of maintenance of plasma with $Q \geq 20$ (for duration longer than about several 100 s) and burn control in ITER
2. Realization of non-inductive steady-state operation with $Q \geq 5$ using the experimental reactor	<ul style="list-style-type: none"> Lay out plans for achieving the goals of ITER 	<ul style="list-style-type: none"> Demonstration of non-inductive current drive plasma with $Q \geq 5$ (for duration longer than about 1,000 s) in ITER
3. Establishment of integration technology using experimental reactor	<ul style="list-style-type: none"> Complete ITER facilities Acquire integration technology related to manufacturing, installation, and adjustment of components 	<ul style="list-style-type: none"> Establishment of integration technology through the operation and maintenance of ITER. Verification of safety technology
4. Establishment of high-beta steady-state operation to prospect economical feasibility	<ul style="list-style-type: none"> Conduct ITER support research and preparatory research for high-beta steady-state plasma and launch research using National Centralized Tokamak 	<ul style="list-style-type: none"> Attainment of sustaining high-beta ($\beta_n = 3.5-5.5$) plasma in collision-less regime in National Centralized Tokamak
5. Development of materials and fusion technologies related to DEMO	<ul style="list-style-type: none"> Complete establishing technological basis for power generation blanket. Complete manufacturing test components to be used for the functional test in ITER Acquire irradiation data of reduced activation ferritic steels up to 80dpa and determine test materials under neutron irradiation environment relevant to fusion reactor 	<ul style="list-style-type: none"> Demonstration of tritium breeding and recovery functions, removal of heat and power generating blanket in a low-fluence DT experiment on ITER Completion of verification of heavy irradiation data of reduced activation ferritic steels up to a level of 80 dpa
6. Conceptual design of DEMO	<ul style="list-style-type: none"> Determine the overall goal of DEMO Conduct preliminary work on the conceptual design of DEMO Make requests for the required development of fusion science and technology 	<ul style="list-style-type: none"> Completion of conceptual design of DEMO consistent with the development of fusion plasma research and fusion technology

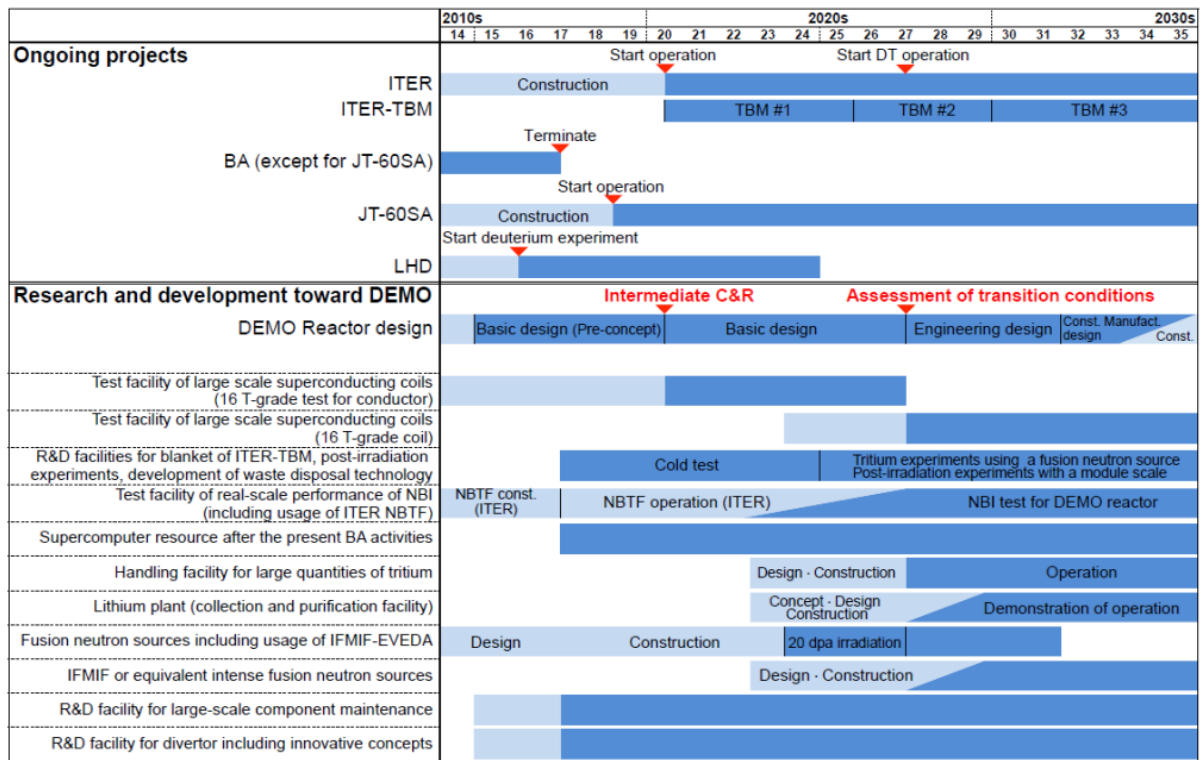


Fig. 1 Summary of Chart of Establishment of Technological Bases for DEMO consisting of major projects, development of the design of DEMO and newly required R&D facilities and platforms (reproduced from Fig. 1 in Ref. 6)

