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Report by the Joint-Core Team for the Establishment of Technology Bases Required for the Development of a Demonstration Fusion Reactor

- Basic Concept of DEMO and Structure of Technological Issues-

Original version in Japanese was reported on 18 July 2014

English version: 19 January, 2015

The Joint Core Team for the Establishment of Technology Bases Required for the Development of a Fusion DEMO Reactor

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## Abstract

In accordance with the request of the Working Group on Fusion Research, the Nuclear Science and Technology Committee, the Subdivision on R&D Planning and Evaluation, the Council for Science and Technology, the Ministry of Education, Culture, Sports, Science and Technology, the joint-core team has worked on strategy for establishment of technology bases required for development of a fusion DEMO reactor by taking into account the latest progress of the ITER project, the BA activities, and academic researches such as the Large Helical Device. In particular, the concept of a fusion DEMO reactor premised for investigation, and the structure of technological issues to ensure the feasibility of this DEMO concept have been examined.

This report is documented by the joint-core team of members and experts from the National Institute for Fusion Science, the Japan Atomic Energy Agency, Kyoto University, the Japan Atomic Industrial Forum, Inc., and Keio University.

The electric file is available at http://www.naka.jaea.go.jp/english/index.html



## Keywords:
fusion DEMO reactor, reactor design, technological bases, technological issues, grand strategy, transition conditions, ITER

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## Agenda

# 1. Introduction

Japanese fusion research and development is now in the phase targeting the achievement of self-ignition condition and realization of long-pulse burn by the International Thermonuclear Experimental Reactor (ITER) project, and the establishment of the technology base required for the development of a "DEMOnstration fusion reactor" (hereafter referred to as "DEMO"). This phase is called the *Third Phase Program* with the goal to show the scientific and technological feasibility of fusion energy. And the present research and development is conducted in the framework of the "Third Phase Basic Program of Fusion Research and Development" decided by the Atomic Energy Commission (AEC) in June, 1992 [1]. In addition, specific guidelines aiming at the next *Fourth Phase Program* with a core project of DEMO, which has the goal of technological demonstration and economic feasibility of fusion energy, have been shown in the "Future Fusion Research and Development Strategy" [2] (hereafter referred to as "Future Fusion R&D") determined by the AEC's Advisory Committee on Nuclear Fusion in Oct. 2005 which backed up the decision "Future Fusion Research and Development Strategy in the Third Phase Basic Program of Fusion Research and Development" by the AEC in November, 2005 [3].

Overseas, for example, Europe compiled "Fusion Electricity, A roadmap to the realization of fusion energy" [4] in November, 2012 in order to clarify the way towards realization of fusion energy, to stipulate priority fields on which the resources will be concentrated, and consequently to reorganize the structure of fusion research and development in line with this new strategy. Like this movement, among a major power, DEMO concept plans have been launched with taking into account the progress of the ITER project. The IAEA has established the DEMO program workshop from 2012 in response to these developments [5].

After "Future Fusion R&D" was issued, the necessity to decide a strategic roadmap with clarification of technology which should be secured, maintained, and developed in Japan, to share this roadmap among industry, government, and academia, and to activate a framework for implementation throughout Japan has been noted in the reports "On Japanese Fusion Research and Development Strategy Including ITER Project and Broader Approach" [6] (hereafter referred to as "BA") in 2007 and "On Human Resource Development and Securement for Promotion of Fusion Research and Development" [7] in 2008 by the Working Group on Fusion Research, the Nuclear Science and Technology Committee, the Subdivision on R&D Planning and Evaluation, the Council for Science and Technology, the Ministry of Education, Culture, Sports, Science and Technology (hereafter referred to as "MEXT"), and "Evaluation of the Basic Concepts of Approaches to the Fusion Research and Development, Specified in the Framework for Nuclear Energy Policy, Etc." [8] in 2009 by the AEC's Advisory Committee on Nuclear Fusion.

Then, the report "The Way Forward to Establish a Technological Basis for DEMO Reactor

Development" [9] (hereafter referred to as the "the 6th Term Report"), which was issued in January, 2013 by the Working Group on Fusion Research, has noted that in order to proceed with posed matters establishment of the function to compose strategy for the development of DEMO with integrated viewpoints is important. This function will be the core engine for the establishment of technology bases for the development of DEMO. This report has also pointed out that this function is expected to be formed through discussions by related people in the Fusion Energy Forum, the Japan Society of Plasma Science and Nuclear Fusion Research, and other organizations in how the young generation in industry, government, and academia who will be responsible for the future development of DEMO will play important roles.

Under this comment, the Working Group on Fusion Research has requested, at the 37th meeting on 3 July 2013, the Fusion Research and Development Directorate, the Japan Atomic Energy Agency (hereafter referred to as "JAEA"), and the National Institute for Fusion Science (hereafter referred to as "NIFS"), which are implementing bodies of large projects, to take the leading role 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 for the establishment of technology bases required for development of DEMO defined by the Working Group on Fusion Research are as follows [10]:

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 activities and academic researches such as the Large Helical Device (LHD), and standing on the consensus in the Japanese fusion community.

2. Issues

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

3. Notes

1) To conduct wide cooperation and exchange with researchers and technological experts in industry, government, and academia so as to stand on consensus in the Japanese fusion community. In particular, expansion of cooperation and exchange between scientific societies is encouraged.
2) In order to refer a political deliberation to the Working Group on Fusion Research, a representative of the joint-core team is requested to report on the status of activities routinely.

The Working Group on Fusion Research expects that the joint-core team will lead detailed discussion about the strategy for the establishment of technology bases together with the Fusion

Energy Forum and the Fusion Network, and that prioritized scientific and technological issues are incorporated in international projects such as the BA activities and academic research programs, and that consequently all endeavours are to organize a framework for implementation throughout Japan towards the establishment of technology bases.

In accordance with the request by the Working Group on Fusion Research, the joint-core team, whose members are listed at the end of this report, has been launched and has worked out assigned issues. The joint-core team has reviewed the analyses in "Future Fusion R&D" and other reports to date and has taken into account the most recent scientific and technological achievements and their latest prospects. Investigated strategy for the establishment of technology bases required for DEMO has been reported as an interim report to show summary of issues at the 38th meeting of the Working Group on Fusion Research (24 February 2014) [11] (hereafter referred to as the "Interim Report"). Based upon the "Interim Report", further analysis has been made by the joint-core team by taking account of comments at the Working Group on Fusion Research and 7 explanatory meetings throughout the country, and complied documentation has been reported at the 41st meeting of the Working Group on Fusion Research (24 June 2014). This is the finalized report with revisions to reflect the comments at that meeting.

The Fusion Energy Forum examined DEMO development taking a tokamak as a case study due to the request "Future regime towards realization of fusion energy" [12] (18 October 2007) by MEXT, and submitted "Roadmap and Technological Strategy towards Commercialization of Fusion Energy" [13] and "Investigation Report on Human Resource Plan for Implementation of Development of Tokamak Demonstration Fusion Reactor" [14] in June, 2008. This present report has not shown a detailed timeline of the development plan, such as a roadmap as in "Roadmap and Technological Strategy towards Commercialization of Fusion Energy." However, it indicates critical points, such as the *Transition Conditions* to the DEMO phase (the *Fourth Phase Program*), which are set based upon the status of the ITER project, etc. And the present report has not closely analysed technological issues in the form of the Working Break-down Structure (WBS) yet, though what a critical issue is in each development field, how issues are linked with each other, and what the process to resolve the issue should be analysed deeply. Also since the embodiment of the fundamental concept required for DEMO has been examined in further depth, definition of some issues of development or the targets of development would be different from the WBS defined in "Roadmap and Technological Strategy towards Commercialization of Fusion Energy" in a variety fields, such as the divertor. The joint-core team plans to work out the detailed timeline of the development plan and a roadmap with WBS.

## 2. On the Concept of DEMO Premised for Investigation

The "Future Fusion R&D" documented discussions towards realization of fusion energy in terms of (1) basic approach, (2) development strategy, (3) consideration of development phases, (4) phase changeover, (5) tokamak demonstration fusion reactor, and (6) check and review (hereafter referred as “C&R”), and proposed a concept of DEMO. The joint-core team has examined how a concept of DEMO which will demonstrate power generation via fusion energy for the first time should be based upon documentation in the “Future Fusion R&D”, the progress of other energy-related technology, and the change of the social understanding of energy-resource demands and safety, as well as the progress of fusion research and development, and revised future prospects after the “Future Fusion R&D”.

## 2-1. Change of Energy Situation and Social Requirement

Since 2005 when the AEC issued the “Future Fusion R&D”, there have been 3 major epochs 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, and the collapse of the nuclear safety myth due to the accident at the Tokyo Electric Power Company Fukushima Daiichi Nuclear Power Station.

Although economic recession and shortage of electric power are temporal phenomena and are expected to be recovered, the change in the general public attitude will be maintained for a long time. Japanese people have recognized with pain that we can prioritize reduction of $CO_2$ only under the conditions of a good economy and sufficiently available reserves electric power. Indeed, we must rely on natural gas and oil to compensate for the shortage of electric power due to the suspension of all nuclear power stations even if $CO_2$ emission increases. The imported volume of natural gas has increased by 18.4 million tons (26%) in 2012 compared with that in 2010. Consequently, a social atmosphere that considered global warming a top priority has declined, and propaganda lacking economic rationality such as “25% reduction compared with 1990” has been eclipsed.

The fundamental revision of atomic energy policy and the long-term suspension of all nuclear power stations have reminded 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 renewable energy is fully expected, its limit is being recognized. Therefore, by considering the security of domestic energy seriously, the importance of fusion research and development can be stressed through general public opinion, and that technological innovation is a Japanese resource.

Commercialization of shale gas refers to a recent global change in energy resources. Shale gas is produced now only in the United States and Canada, and this is the only area of demand that can be connected by pipelines and where shale gas depresses gas prices at present. However, its deflationary trend will propagate to LNG, which Japan imports. Thermal power generation by natural gas will then be a more attractive option than at present in terms of the unit price. There will be a possibility that the supply and demand scenario for electric power in the late 21st century in Japan will develop based upon natural gas and coal. Since the thermal power generation by gas, which has good load following capability, is preferable for co-prosperity with wind and solar power, its significant increase may be feasible. The Strategic Energy Plan decided by the Cabinet on 11 April 2014 [15] states that dependence on nuclear power generation is reduced to the extent possible by promoting energy conservation, and introducing renewable energy and improved thermal power stations. These circumstances can be rephrased into 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 the capability and the attractiveness to replace thermal power generation, and the establishment of complementary relations with renewable energy.

It is necessary to analyse seriously the effect of the collapse of the nuclear safety myth and a loss of national trust in science and technology in justifying DEMO directly connected to the realization of fusion energy and to take an appropriate measures. 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 the third order 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.

Relationships between economic growth and $CO_2$ emission are discussed here. There exists a strong correlation between the growth of GDP and $CO_2$ emission, and the reduction of $CO_2$ emission with simultaneous economic growth is impossible by the presently available technology. In case expansion of electric power by nuclear power is difficult, the Japanese reduction target of $CO_2$ in the short and the medium terms should be defined to the low level. However, it is not reasonable to pay attention only to $CO_2$ emission from Japan because the Japanese $CO_2$ emission is about only 4% of the total global amount. It is important to develop technological options to reduce $CO_2$ globally in the very long term. In this line, fusion research and development processes will benefit global society, and the reasons for their necessity are persuasive. Realization of fusion energy should be positioned as an innovative technology to change the correlation between global economic growth and $CO_2$ emission, and should be promoted with careful attention to economic rationality compared with other technologies to reduce $CO_2$ emission.

## 2-2. Fundamental Strategy

The goal in the promotion of research and development of fusion energy is acquisition of both economic and social rationality competitive with other power generation based upon the fundamental condition of scientific and technological feasibility so as to be commercialized. It is also necessary to establish a design that takes advantage of intrinsic properties of high safety and to minimize environmental load throughout the 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 C&R* around 2020 and the *Changeover* toward the *Fourth Phase Program* around 2027, both of which are described in the "Future Fusion R&D".

Industrial, governmental, and academic sectors should cooperate with each other effectively so that this fundamental strategy will be positioned appropriately in the grand policy, such as Strategic Energy Plan, the Science and Technology Basic Plan, and others, by the government.

## 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.

Strategy to gain the support of public opinion about social rationality with regard to acceptance of DEMO in addition to the economy is necessary. The design of DEMO which satisfies social request and acceptance, as well as resolution of issues and technological integration to enable construction of DEMO, is required. This means the necessity of reinforcement of a DEMO design team assembled by compound 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.

Projecting the goal of DEMO, it is necessary to define the technological issues to fulfil the *Transition Conditions* towards the *Fourth Phase Program* first by a tokamak, which exhibits the most advanced development, and to approach defined issues by 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 resolution of technological issues of 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.

In order to promote acceleration and resolution by innovation and to incorporate a comprehensive state of progress of fusion R&D at the *Changeover* to the *Fourth Phase Program*, complementary and alternative concepts, for example, a helical system and laser fusion to a tokamak, and, further, diversified R&D approach of innovative concept to realize breakthrough should be managed in good balance and in a strategically linked manner.

* *Externality* refers to indirect load and cost on environment by energy supply, and is distinguished from directly visible cost (internal cost) such as fuel cost and construction cost, etc. This is also called external cost. In the field of energy supply, it is a social and environmental cost that both supplier and consumer cannot recognize directly. Since the external cost does not affect the price of energy in the case that a specific regime such as $CO_2$ emission tax is not incorporated, market principle does not work in the external cost. Consequently, there is a danger that invisible social loss emerges.

## 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 to achieve economic and social rationality of fusion energy 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 reachable for commercialization, and overall tritium breeding to fulfil self-sufficiency of fuels.

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 milestones at each phase. And 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 (see Fig.1).

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 should be aimed at demonstration of availability enough for commercialization at its final phase.

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 towards commercialization. Although the divertor and the blanket are based upon technology obtained 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 for 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 definition of technological specification of heat and particle flux on the divertor, and neutron and heat flux on the first wall of the blanket.

Security of safety to suppress exposure of the public as well as the workers in a DEMO plant to as low as possible (ALARA) rationally is necessary.

The construction cost of DEMO should be at the 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 1).

The “6th Term Report” stated, “The Working Group on Fusion Research continues to revise the report by deepening discussion about the *Transition Conditions* to the DEMO phase.” In particular, 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 are critical elements directly connected to the assessment at the *Transition Conditions* to the DEMO phase. Therefore, it is necessary to investigate the appropriateness and the timeline of these critical elements by revisiting the original point of these criteria.

Above all, “demonstration of maintenance of plasma with Q≥20 (for duration longer than about several 100 s) and burn control in ITER” (here, Q is the fusion energy gain and defined by the ratio of energy released by fusion reaction to externally applied energy to reactor-core plasma) and “demonstration of non-inductive current drive plasma with Q≥5 (for duration longer than about 1,000 s) in ITER” in the C&R items (planned) of the *Transition Conditions* to the DEMO phase are requested to be discussed in the Working Group on Fusion Research and in other councils. In order to address re-definition of the C&R items, the fusion community should form common recognition so as to provide rational answers to these questions. For the former item, the goal of ITER is defined as Q=10 and a pulse length is linked with not only validation of performance of reactor-core plasma but also demonstration of functions of breeding and collection of tritium, heat removal, and power generation** in ITER-TBM. Since the latter item is planned in the later phase of the ITER project, should these specific *Transition Conditions* be replaced by integration of results from achievements ITER, JT-60SA (Japan Atomic Energy Agency: JAEA) and numerical simulation instead earlier than its full demonstration in ITER?

** Basically ITER-TBM’s are aimed at tritium breeding, and not at power generation. Nonetheless, the Japanese TBM plans to generate power even though it is a limited level since it can generate steam because of the employment of water as coolant.

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 before. The “Future Fusion R&D” stated, “This milestone is presumed around ten years after the establishment of the ITER Organization.” While the examination in this present report endorses that the draft targets at the *Intermediate C&R* described in the “Future Fusion R&D” are appropriate, the time should be presumed to be around 2020, when the first plasma of ITER is expected, since the assessment of achievements of construction and development in the ITER project is crucial at the *Intermediate C&R*. Further embodiment of targets and their assessment should then be prepared.

Full-scale engineering R&D towards construction of DEMO will be launched by the success in the *Changeover* to the *Fourth Phase Program*. On the other hand, in case commercialization of fusion energy in the middle of the 21st century is aimed at, the start of engineering R&D at the proper level in the preparation term before the assessment of the *Transition Conditions* should be promoted for early realization of DEMO.

The significance of the statement “In deciding the *Changeover* to DEMO phase, it is important to gain the prospect for its commercialization and to get the 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" should be explored and embodied in succession.

Table I C&R Items in future fusion R&D (draft)

from "Future Fusion Research and Development" The Atomic Energy Commission's Advisory Committee on Nuclear Fusion, October 2005

| 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 experimental reactor | • Lay out plans for achieving the technological goals of experimental reactor based upon the actual ITER | • Demonstration of maintenance of plasma with Q≥20 (for duration longer than about several 100 s) and burn control in ITER |
| 2. Realization of non-inductive steady-state operation with Q≥5 using experimental reactor | • Lay out plans for achieving the goals based upon the actual ITER | • Demonstration of non-inductive current drive plasma with Q≥5 (for duration longer than about 1,000 s) |
| 3. Establishment of integration technology using experimental reactor | • Complete ITER facilities<br>• Acquire integration technology related to manufacturing, installation, and adjustment of components | • Establishment of integration technology through the operation and maintenance of ITER. Verification of safety technology |
| 4, Establishment of high-beta steady-state operation method to obtain economical prospects | • Conduct ITER support research and preparatory research for high-beta steady-state plasma and launch research using National Centralized Tokamak | • 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 reactor | • Complete establishing technological basis for power generation blanket. Complete manufacturing test components to be used in the functional test of ITER<br>• Acquire reactor irradiation data of reduced activation ferritic steels up to 80dpa and determine test materials to be used in the irradiation test under neutron | • Demonstration of tritium breeding and recovery functions, removal of heat and power generating blanket in a low-fluence DT experiment on ITER<br>• Completion of verification of heavy irradiation data of reduced activation ferritic steels up to a level of 80 dpa |

| | | |
|---|---|---|
| | irradiation environment similar to that of fusion reactor | |
| 6. Conceptual design of DEMO | • Determine the overall goal of DEMO<br>• Conduct preliminary work on the conceptual design of DEMO<br>• Make requests for the required development of fusion plasma research and fusion technology | • Completion of conceptual design of DEMO consistent with the development of fusion plasma research and fusion technology |

## 3. Technological Issues of Elements of DEMO

In accordance with the "6th Term Report", technological issues of elements of 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

Then, each element has been analysed in order to clarify the procedure to demonstrate the technological feasibility of DEMO, which is the most fundamental base, and to develop the roadmap with the timeline and implementing bodies.

Analysis has been done in line with the following procedure and remarks based upon "②Issues" and "③ Measure and Managing System Required for Resolution" documented in the "6th Term Report".

1) To reconfirm the documentation pointed out in the "6th Term Report".
2) To analyse 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 C&R* and the

assessment of the *Transition Conditions* presumed around 2020 and 2027, respectively.

3) To define the packaged measure consisting of "Concern" which prevents development/evolution, in other words, necessary conditions to move forward, "Defined Issue" in order to resolve concern, and "Implementing body/Platform" which is charged with Defined Issue.
4) This packaged measure consisting of 3 elements can be understood as a project. To sort out the linkage between these packages and to align these packages with each other logically.
5) 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.
6) To pursue the main stream in order to ensure sufficient feasibility and to contrast the side stream which plays a complementary role and is expected to innovate breakthroughs.
7) To show interaction between the projects described by the package and interface with other elements and the DEMO design.
8) To show implementing bodies/platforms corresponding to defined issues in a table. Those which play a major essential role, those which play an important role, and those which can make a limited contribution are described by ◎, ○, and △, respectively. These tables indicate what can be dealt with by the presently ongoing projects and existing implementing bodies/platforms or their expansion/reinforcement, as well as what are not yet dealt with because of lack of corresponding projects and implementing bodies. The ITER project and the BA activities are the core in the presently ongoing projects. JT-60SA, which is a part of the BA activities, is described separately.
9) In the figures and the tables, the Japan Atomic Energy Agency, the National Institute for Fusion Science, and the National Institute for Materials Science are abbreviated as JAEA, NIFS, and NIMS, respectively.

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) Technological issues, and measures and the management systems required for resolution, which have been indicated in the "6th Term Report," are summarized as follows below.

1-1) Issues

(a) Improvement of strength of structural material. High 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) $Nb_3Sn$: 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) $Nb_3Al$: 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 of used amount of silver. 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 joint 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.

1-2) Measures and Management Systems Required for Resolution

(a) Towards accomplishment of the targeted performance, implement selection of materials from variety of candidates efficiently in a framework including universities, industries, and other contributors throughout Japan.

(b) Vigorously promote improvement of the mechanical property of the $Nb_3Sn$ conductor and development of high performance $Nb_3Al$ conductor in parallel and in a competitive manner. Develop the high temperature superconductor in a long-term strategy. Review technologies developed for ITER construction in terms of their application to DEMO. And compose a concrete R&D plan in the areas where further evolution and/or innovation are necessary with a consideration for human resource development and implement this steadily.

(c) Quickly implement a development plan to improve $J_c$ of the $Nb_3Sn$ conductor at higher magnetic field into concrete shape and promote the planned action under appropriate role sharing among universities, national institutes and industries while also utilizing international cooperation

(d) With regard to rapid heating and quenching of the $Nb_3Al$ conductor, develop a large current conductor and demonstrate its applicability to DEMO through the R&D coil test under collaboration between JAEA and the National Institute for Material Science (NIMS). Based upon the demonstration, the development plan to enable industrial production capability in industries is required.

(e) R&D on ReBCO is in progress for its application to high field magnets and power equipment such as a motor. Since a large current conductor, however, is specific for magnetic fusion application, the strategy of development and the concrete plan should be identified in the context of DEMO R&D.

(f) Maintain and upgrade existing conductor test facilities at JAEA and NIFS, and establish the scheme for conductor tests.

(g) Mature theoretical and numerical simulation methodology in order to document microscopic electromagnetic phenomena in a superconductor and its macroscopic properties. Establish a framework to enhance mutual exchange of information or personnel between and among other fields, and between and among government, academia, and industry.

2) Analysis of Issues

2-1) Sorting-out Issues

Unfolding issue (b) in 1-1), it has common elements in issues (a), (c), (d) and (e). Issues (f) and (g) are concerned with the infrastructure to tackle issues (c), (d) and (e). On the other hand, outcomes from the DEMO study in BA imply that some requirements for superconducting coils, maximum magnetic field of 16T at TFC, for example, which have been premises of those issues might be modified through design harmonization across the entire system. Also manufacturing with a tolerance of 1/10000 required for the TFC of ITER might be a limit of accuracy in manufacturing a large component from industry’s point of view.

Taking account of the argument above, the structure of the issues in Superconducting Coils is arranged in Fig. 2. Sectors in charge and necessary facilities, which are described in Fig. 2, are summarized in Table 2.

2-2) Extraction of Core 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.

Based upon the structure of the issues, which is shown in Fig. 2, the prioritized core issues addressed in Superconducting Coils are summarized as follows below.

**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 $Nb_3Sn$ 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 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 $Nb_3Sn$ 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 $Nb_3Sn$ is a current prime candidate for the superconducting material. $Nb_3Al$ 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 $Nb_3Sn$ not only for adoption to DEMO but also for the prospect of further performance improvement that is favourable 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 shown in Fig. 2 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) Technological issues, and measures and the management systems required for resolution, which have been indicated in the "6th Term Report", are summarized as follows below.

1-1) 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.

1-2) Measures and Management Systems Required for Resolution

(a) <Measure> Compile reference data of both structural and functional materials (including loading, irradiation, and corrosion effects, etc.) required for development of standards/criteria and safety guidelines.

<Managing System> Develop the DEMO engineering database through integrated evaluation of neutronic, thermo-structural, and tritium properties of in-vessel components by using an intensive fusion neutron source.

(b) <Measure> Carry out steadily design and manufacturing of ITER-TBM based upon a water-cooled solid-breeder concept and confirm the fulfilment of the performance specifications by the performance evaluation test required for the licensing safety review of ITER. And also demonstrate compatibility with high magnetic field environment and soundness of response to changing load and environment.

<Managing System> From the initial stage of development, close collaboration among universities, research institutes, and industries is indispensable to develop a world standard. Demonstration test under high-dose irradiation environment is required to assess neutron irradiation effects.

(c) <Measure> Through the development of cooling, tritium measurement, and recovery systems for ITER-TBM, demonstrate feasibility of overall tritium self-efficiency of DEMO under sustainable operational conditions and prevention of tritium permeation and release to the environment required for environmental safety and security of the amount of tritium in DEMO. Also aim at demonstration of electric power generation even if its scale might be small.

(d) <Measure> With regard to the concept of remote handling maintenance, develop the system to be able to cope with trouble and accidents and verify the concept of safety security in full maintenance. Establish a blanket system to be able to secure safety and manage incidents. By carrying out receiving of TBM irradiated in ITER, post-irradiation experiment and storage, complete a database of the TBM program and verify the totalized handling technology of radio isotopes through advancement of disassembling and treating technology of large-scale activated components for DEMO. With regard to establishment of codes and standards, seek rational codes and standards taking into account intrinsic safety features of DEMO.

(e) <Measure> With regard to liquid breeder blanket concepts, the database construction, operational demonstration, and experimental and analytical investigation of accidental events should be promoted for specific issues related to a high magnetic field, separate recovery of tritium and heat, composition and impurity control, control of solid-liquid interface, etc., by using separate and/or integral coolant circulation systems. Development of operation systems to derive advantages of liquid blanket systems is important. With regard to solid breeder blanket systems (He cooled), future investigation is required by involving progress in structural material development and R&D in other countries.

2) Analysis of Issues

2-1) Sorting-out Issues

○ Difficulty to sort out issues related to the blanket is attributed to the fact that the target of DEMO has not been fully decided upon while the specification required for the blanket is directly linked with the performance specification of DEMO.

○ Since necessary elemental technologies related to blanket development are already clear, definition of quantified targets and confirmation of those consistencies are important to materialize and to accelerate activities.

○ With regard to a water-cooled solid-breeder concept, it is necessary to carry out steadily design and manufacturing of ITER-TBM. Early realization of integrated functional test facilities (heat load, irradiation, and tritium behaviour) and demonstration test of performance using the facilities are required.

○ With regard to advanced concepts, the development schedule should be arranged while maintaining consistency with the development of the solid-breeder concept.

Taking account of the arguments above, the structure of the issues in Blanket is arranged in Fig. 3. Sectors in charge and necessary facilities, which are described in Fig. 3, are summarized in Table 3.

2-2) Extraction of Core 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 arranged.

Based upon the structure of the issues, which is shown in Fig. 3, the prioritized core issues addressed in Blanket are summarized as follows below.

**What are necessary tasks is 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 technological bases of blanket system including design and manufacturing technology of blanket, tritium handling and neutron measurement, etc.

③ Fabrication of 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 analyse 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, removal of heat and power generation (see Points of note below) 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) Technological issues, and measures and the management systems required for resolution, which have been indicated in the "6th Term Report," are summarized as follows below.

1-1) 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, particle 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 which are compatible with the soundness, and the maintainability of the divertor components

1-2) Measures and Management Systems Required for Resolution

(a) Ensure the extrapolation reliability of the detachment plasma based upon the demonstration of the detachment discharges in large-scale experiments and validation of the convincing theoretical model by the experimental results.

(b) Build a framework and develop a research environment to acquire comprehensive knowledge of the plasma-wall interactions including tritium in terms of materials, surfaces, boundary plasmas, diagnostics, and neutron irradiation effects

(c) Select the cooling method based upon assessment of economy, safety of the entire the DEMO reactor system and the divertor heat load. If it is necessary to choose a cooling method other than water-cooling, construct a framework of the basic and technological research and development as early as practicable

(d) Develop the integrated simulation code which can cover from the core plasma to the divertor components

2) Analysis of Issues

2-1) Sorting-out Issues

○ With regard to the concern with the divertor heat-load, this cannot be solved in a simple way because there are major gaps between required conditions and present technologies. It is necessary to determine the acceptable compromises by optimizing both reduction of the heat-flux to the divertor and improvement of the heat removal property of the divertor. Furthermore, degradation of material property is unavoidable due to the neutron irradiation of the reactor condition. In particular, the lifetime of material has a great impact on the policy of maintenance of the facility.

○ Plasma facing components are a complex of the plasma facing materials and heat transfer materials. It is important to select adequate materials based upon the overall performances of heat removal and the lifetime of the complex, in addition to merits and demerits of the individual material properties.

○ Detachment discharge is indispensable for the mitigation of the divertor heat load, and it is necessary to introduce impurity gas for the realization. Since reduction of the divertor particle flux is expected as a consequence of detachment, there is concern that the impurity gas introduction will be an obstacle to the burning due to impurity influx to the core plasma and reduction of the pumping efficiency. Divertor configuration and components is required to enable a balance among the impurity behavior, particle pumping property, and the operating scenario in order to mitigate divertor heat flux by means of detachment discharge.

Taking into account the argument above, the structure of the issues in Divertor is arranged in Fig. 4. Sectors in charge and necessary facilities, which are described in Fig. 4, are summarized in Table 4.

2-2) Extraction of the Core 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.

Based upon the structure of the issues, which is shown in Fig. 4, the prioritized core issues addressed in the Divertor are summarized as follows below.

**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 a 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) Technological issues, and measures and the management systems required for resolution, which have been indicated in the "6th Term Report," are summarized as follows below.

1-1) 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.

1-2) Measures and Management Systems Required for Resolution

(a) Construct a core test facility as a domestic joint project (by completion of ITER construction).

(b) NBI: Urgently initiate development of photo-neutralizer which requires innovative technology.

(c) ECH: Keep continuous development by utilizing existing facilities.

(d) Neutron irradiation resistance: Validate in ITER and promote neutron irradiation materials examination, etc.

2) Analysis of Issues

2-1) Sorting-out Issues

○ NBI and ECH which are expected to be a main heating and current drive system in DEMO should be examined. Major technological development of both NBI and ECH is an extension of ITER technologies. Therefore, steady technological development in ITER is crucially important.

○ With regard to NBI, the new technology required for DEMO includes development of a Cs-free ion source (development of electrode material with low work function), high efficiency neutralizer (high-efficiency plasma neutralizer or laser neutralizer), and neutron irradiation resistance (deflection and focusing technologies for MeV-class beam). In addition, accumulation of the operating experience in ITER is crucially important. In particular, issues of irradiation effect on beam acceleration should be sorted out and reflected in design.

○ With regard to ECH, the newly required technology for adapting DEMO includes increase of frequency, development of fast variable frequency to dispense with a steerable mirror, improvement of multiple-stage energy recovery technology, and development of a mirror-less waveguide-injector-type launcher system for minimizing the occupied volume of in-vessel components. In addition, accumulation of the operating experience in ITER is crucially important, and development of fast dual frequency technology should be steadily advanced in JT-60SA.

○ The significance of Lower Hybrid (LH) and Ion Cyclotron Resonance (IC) in terms of the R&D for DEMO should be clarified because of their major issues for adapting DEMO on the heat load on launcher and antenna, and the plasma-coupling characteristics.

Taking account of the argument above, the structure of the issues in Heating and Current Drive System is arranged in Fig. 5. Sectors in charge and necessary facilities, which are described in Fig. 5, are summarized in Table 5.

2-2) Extraction of Core 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.

Based upon the structure of the issues, which is shown in Fig. 5, the prioritized core issues addressed in Heating and Current Drive System are summarized as follows.

**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 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 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) Technological issues, and measures and the management systems required for resolution, which have been indicated in the "6th Term Report," are summarized as follows below.

1-1) 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.

1-2) Measures and Management Systems Required for Resolution

(a) Close coupling is necessary between experimental researches, and large scale simulation and integrated modelling researches for understanding of physical mechanisms for transport barrier, density limit, beta limit, etc. It is necessary to consider promotion of international collaboration through frameworks such as international tokamak physics activity (ITPA) and task force like study which concentrates resources on important issues.

(b) It is necessary to make efforts for realizing linkage among Japanese fusion plasma modelling codes based upon the establishment of integrated code infrastructures compatible with the ITER standard and to verify their physics models based upon comparison with existing experimental data and large scale simulation data. Furthermore, it is necessary to enhance their international competitiveness by developing advanced original components. For this purpose, it is necessary to promote systematic code development based upon formation of standing research groups for each core component of an integrated fusion plasma simulation code such as equilibrium, transport, stability, heating, edge plasma, etc.

(c) Fusion plasma simulations including not only the steady state condition but also the time dependent condition enable activities for the DEMO design which has reality and includes optimization of an operation scenario. Therefore, close cooperation between an integrated fusion plasma simulation group and the DEMO design code group is necessary.

(d) It is necessary to develop an integrated blanket code by linkages of individual fusion reactor engineering codes for each component and develop an integrated fusion reactor engineering code continuously including a reactor material simulation code focusing on fusion reactor materials.

(e) It is expected that researches for an integrated fusion plasma simulation code, an integrated fusion reactor engineering code, and the DEMO design code will be integrated in the research for development of an integrated fusion reactor system simulator.

(f) It is important to effectively use large scale computer resources based upon promotion of collaborative research supported by a large number of researchers. It is necessary to build the DEMO simulation centre. Furthermore, it is important to maintain a certain level of research activities in universities which will educate future generations.

2) Analysis of Issues

2-1) Sorting-out Issues

○ Definition of integrated code 1: the simulation code which can treat systematically from core plasma through edge plasma and scrape-off layer plasma to divertor plasma.

① Multi scales (time : 10ps – 1000s, spatial : 10μm – 10 m).

② Various physics processes (MHD, microinstability, macroinstablity, high energy particle, atomic and molecular process, plasma material interaction, etc.).

③ Various phenomena (equilibrium, transport, current drive, heating, radiation, detachment etc.).

④ From steady state to temporal evolution.

○ Definition of integrated code 2: wide range use from understanding of physical mechanisms, to reactor design, and to operational control simulator.

① From multi-days large scale simulation to real time simulator.

② Simulation based upon basic physics model, modelling, and empirical scaling.

③ Output which enables easy comparison with experimental data.

④ Interface with engineering codes such as molecular dynamics simulations in materials, thermal analyses, electromagnetic force analyses, stress analyses, and neutronics analysis.

○ The comparison between simulation results of each component code and experimental results is limited case by case, and reproduction of the experimental results by the simulation code remains insufficient. In particular, treatment of vertical displacement event (VDE), halo current and runaway electrons during disruption is insufficient. For the divertor simulation, it is necessary to clarify phenomena which can be reproduced by a fluid code and only by a particle code, and to accelerate simulation speed by development of modelling of the divertor plasma phenomena.

○ It is necessary to promote research as an organized project, to clarify sharing of roles and allocation of responsibilities, and to define concrete milestones which are consistent with the roadmap towards DEMO.

○ Extension to a plant simulation code by combination with engineering codes.

○ Securing resources: securing personnel resources and human training (especially personnel resources for comparison with experimental results and code integration), computer resources.

Taking account of the argument above, the structure of the issues in Theory and Numerical Simulation Research is arranged as shown in Fig. 6 (in particular, code development towards design and operational control for DEMO). Sectors in charge and necessary facilities, which are described in Fig. 6, are summarized in Table 6.

2-2) Extraction of Core 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: one is improvement of accuracy for each component code, and the other is systematic code management.

Based upon the structure of the issues, which is shown in Fig. 6, the prioritized core issues addressed in Theory and Numerical Simulation Research are summarized as follows below.

**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 machines.

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 Inter*mediate 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) Technological issues, and measures and the management systems required for resolution, which have been indicated in the "6th Term Report," are summarized as follows.

1-1) 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 academic systematization of toroidal plasmas.

(c) Implement many of 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 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 their long-period or resident stay. Secure human resources steadily from a long-range perspective.

2) Analysis of Issues

2-1) Sorting-out Issues

○ Demonstrate steady-state operation

○ On ensuring divertor soundness, establish a divertor plasma control scenario enabling maintenance of detachment, high radiation loss by impurity injection and suppression of edge localized mode (ELM), in addition to assessment of the heat load corresponding to fusion output and the cooling capability from divertor configuration.

○ Mitigate influence of reactor plasma properties attributed to high beta (high heat flux, high neutron flux, and frequency of disruption) under the DEMO environment, where there are engineering constraints of cooling performance of in-vessel components and materials and control coils cannot be installed inside the vacuum vessel

○ With regard to avoidance and mitigation of disruption, prediction of the occurrence by real time assessment code based upon diagnostics is a critical issue and assessment of the margin of operating limits is important.

○ With regard to establishment of control technique and logic, develop the database of physics parameters to be controlled and their response characteristics and establish an operation scenario based upon the database.

○ It is important to demonstrate the burning control technique in ITER, the integrated reactor plasma performance required for DEMO in JT-60SA, and their extrapolation to DEMO based upon theoretical modeling.

Taking into account the argument above, the structure of the issues in Reactor Plasma Research is arranged in Fig. 7. Sectors in charge and necessary facilities, which are described in Fig. 7, are summarized in Table 7.

2-2) Extraction of Core 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 devices and by optimizing the use of the achievements in ITER towards DEMO. In particular, it is important to get the prospect for ensuring 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.

Based upon the structure of the issues, which is shown in Fig. 7, the prioritized core issues addressed in Reactor Plasma Research are summarized as follows below.

**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 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 to threaten 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 the system from now which enables human resource development and participation of researchers from universities and others for their long 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) Technological issues, and measures and the management systems required for resolution, which have been indicated in the “6th Term Report,” are summarized as follows below.

1-1) 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.

1-2) Measures and Management Systems Required for Resolution

(a) A new large-scale facility is necessary for development of the tritium technology. It is possible to set equipment for development of material accountancy technology in the test facility under the DT environment for the blanket and the divertor. It is necessary to examine the production process for initial loading of tritium.

(b) With regard to the technology of waste handling, the technology obtained in ITER is not sufficient. Therefore, it is necessary to establish an implementation framework for development of large-scale technology and verification of operation.

(c) With regard to the technology of tritium collection and the recovery system, it is necessary to develop the technology, including material accountancy, with high resolution through the experiments of ITER and JT-60SA, etc.

(d) It is necessary to select the production process for securing lithium 6 and to start promptly the research and development for scale-up. It is important to formulate a plan so that an isotope separation process is incorporated into the strategy of securing large amounts of lithium resource for batteries.

2) Analysis of Issues

2-1) Sorting-out Issues

○ Research and development towards ITER

① Research and development of individual processes necessary for the tritium fuel cycle in a fusion reactor (such as isotope separation and impurity removal).

② Compilation of data for material-tritium interactions.

③ Accumulation of experiences for safe tritium handing (from operation in world-wide tritium facilities including material accountancy and the detritiation process)

○ Research and development in ITER

① Operation and demonstration of tritium fuel cycle system as an integrated system.

② Accumulation of experiences for safety tritium handing as a fusion reactor.

③ Demonstration of the detritiation system (wet scrubber technology) which is adopted for the first time in ITER.

④ Demonstration of tritium collection and recovery in blanket and water handling.

○ Research and development other than ITER

① Examination of a large-scale facility (including human training)

② Development of equipment treating gases and water, in which tritium is contained: vacuum pump (ex. membrane pump), turbine, etc.

③ Securing initial loading of tritium: examination of the production process (collection from a heavy water nuclear reactor and/or reprocessing facilities), import from abroad on a massive scale (exs. Canada and South Korea), start-up scenario without initial loading (consistency of necessity of neutral beam heating with a heating scenario).

④ Examination of technology for securing lithium 6 and development of its plant.

○ With regard to the research and development towards ITER, it is important to promote research and development effectively for the above items using domestic facilities such as the Tritium Process Laboratory (TPL) in the JAEA Tokai site, the DEMO R&D building constructed in BA activities in the JAEA Rokkasho site, and the hydrogen isotope research centre at the University of Toyama. With regard to the research and development towards DEMO, in addition to demonstration and accumulation of the technology in ITER, demonstration and accumulation of the technology in a large scale facility and human training in this facility are important.

Taking account of the argument above, the structure of the issues in Fuel System is arranged in Fig. 8. Sectors in charge and necessary facilities, which are described in Fig. 8, are summarized in Table 8.

2-2) Extraction of Core 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.

Based on the structure of the issues, which is shown in Fig. 8, the prioritized core issues addressed in the Fuel System are summarized as follows below.

**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 Inter*mediate 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 time.

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) Technological issues, and measures and the management systems required for resolution, which have been indicated in the “6th Term Report,” are summarized as follows below.

1-1) Issues
(a) Towards establishment of codes and standards for a 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.

1-2) Measures and Management Systems Required for Resolution
(a) <Measure> Establish the basic policy for ensuring the safety of the fusion reactor and structural design codes and standards. And also clarify design requirements for the structural materials.
<Management system> Grapple with the related BA activities in a framework for implementation throughout Japan. Take into account feasible cooperation with the Japan Society of Mechanical Engineers (JSME) and the American Society of Mechanical Engineers (ASME).
(b) <Measure ①> Define the design activities based upon expected irradiation data before the engineering design activities of DEMO.

<Management system ①> Based upon the irradiation data obtained from the fission reactors, spallation neutron sources and other facilities, the reduced-activation ferritic steel is expected to be utilized in a range up to the critical condition that will emerge from fusion neutron-specific irradiation effects. These activities are being promoted in the BA activities as irradiation simulation experiments and modelling studies, as well as in the broad contributions of basic research performed in universities.

<Measure ②> This strategy requires large amounts of neutron irradiation data.

<Management system ②> In addition to further enhancement of current irradiation studies through international cooperation, the development of domestic high-dose irradiation research using fission research reactors in Japan is highly expected.

< Measure ③> Early realization of IFMIF is particularly desirable in terms of the compilation of real environment irradiation data for the engineering design. It should also be noted that demonstration of the critical condition of fusion neutron-specific degradations by the initial operation of IFMIF is important.

<Management system ③> Development of IFMIF is being currently performed mainly by Japan and Europe under the EVEDA (Engineering Verification and Engineering Design Activity) in the framework of the BA. In order to initiate construction of IFMIF and the related activities, it is necessary to clarify the role of promoting the international body and to strengthen the preparatory activities. Although international organization has been established in the International Energy Agency (IEA) as the existing framework, its activities outside Japan and Europe are inactive. Enhancement of international cooperation is necessary.

<Measure ④> Even in the pre-conceptual design phase, if early acquisition of irradiation data close to the fusion environment is demanded for ensuring safety and design requirements, the availability of an irradiation facility preceding IFMIF is an urgent issue. Development of a neutron irradiation facility by extending the accelerator constructed in BA activities is thought to be the nearest term option.

<Management system ④> In order to realize this kind of facility, it is urgently required to launch the framework for implementation throughout Japan.

(c) <Measure> In order to utilize the currently compiled neutron irradiation data and future IFMIF irradiation data as the design data of DEMO, the establishment of standards for SSTTs is required. Development of the guidelines for SSTTs standards must be decided quickly.

<Management system> Establishment of the organization and the management system for the standardization of materials testing is urgently required. Activities in academic societies should be initiated immediately so to begin the deliberation of standards. In addition, it is necessary to further promote international cooperation programs.

(d) <Measure> It is expected that declaration of a national policy of energy resource development in its early stage will encourage the active participation of industry. Also, in terms of human resource development, efforts to increase the willingness of young researchers to engage in fusion research, in particular, in the field of fusion materials development, are expected.

2) Analysis of Issues

2-1) Sorting-out Issues

- ○ Towards establishment of codes and standards, it is necessary to characterize material properties and to understand degradation mechanisms. Establishment of basic policies of safety and corresponding structural design criteria are required.
- ○ Material standards that take into account the fusion neutron irradiation effect are necessary. It is necessary to clarify the methodology of testing standards for the utilization of irradiation data obtained by small specimens in past experiments and in future tests in IFMIF. And consideration of alternative and compound approaches that do not relying solely upon the early realization of the IFMIF for clarifying of radiation effects of fusion neutrons and their implementations is demanded.
- ○ Development of human resources with a point of complex views and continued long-term cooperation with industries is necessary

Taking into account the argument above, the structure of the issues in Material Development and Establishment of Related Codes and Standards (in particular, for the blanket structural material) is arranged in Fig. 9. Sectors in charge and necessary facilities, which are described in Fig.9, are summarized in Table 9.

2-2) Extraction of Core 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.

Based upon the structure of the issues, which is shown in Fig.9, the prioritized core issues addressed in Material Development and Establishment of Related Codes and Standards, in particular the reduced-activation ferritic steel are as follows below.

**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) Technological issues, and measures and the management systems required for resolution, which have been indicated in the “6th Term Report,” are summarized as follows.

1-1) 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 behaviour 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 behaviour and appropriate measures.

1-2) Measures and Management Systems Required for Resolution

(a) <Measure> Clarify the accident sequence, which is important in DEMO, develop safety design measures to prevent and/or mitigate effects of the accident and establish the safety guidelines. Compile material data by future experiments sufficient to predict chemical energy in the blanket. With regard to tritium inventory, mature data so as to manage tritium in the vacuum vessel, the surface and the inside of blankets appropriately. Develop the safety requirement standard to meet the natural feature and social circumstances in Japan and the corresponding guideline of the safety design of DEMO.

<Managing System> Long term strategy to keep human resources is necessary while taking account of the situation that researchers in the safety field are lacking worldwide.

(b) <Measure> Build and establish social understandings of radiation based upon steady sharing of substantial support to the assessment research on environmental effects of radiation. Accumulate operating experience in the tritium handling facility in the BA activities and other fusion facilities, and build relationships of mutual trust with the local societies so as to lay the social groundwork to accept fusion energy.

<Managing System> With regard to the issue of environmental safety, cooperation with researchers in wide fields including fission, radio-biology environmental, etc., is indispensable. With regard to the fact that tritium can be detected in the environment even under normal operation, and its effects, establishment of a research framework to gain social understanding and long-term accumulation of research achievement is important.

(c) <Managing System> It is necessary to create a favourable environment for a long-term nurturing of human resources to solve the serious organizational problem that researchers supporting the base of the environmental safety field (e.g.: environmental behaviour of tritium) are not supported by the fusion field. Training of young engineers and/or researchers who will collect and retrieve the experience of tritium handling in ITER is also necessary. Since the safety research is inseparably related to the conceptual design activity of DEMO, it is critically important to organize a framework of implementation throughout Japan which works as a core of the DEMO design.

2) Analysis of Issues

2-1) Sorting-out Issues

○ Data related to examination of safety (material properties, chemical reaction) is not sufficient. The reason preventing earnest development is that the material for the DEMO blanket has not been selected.

○ It is a serious common issue that researchers in charge of examination of a plant, including safety assessment, in particular, and researchers in charge of environmental behaviour and effects of tritium are few.

○ After the invitation activity of ITER, development of both computer simulation codes for safety analysis and verification and validation test facilities remains stagnant.

Taking account into account the argument above, the structure of the issues in Safety of DEMO and Safety Research is arranged in Fig. 10. Sectors in charge and necessary facilities, which ae described in Fig. 10, are summarized in Table 10.

2-2) Extraction of Core 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.

Based upon the structure of issues, which is shown in Fig. 10, the prioritized core issues addressed in Safety of DEMO and Safety Research are summarized as follows below.

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

① It is necessary to review plans and 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 study 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) Technological issues, and measures and the management systems required for resolution, which have been indicated in the “6th Term Report”, are summarized as follows below.

1-1) Issues

(a) Understanding on 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.

1-2) Measures and Management Systems Required for Resolution

(a) Establish RAMI as an evaluation formula of DEMO system to obtain perspectives on availability and economy. Build database on failure rates of equipment and devices utilizing ITER and other international cooperation.

(b) It takes significant time to understand erosion of plasma facing materials which is the most critical factor to determine the lifetime. Grapple with this issue based upon sustaining efforts with long-term perspective.

(c) Initiate development and tests on remote handling techniques, radiation resistant equipment and lifetime evaluation of in-vessel components aiming for DEMO after the BA activities. Ensure long-term availability of a high-dose rate gamma-ray irradiation facility and carry out radiation hardness tests. Apply experiences in ITER to handling of large-scale components, hot cells, decontamination, repair of in-vessel components, inspection, waste disposal, etc. Construct a framework in which industry can join as one of the major players for investigation and determination of feasibility of a maintenance concept and manufacturing.

2) Analysis of Issues

2-1) Sorting-out Issues

○ Construction of a comprehensive maintenance concept including a maintenance method, reactor structure, reactor building and hot cell, and making a proposal of availability (with higher priority).

○ Lifetime prediction for in-vessel plasma facing components, especially for divertors, is difficult (with higher priority).

○ Development of criteria of demonstration in a DEMO and the corresponding R&D plan based upon a scheduled maintenance scenario and the method which can achieve availability with prospects for economy.

○ Investigate risk factors for unscheduled shutdowns of a system and study inspection, mitigation, redundancy, and measures to deal with them.

○ Promote R&D on remote handling techniques for replacement of packaged large-scale components, transport, etc., required newly in a DEMO.

○ Promote R&D on functional materials, devices and equipment with higher radiation resistant performances. (Development during ITER-EDA aiming at 100 MGy. The target for a DEMO is >200 MGy.)

Taking into account the argument above, the structure of the issues in Availability and Maintainability is arranged in Fig. 11. Sectors in charge and necessary facilities, which are described in Fig. 11, are summarized in Table 11.

2-2) Extraction of Core 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 it will determine the periodic maintenance cycle, prediction of the lifetime of divertors is required to obtain prospect of economy.

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.

Based upon the structure of issues, which is shown in Fig. 11, the prioritized core issues addressed in Availability and Maintainability are summarized as follows

**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 make 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 make 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) Some issues regarding diagnostics and the control system have been pointed out in the "6th Term Report", though a specific chapter was not allocated. The issue of the development of diagnostics and the control system is recognized as one to be discussed specifically, and technological issues, measures and the management systems were analyzed because this issue is essential for the technological development of diagnostics and actuators, and for the development of the concept of integrated operating scenario of DEMO. Technological issues, and measures and the managing systems required for resolution, which have been documented in the "6th Term Report" are summarized as follows below.

1-1) Issues

(a) Development of the integrated and consistent plasma scenario including heat load control, helium exhaust capability, and core and edge plasmas (Sec. 3.2.3 Divertor in the "6th Term Report").

(b) Development of an operating scenario for edge plasma consistent with erosion, embrittlement and maintenance of divertor components (Sec. 3.2.3 Divertor in the "6th Term Report").

(c) Development of the integrated reactor system simulator for the design of diagnostics and the control system for DEMO (Sec. 3.2.5 Theory and Numerical Simulation Research in the "6th Term Report").

(d) Establishment of practical and reliable control techniques and control logic (Sec. 3.2.6 Reactor Plasma Research in the "6th Term Report").

1-2) Measures and Management Systems Required for Resolution

(a) Large-scale simulation experiment by utilizing magnetic confined devices is indispensable. Ensure extrapolating capability of edge plasma in DEMO based upon the experimental research on LHD, JT-60SA, and ITER, and modeling of laboratory plasmas (Sec. 3.2.3 Divertor in the “6th Term Report”).

(b) Develop integrated codes covering from core plasma to divertor components (Sec. 3.2.3 Divertor in the “6th Term Report”).

(c) It is expected that reactor plasma integrated codes, reactor engineering integrated codes, and reactor design codes will be assembled into the reactor system integrated simulator (Sec. 3.2.5 Theory and Numerical Simulation Research in the “6th Term Report”).

(d) Organize a systematic activity by combining experiments on ITER and JT-60SA, and theoretical modeling.

2) Analysis of Issues

2-1) Sorting-out Issues

○ Need to define operational standard point allowable for operating ranges derived from operating margin against the limit and allowable fluctuation to connect to transmission grid. This enables development of the operational control logic and simulator and focusing controlled variables and actuators.

○ Validation of the plasma modeling is necessary for development of an operational control simulator. The accumulation of plasma response property data is important by utilizing ITER, JT-60SA, and LHD, and enhancement of collaboration with ITPA is also important. Examination of the response property of variables to the actuator should be reflected to the technological specification of diagnostics.

○ Lifetime and installation position of diagnostics are restricted by high irradiation field in DEMO. In particular, influence of degradation in the precision of magnetic field measurements due to eddy currents in structures on the control of plasma position and shaping is the issue of concern. Therefore, approaches to resolve the issue, for example, the magnetics are placed far from plasma or close to structural material in JT-60SA.

○ Development of diagnostics equipment which is indispensable for operational control of DEMO and can be used under the DEMO environment (high irradiation field). Therefore, development of advanced diagnostics towards DEMO in JT-60SA and LHD together with accumulation of operating experience in ITER and summarizing of issues is necessary. Moreover, it is important to improve reliability at high irradiation field by heavy irradiation testing of components constituting diagnostics and actuators.

Taking into account the argument above, the structure of the issues in Diagnostics and Control System is arranged in Fig. 12. Sectors in charge and necessary facilities, which are described in Fig. 12, are summarized in Table 12.

2-2) Extraction of Core Issue

It is important to focus clusters of essential and applicable diagnostics based upon performance and operating results of diagnostics developed and prepared in 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..

Based upon the structure of the issues, which is shown in Fig. 12, the prioritized core issues addressed in Diagnostics and Control System are summarized as follows below.

**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 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 analyse 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 fulfils 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. 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 fulfils social requests. Here DEMO is on only one-step from ITER to commercialization, which is prospected in the middle of the 21st century.

Development of DEMO is arranged so as to bring together all related technology from a position of integration. Therefore, the DEMO design activity in wide definition is requested to manage the overall development plan by definition of the target of each technology and assessment of technological maturity, and to pronounce newly required technological developments.

In order to show the economic feasibility of fusion energy by DEMO, DEMO is requested to pursue superior performance for high-efficiency energy production by improvement of components in addition to accumulation of operating experience (guarantee of availability reachable to commercialization, reduction of unplanned downtime ratio, etc.) in order to prove reliability as an energy production system. 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 be conducted from a position of integration covering all features from technological feasibility to social acceptance. Therefore, it is necessary to collect the wisdom of knowledgeable people in each field in order to cope with a wide range of problems as well as to gather together related experts specific to DEMO technology. The system to promote personal exchange is required in order to set up the activity organization endowed with compound talents.

The DEMO design should secure design rationality involving material, productivity, workability, assembly precision, maintainability, inspectionability, and refinement to prospect 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 it.

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.)

To implement the above mentioned actions, structural mechanism to grapple strategically should be arranged in the organized framework for implementation throughout Japan promptly. This mechanism is requested not only to reinforce the present DEMO design activity but also to make the function of the so-called PDCA cycle, in particular, Check and Action, work effectively in planning, management, and coordination of the R&D plan required for engineering development for DEMO, and to organize activity including coordination with other fields and academic societies to resolve issues.

## 5. International Cooperation and Collaboration

Summary of activities abroad about DEMO has been described in the “Interim Report”. 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. Approach 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 investigation 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 Chap. 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 it, 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 relation should be established so that achievement by other countries/party will be reflected in the DEMO design appropriately.

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

In accordance with the request of the Working Group on Fusion Research, the joint-core team has worked on strategy for establishment of technology bases required for development of DEMO by taking into account the progress of the ITER project, the BA activities, and academic researches such as 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 indicate the prospect to achieve 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. And 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 phase.

In accordance with the “6th Term Report”, required technological activities of 11 elements of DEMO have been sorted out in looking forward to the roadmap from the summary of issues in the “Interim Report”.

Then, each element has been analysed 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 shown. 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. These two classes are distinguished in Tables 2 - 12. Based upon the analysis of the structure of technological issues, aligned R&D programs with defined milestones, and plans of research bodies grappling 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
4) Points of note

While the investigation in this present report endorses the view that the draft targets at the *Intermediate C&R* described in the "Future Fusion R&D" are appropriate, the progress of the ITER project will have a great impact on time 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, time and criteria at the *Transition Conditions* should be discussed in a council such as Working Group on Fusion Research at an appropriate time.

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 unfavourable 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 favourable 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, the DEMO design activity in wide definition is requested to manage the overall development plan by the definition of the target of each technology and assessment of technological maturity, to promote secure progress of the main stream, and to pronounce innovative technological developments for breakthrough. In the DEMO design activity, a structural mechanism to grapple strategically should be arranged in the organized a framework for implementation throughout Japan promptly in order not only to reinforce the present DEMO design activity but also to make the function of the so-called PDCA cycle, in particular, Check and Action, work effectively in planning, management, and coordination of the R&D plan required for engineering development for DEMO, and to organize activity including coordination with other fields and academic societies to resolve issues. This report here requests the Working Group on Fusion Research to discuss this mechanism to plot a comprehensive strategy of establishment of technological base for DEMO.

At the end, although the joint-core team is responsible only for scientific and technological analysis, it would like to express expectations to governmental administration. Since the appropriateness of DEMO is judged by society, the joint-core team expects leadership by governmental administration to define the responsibility of the implementing body as it should be, to create a mechanism to involve stakeholders and the public in technological assessment to prevent self-centered planning, and to define locational conditions and environmental assessments as they should be based upon the intrinsic safety features of fusion.

This report is founded on intensive discussions and upon opinions received from the Japanese fusion community at a variety of opportunities. This report was intended to have been based upon a consensus in the fusion community in Japan, and a shared understanding is emerging in the fusion community. We will continue to strive to collect opinions and work toward a broad consensus. The joint-core team is deeply grateful to all contributors for their important communications.

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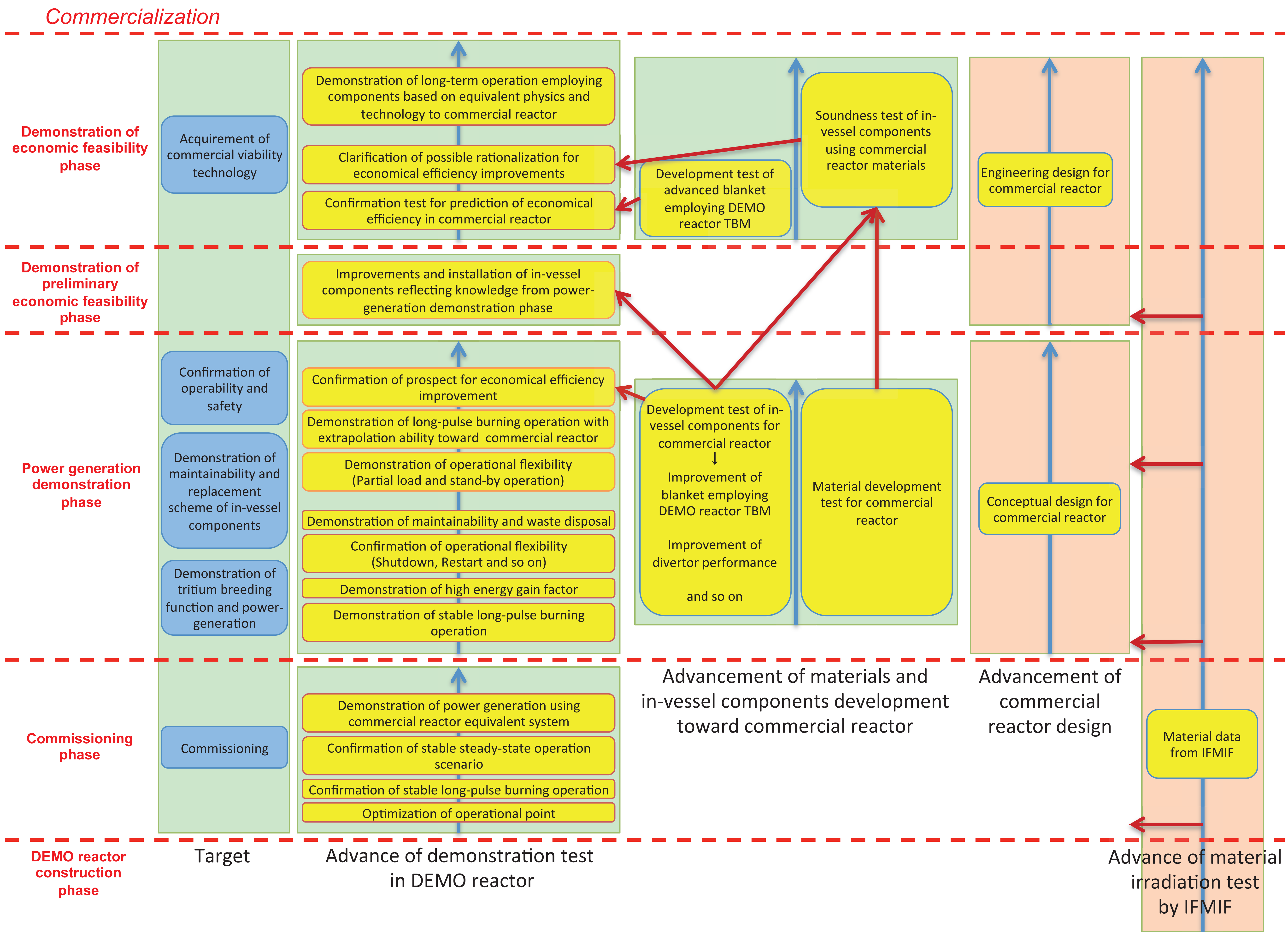


Fig. 1. Operational phase of DEMO reactor and its target

# Superconducting Coils

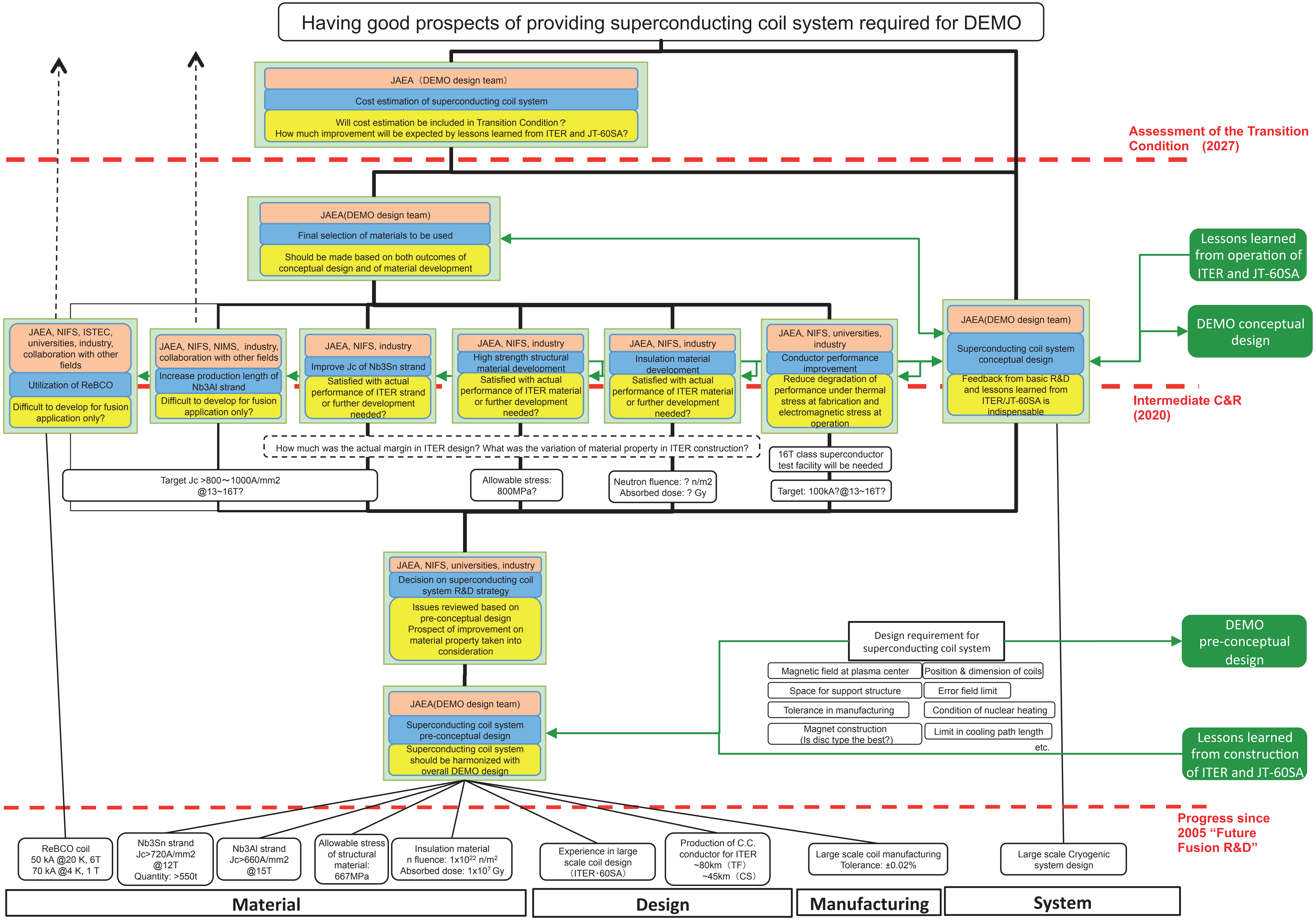


Fig. 2. Structure of issues in "Superconducting Coils"

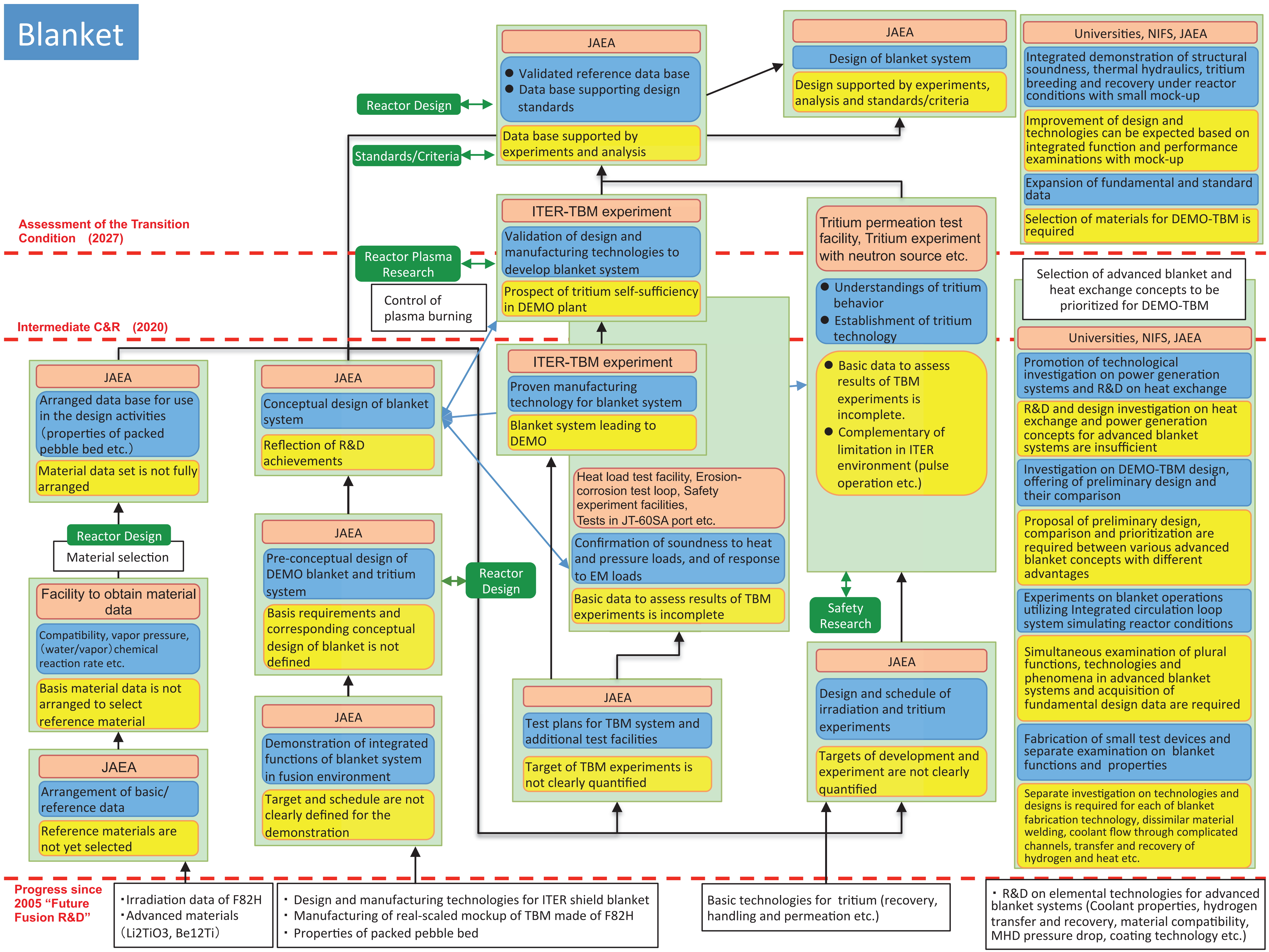


Fig. 3. Structure of issues in "Blanket"

# Divertor

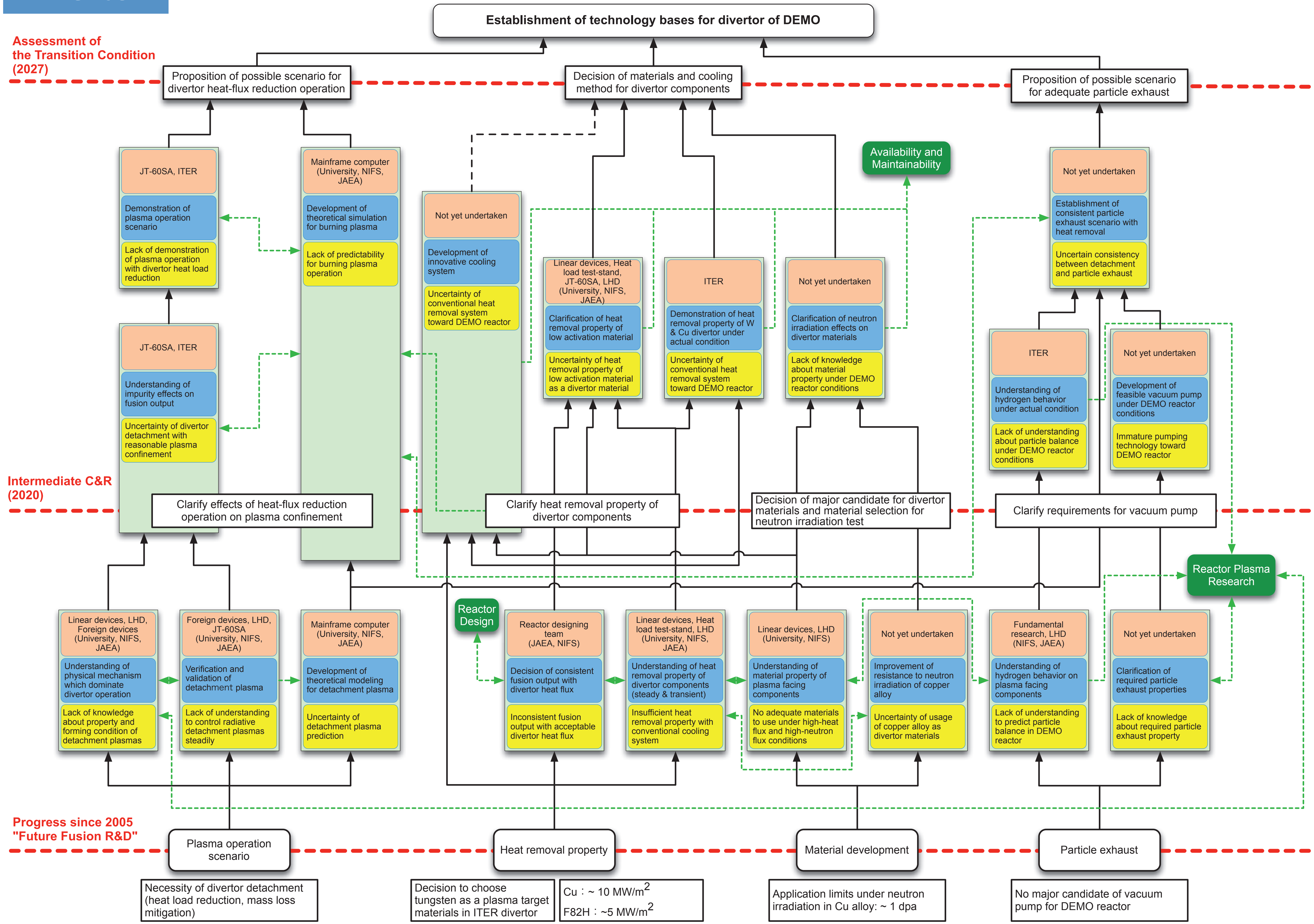


Fig. 4. Structure of issues in “Divertor”

# Heating and Current Drive Systems

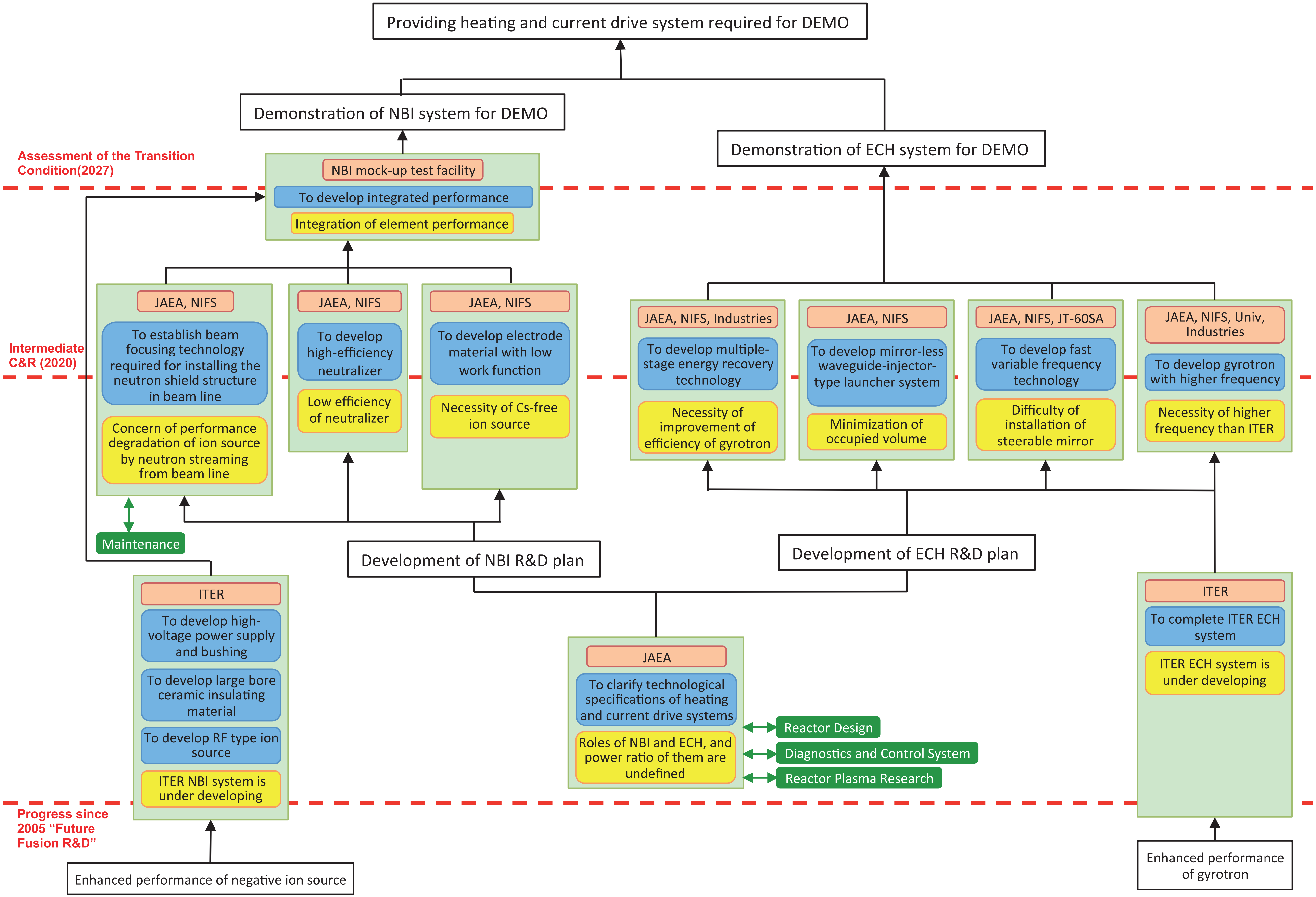


Fig. 5. Structure of issues in “Heating and Current Drive Systems”

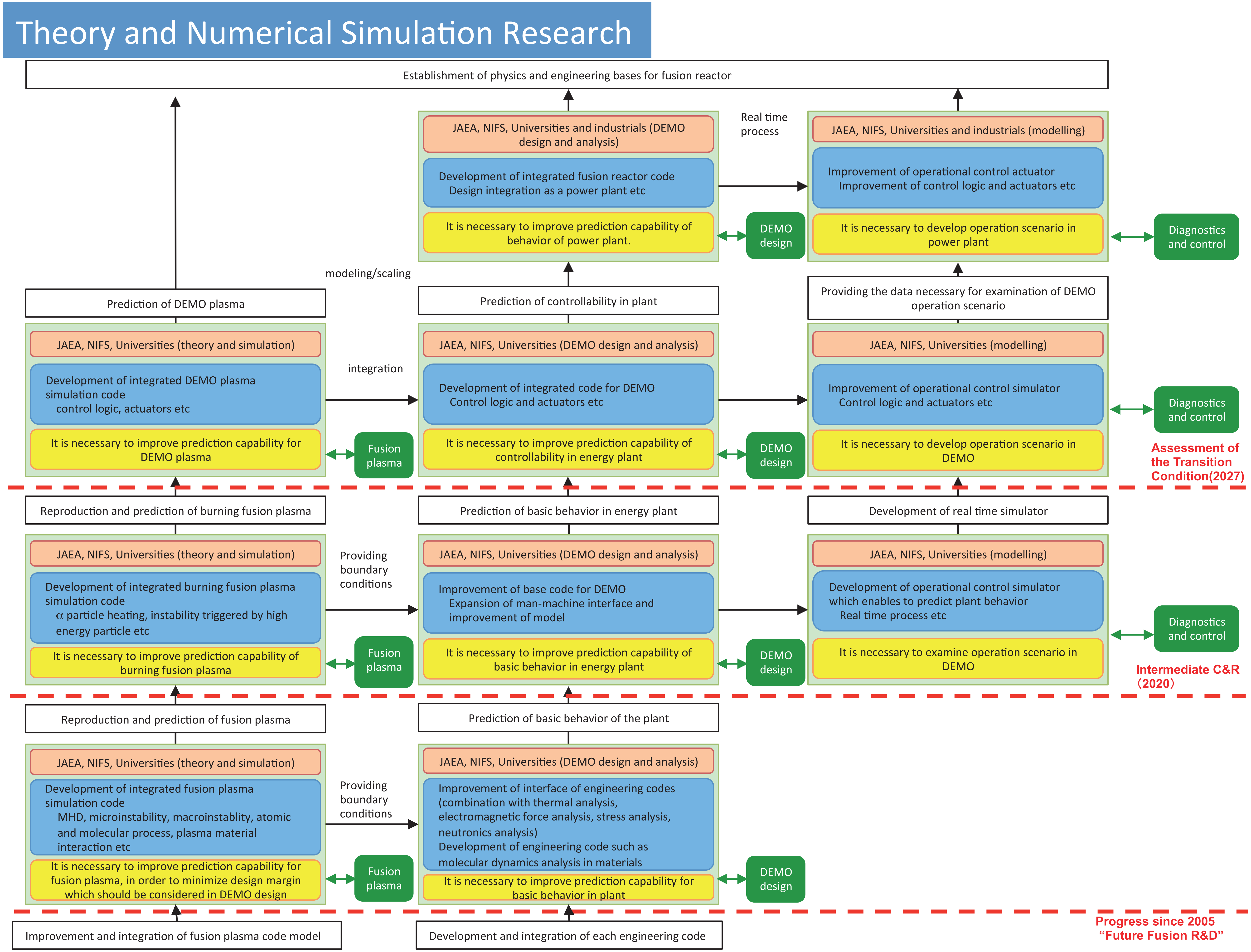


Fig. 6. Structure of issues in "Theory and Numerical Simulation Research"

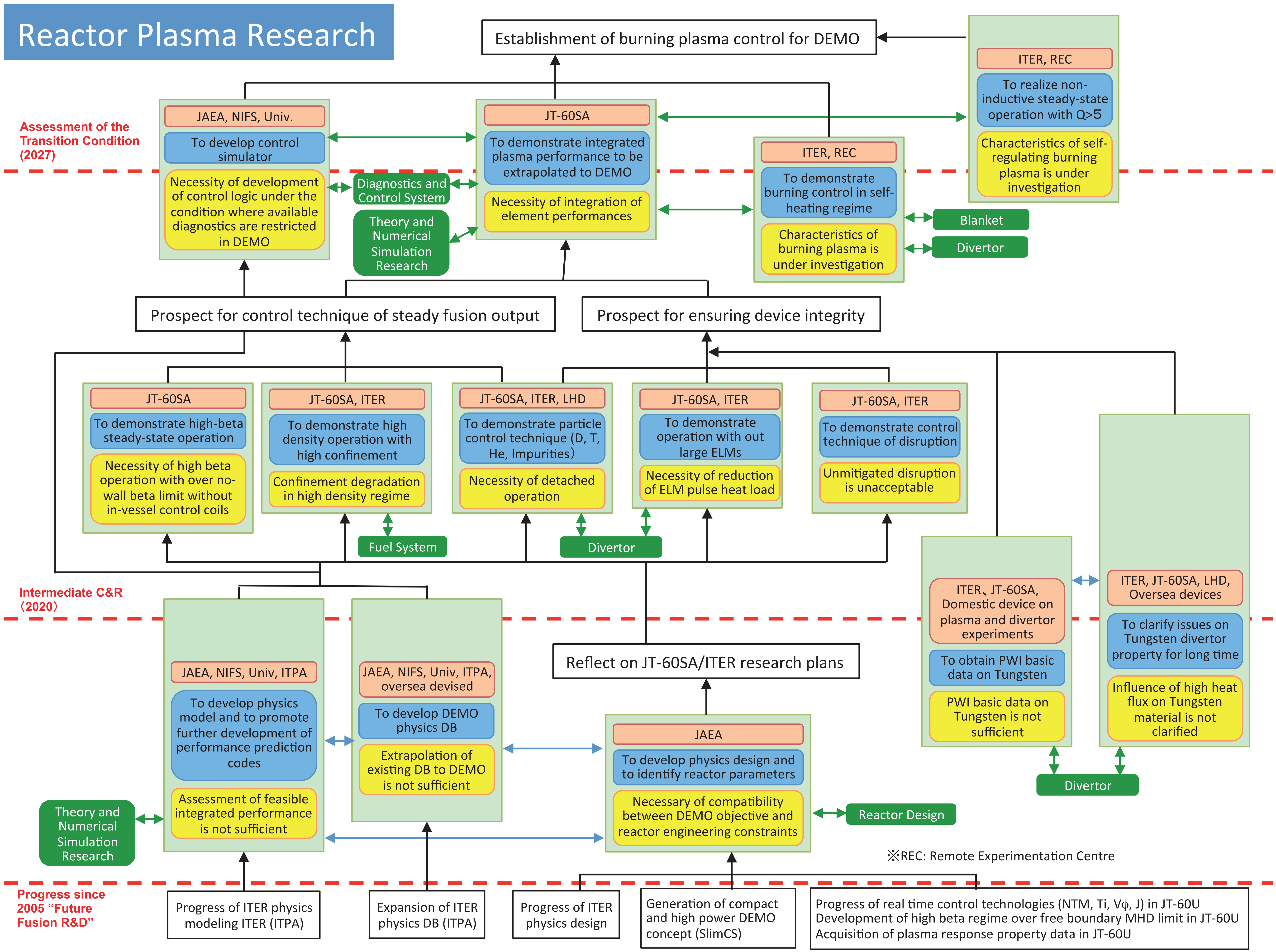


Fig. 7. Structure of issues in “Reactor Plasma Research”

# Fuel Systems

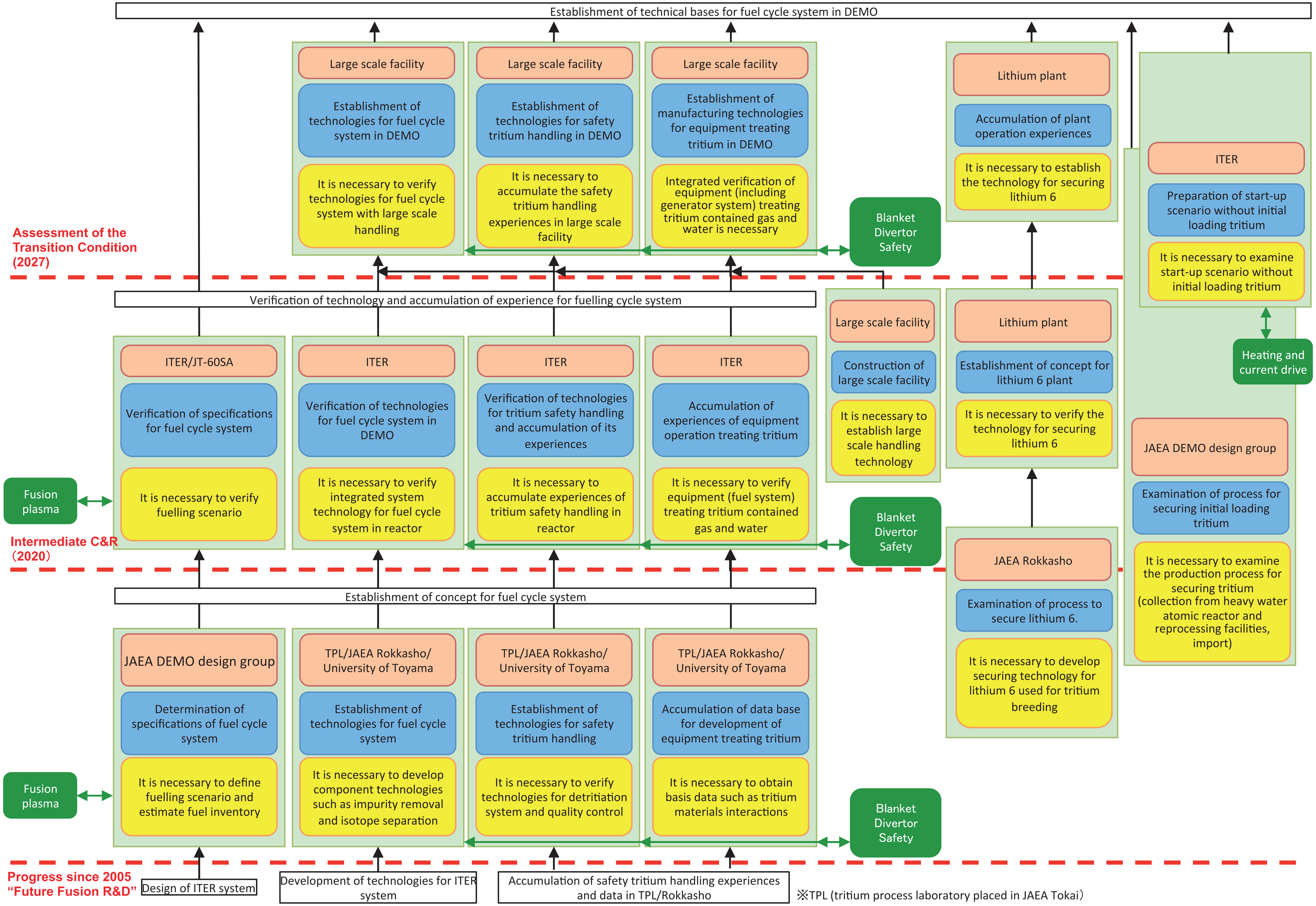


Fig. 8. Structure of issues in "Fuel Systems"

# Material Development and Establishment of Codes and Standards

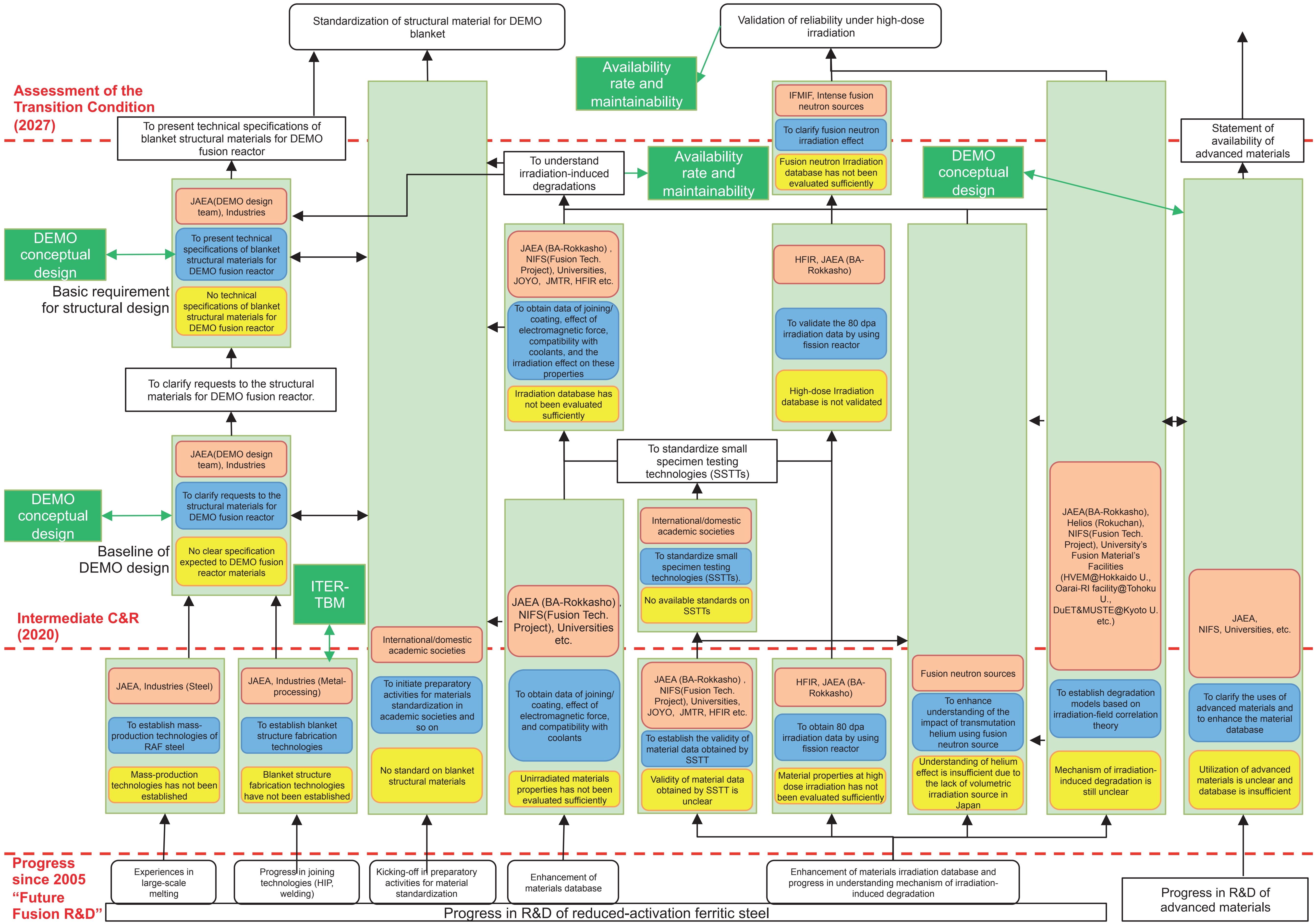


Fig. 9. Structure of issues in "Material Development and Establishment of Codes and Standards"

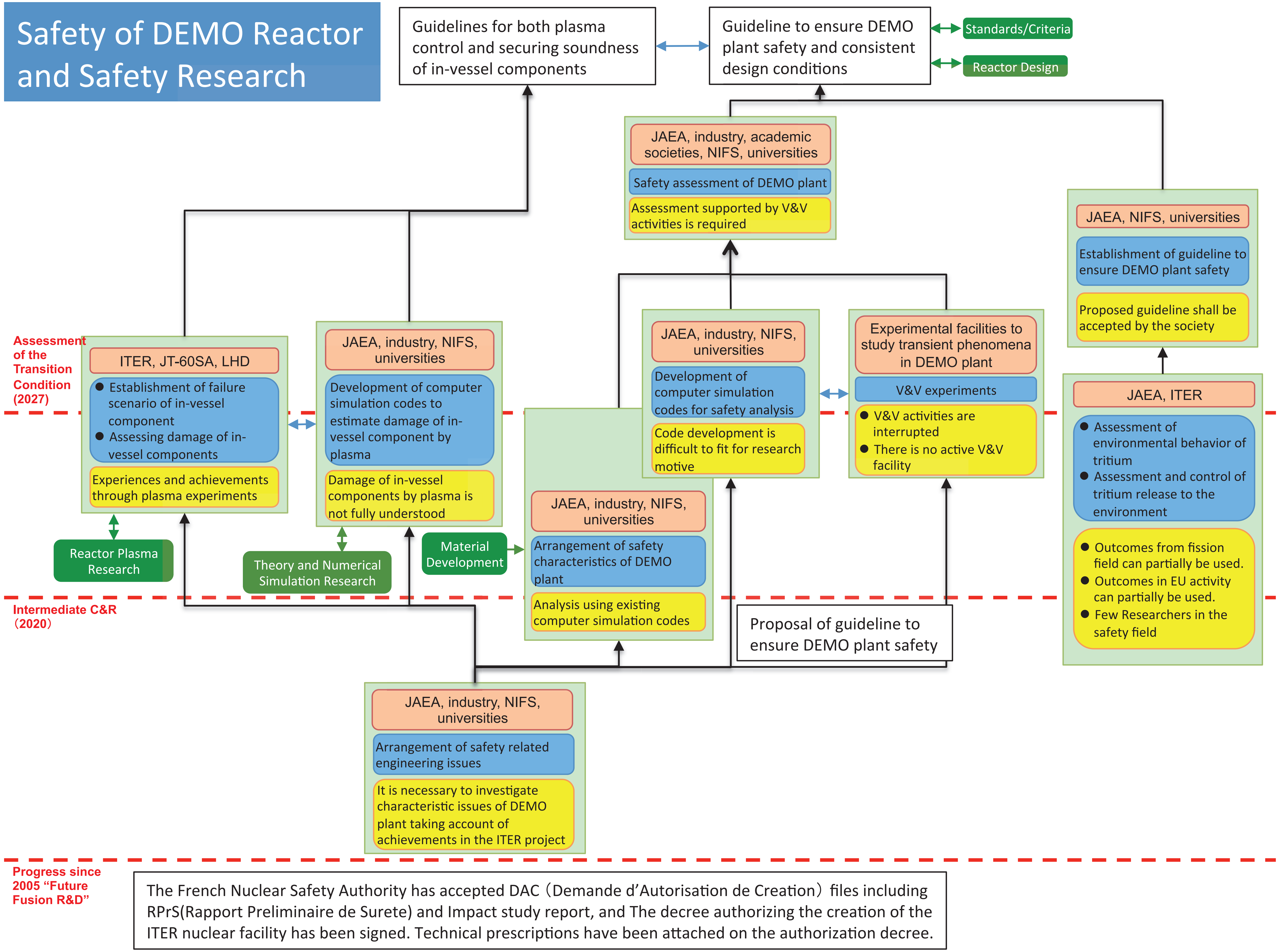


Fig. 10. Structure of issues in "Safety of DEMO Reactor and Safety Research"

# Availability and Maintainability

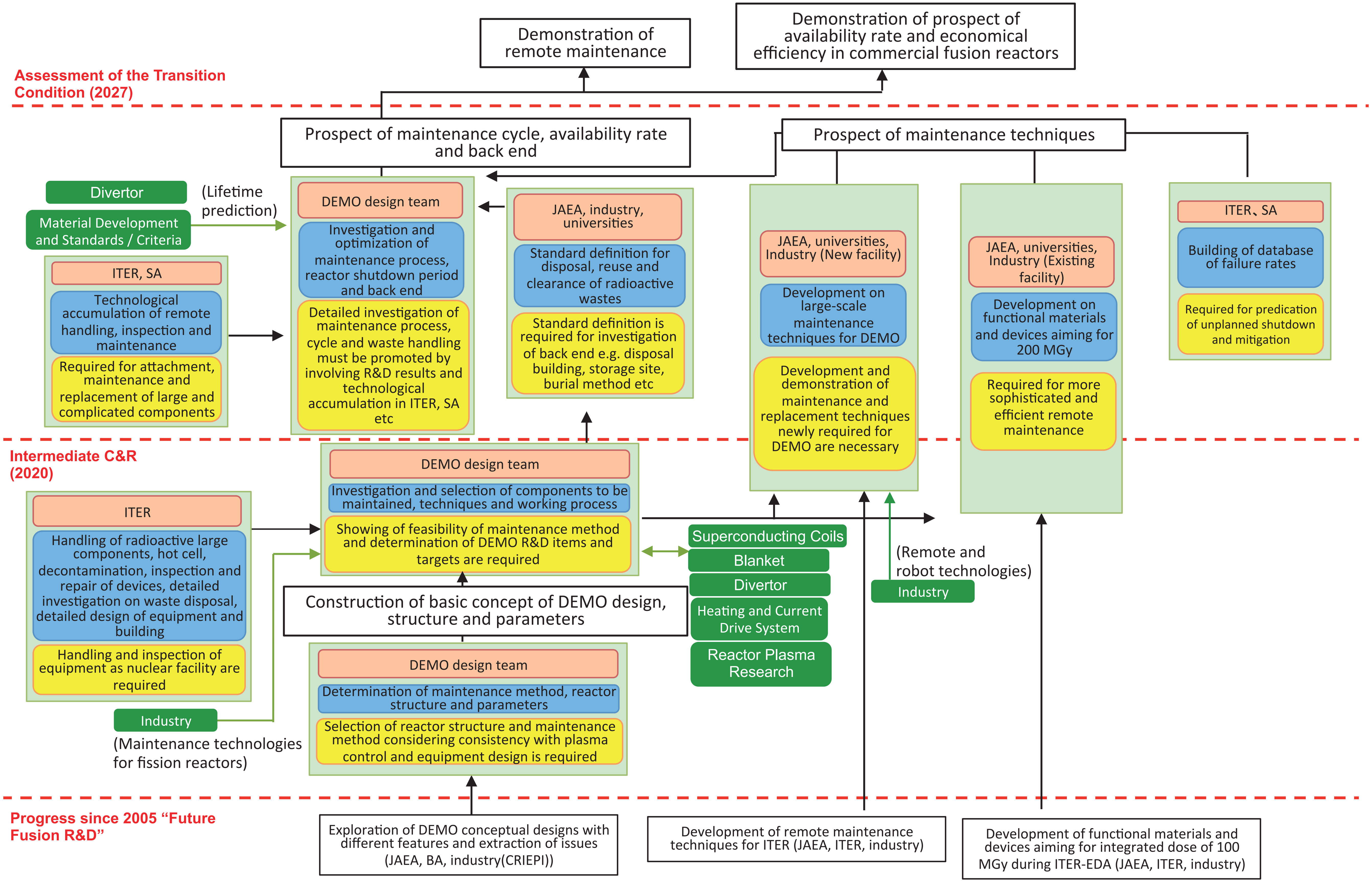


Fig. 11. Structure of issues in "Availability and Maintainability"

# Diagnostics and Control Systems

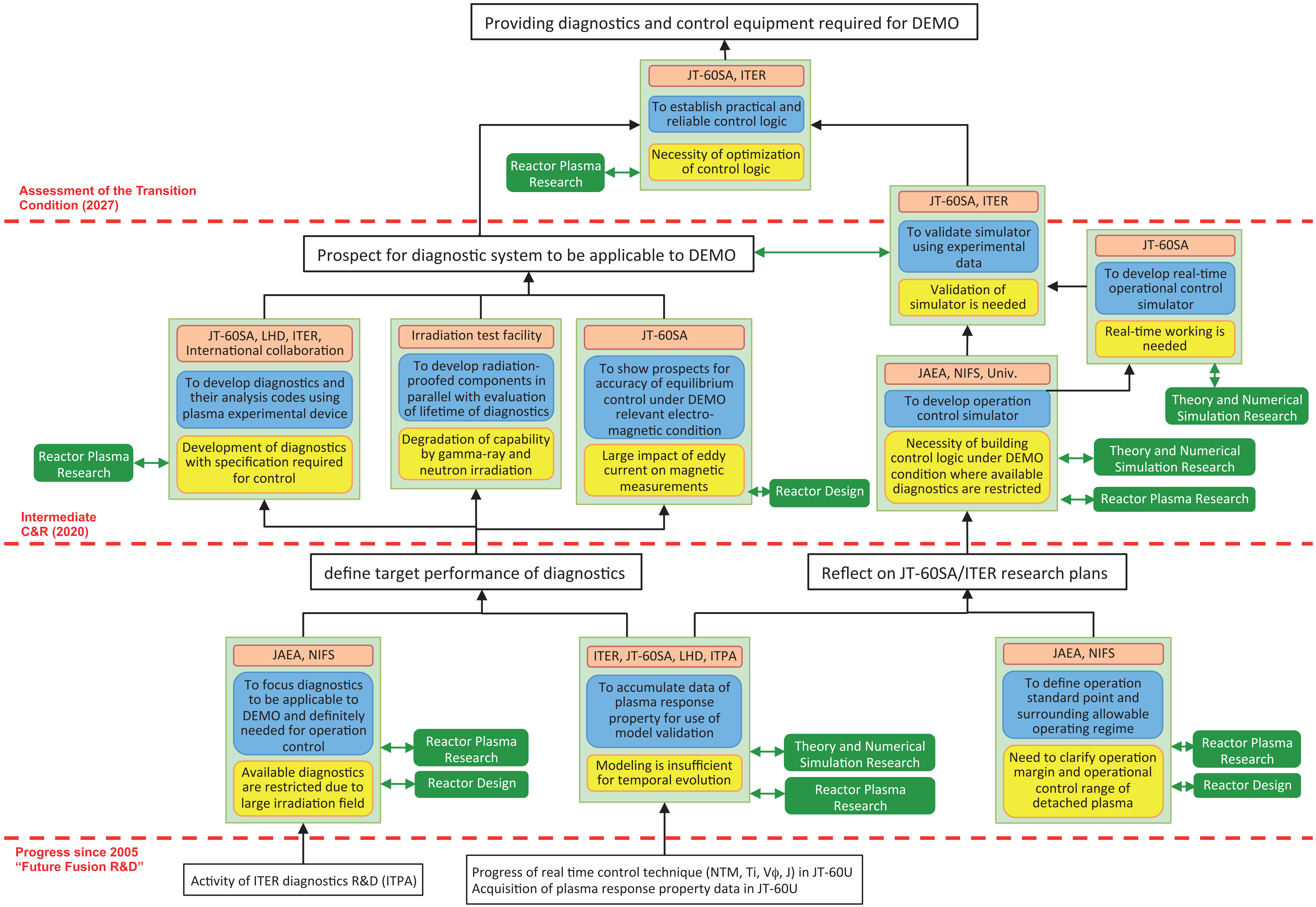


Fig. 12. Structure of issues in "Diagnostics and Control Systems"

Table 2　Sectors in charge and necessary facilities for "Superconducting Coils"

| | ITER | BA | JT-60SA | Others | Not yet launched |
|---|---|---|---|---|---|
| Superconducting coil system pre-conceptual design | ○ Lessons learned from construction | ○ Output of design study | ○ Lessons learned from construction | ◎ JAEA (DEMO design team) | |
| Decision on superconducting coil system R&D strategy | ○ Lessons learned from construction | | ○ Lessons learned from construction | ◎ JAEA, NIFS, universities, industry | |
| Utilization of ReBCO | | | | ◎ JAEA, NIFS, ISTEC, universities, industry, collaboration with other fields | |
| Extend production length of Nb3Al strand | | | | ◎ JAEA, NIFS, NIMS, industry, collaboration with other fields | |
| Improve Jc of Nb3Sn strand | ○ actual performance data | | | ◎ JAEA, NIFS, industry | |
| High strength structural material development | ○ actual performance data | | | ◎ JAEA, NIFS, NIMS, universities, industry | |
| Insulation material development | ○ actual performance data | | | ◎ JAEA, NIFS, universities, industry | |
| Conductor performance improvement | | | | | ◎ JAEA, NIFS, universities, industry, 16 T class test facility will be needed |
| Superconducting coil system conceptual design | △ Lessons learned from operation | | △ Lessons learned from operation | | ◎ JAEA (DEMO design team) |
| Final selection of materials to be used | | | | | ◎ JAEA (DEMO design team) |
| Cost estimation of superconducting coil system | △ Lessons learned from construction | | △ Lessons learned from construction | | ◎ JAEA (DEMO design team) |

Table 3　Sectors in charge and necessary facilities for "Blanket"

| | ITER | BA | JT-60SA | Others | Not yet launched |
|---|---|---|---|---|---|
| Arrangement of basic/reference data | | △ | | | JAEA (extension of facilities) |
| Demonstration of integrated functions of blanket system in fusion environment | ◎ | | | | JAEA (addition and extension of facilities) |
| Arranged data base for use in the design activities | | △ | | | JAEA (addition and extension of facilities) |
| Test plans for TBM system and additional test facilities | | | | JAEA | |
| Confirmation of soundness to heat and pressure loads, and of response to EM loads | | | △ | | JAEA (addition and extension of facilities) |
| Validation of design and manufacturing technologies to develop blanket system | | | | ◎JAEA, Manufacturers | |
| Design and schedule of irradiation and tritium experiments | | ◎ | | JAEA | |
| Understandings of tritium behavior, establishment of tritium technology | ◎ | | | | JAEA (addition and extension of facilities) |
| Validated reference data base, data base supporting design standards | ◎ | | | | JAEA (addition and extension of facilities) |
| Design of blanket system | | | | JAEA | |
| <Advanced blanket R&D for DEMO-TBM><br>• Fabrication of small test devices and separate examination on functions and properties<br>• Experiments on blanket operations with reactor conditions utilizing Integrated circulation loop system<br>• Technological investigation on power generation systems and R&D on heat exchange<br>• Investigation on design, offering of preliminary design and their comparison | | | | ◎ Universities, NIFS, ○ JAEA | |
| • Expansion of fundamental and standard data<br>• Integrated demonstration with small mock-up | | | | | ◎ Universities, NIFS ○ JAEA |

Table 4 Sectors in charge and necessary facilities for "Divertor"

| | ITER | BA | JT-60SA | Others | Not yet launched |
|---|---|---|---|---|---|
| Modeling of detachment plasma | ○ | ◎ | ○ | ○ NIFS | |
| Verification and validation of detachment plasma | ◎ | | ○ | ○ NIFS | |
| Optimization of divertor configuration | | ◎ | | | |
| Consistent fusion output with divertor heat-flux | | ◎ | | | |
| Improvement of neutron irradiation resistance of copper alloy | | | | | ○ |
| Material property of plasma facing materials | ○ | | ○ | ○ NIFS, University | |
| Maintenance scenario for divertor | | ◎ | | ○ NIFS | |
| Development of innovative cooling system | | | | | ○ |
| Development of feasible vacuum pump under DEMO reactor conditions | | | | | ○ |

Table 5 Sectors in charge and necessary facilities for "Heating and Current Drive Systems"

| | ITER | BA | JT-60SA | Others | Not yet launched |
|---|---|---|---|---|---|
| To develop NBI & ECH systems for ITER | ◎ | | | ◎ JAEA | |
| To clarify technological specifications of heating and current drive systems | ○ Reflect achievement | | | ◎ JAEA | |
| To establish beam focusing technology required for installing the neutron shield structure in beam line | | | | ◎ JAEA, NIFS | |
| To develop high-efficiency neutralizer | | | | ◎ JAEA, NIFS | |
| To develop electrode material with low work function | | | | ◎ JAEA, NIFS | |
| To develop integrated performance of mock-up NBI | ○ Reflect achievement | | ○ Reflect achievement | ○ JAEA, NIFS | ◎ NBI mock-up test facility |
| To develop multiples-stage energy recovery technology for gyrotron | ○ Reflect achievement | | | ◎ JAEA, NIFS, Industries | |
| To develop mirror-less waveguide-injector-type launcher system | | | | ◎ JAEA, NIFS | |
| To develop fast variable frequency technology | | | ○ | ◎ JAEA, NIFS | |
| To develop gyrotron with higher frequency | ○ Reflect achievement | | | | ◎ JAEA, NIFS, Univ. Tsukuba, Industries |

Table 6 Sectors in charge and necessary facilities for "Theory and Numerical Simulation Research"

| | ITER | BA | JT-60SA | Others | Not yet launched |
|---|---|---|---|---|---|
| Operational control simulator | | | | | |
| Upgrade of operational control simulator | ○<br>Validation of model | | | | ◎<br>Organization of activities |
| Improvement of operational control simulator | ○<br>Validation of model | | | | ◎<br>Organization of activities |
| Development of operational control simulator | ○<br>Validation of model | | △<br>Validation of model | | ◎<br>Organization of activities |
| Plant simulation code | | | | | |
| Development of integrated fusion reactor code | ○<br>Validation of model | | | | ◎<br>Organization of activities after BA |
| Development of integrated DEMO code | ○<br>Validation of model | | | | ◎<br>Organization of activities after BA |
| Improvement of base code for DEMO | ○<br>Validation of model | | △<br>Validation of model | | ◎<br>Organization of activities after BA |
| Improvement of engineering base codes and development of engineering code | ○<br>Validation of model | ○<br>Code improvement | △<br>Validation of model | ◎<br>JAEA, NIFS, Universities | |
| Fusion plasma simulation code | | | | | |
| Integrated DEMO plasma simulation | ○<br>Validation of model | | △<br>Validation of model | | ◎<br>Securing computer resource after BA |
| Integrated burning fusion plasma simulation | ○<br>Validation of model | | △<br>Validation of model | ◎<br>JAEA, NIFS, Universities | ◎<br>Securing computer resource after BA |
| Integrated fusion plasma simulation | ○<br>Validation of model | ○<br>Computer resource | ○<br>Validation of model | ◎<br>JAEA, NIFS, Universities | |

Table 7 Sectors in charge and necessary facilities for "Reactor Plasma Research"

| | ITER | BA | JT-60SA | Others | Not yet launched |
|---|---|---|---|---|---|
| To develop physics design and to identify reactor parameters | | ◎ | | | |
| To develop DEMO physics DB | ○<br>Reflect achievement | | ○<br>Reflect achievement | ◎<br>JAEA, NIFS, Univ., ITPA, Oversea devices | |
| To develop physics model and to promote further development of performance prediction codes | ○<br>Reflect achievement | | ○<br>Reflect achievement | ◎<br>JAEA, NIFS, Univ., ITPA | |
| To clarify issues on Tungsten divertor property for long time | ○<br>Reflect achievement | | ○<br>Reflect achievement | ◎<br>LHD | Oversea devices |
| To obtain PWI basic data on Tungsten | ○<br>Reflect achievement | | ○<br>Reflect achievement | ◎<br>Domestic devices | |
| To demonstrate high-beta steady-state operation | | | ◎ | | |
| To demonstrate high density operation with high confinement | ○<br>Reflect achievement | | ◎ | | Necessity of securing of computational resource |
| To demonstrate particle control technique (D, T, He, Impurities) | ◎<br>Reflect achievement | | ◎ | ○<br>LHD | Necessity of securing of computational resource |
| To demonstrate operation with out large ELMs | ◎<br>Reflect achievement | | ◎ | | Necessity of securing of computational resource |
| To demonstrate control technique of disruption | ◎<br>Reflect achievement | | ◎ | | Necessity of securing of computational resource |
| To develop control simulator | ○<br>Reflect achievement | | ◎ | ◎<br>JAEA&NIFS | Necessity of securing of computational resource |
| To demonstrate integrated plasma performance to be extrapolated to DEMO | ◎<br>Reflect achievement | | ◎ | | Necessity of securing of computational resource |
| To demonstrate burning control in self-heating regime | ◎<br>Reflect achievement | ◎<br>Utilize ITER REC | | | |
| To realize non-inductive steady-state operation with Q>5 | ◎<br>Reflect achievement | ◎<br>Utilize ITER REC | ◎ | | |

Table 8　Sectors in charge and necessary facilities for “Fuel Systems”

| | ITER | BA | JT-60SA | Others | Not yet launched |
|---|---|---|---|---|---|
| Determination of specifications for fuel cycle system | | ◎ | | | |
| Verification of specifications for fuel cycle system | ◎ | | ○ | | |
| Development of technologies necessary for fuel cycle system | ◎ | ○<br>DEMO R&D building in Rokkasho | | ○<br>TPL, Univ. of Toyama | |
| Development of technologies for safety tritium handling | ◎ | ○<br>DEMO R&D building in Rokkasho | | ○<br>TPL, Univ. of Toyama | |
| Development of equipment treating tritium | ◎ | ○<br>DEMO R&D building in Rokkasho | | ○<br>TPL, Univ. of Toyama | |
| Construction of large scale facility for tritium handling | | | | | ◎<br>JAEA |
| Development of technology for securing lithium 6 | | | | ◎<br>JAEA | |
| Construction of lithium 6 plant | | | | | ◎<br>JAEA |
| Examination of process for securing initial loading tritium | | | | | ◎<br>JAEA |
| Examination of start-up scenario without initial loading tritium | ○ | | | | ◎<br>JAEA |

Table 9　Sectors in charge and necessary facilities for “Material Development and Establishment of Codes and Standards”

| | | | ITER | BA | JT-60SA | Others | Not yet launched |
|---|---|---|---|---|---|---|---|
| Reduced-activation ferritic steel | Production/ fabrication technology | Establishment of mass-production technologies | | ◎ | | Industries (Steel) | |
| | | Establishment of blanket structure fabrication technologies | ○<br>Reflect achievement | ○ | | Industries (Metal processing) | |
| | | Clarification of requests to structural materials for DEMO reactor | | △ | | Industries | DEMO design team |
| | | Presentation of technical specifications of blanket structural materials for DEMO reactor | | △ | | Industries | DEMO design team |
| | Materials standardization | Preparatory activities for materials standardization in academic societies and so on | | ○ | | International/domestic academic societies | |
| | | Standardization of structural material for DEMO blanket | | | | | International/domestic academic societies |
| | Materials database | Data of joining/coating, effect of electromagnetic force, and compatibility with coolants | ○<br>Reflect achievement | △ | | JAEA (BA), NIFS, Universities, etc. | Clarification of required data |
| | | Acquisition of 80 dpa irradiation data by using fission reactor | | | | HFIR, JAEA (BA) | JAEA, US–Japan collaboration |
| | | Data of joining/coating, effect of electromagnetic force, compatibility with coolants, and the irradiation effect on these properties | | | | JAEA (BA), NIFS, Universities, JOYO, JMTR, HFIR, etc. | Establishment of plan for irradiation |
| | Mechanism of irradiation-induced degradation, Fusion neutron source | Establishment of degradation models based on irradiation-field correlation theory | | △ | | JAEA(BA, Helios), NIFS, University's Fusion Material's Facilities (HVEM@Hokkaido U., Oarai-RI facility@Tohoku U., DuET&MUSTE@Kyoto U., etc.) | |
| | | Understanding of the impact of transmutation helium using fusion neutron source | | △ | | Fusion neutron sources | |
| | | Establishment of validity of material data obtained by small specimen testing technologies | | ○ | | JAEA (BA), NIFS, Universities, JOYO, JMTR, HFIR, etc. | |
| | | Standardization of small specimen testing technologies | | | | | International/domestic academic societies |
| | | Clarification of fusion neutron irradiation effect | | | | | IFMIF, Intense fusion neutron sources |
| Advanced materials | | Clarification of the uses of advanced materials and to enhance the material database | | △ | | JAEA, NIFS, Universities, etc. | DEMO design team |

Table 10 Sectors in charge and necessary facilities for "Safety of DEMO Reactor and Safety Research"

| | ITER | BA | JT-60SA | Others | Not yet launched |
|---|---|---|---|---|---|
| Arrangement of safety related engineering issues | ○ Reflection of achievements | ◎ | | | |
| Arrangement of safety characteristics of DEMO plant | ○ Reflection of achievements | ◎ | | | |
| Development of computer simulation codes for safety analysis | | | | | JAEA/ Industry/ NIFS/ Universities |
| V&V experiments | △ Reflection of achievements | | | | JAEA/ Industry/ NIFS/ Universities |
| Assessment of environmental behavior of tritium | ○ Reflection of achievements | | | | |
| Establishment of guideline to ensure DEMO plant safety | | | | | JAEA/ NIFS/Industry |
| Establishment of failure scenario of in-vessel component, Assessing damage of in-vessel components | ◎ | | ○ | LHD | |
| Development of computer simulation codes to estimate damage of in-vessel component by plasma | | | | | JAEA/ Industry/ NIFS/ Universities |
| Safety assessment of DEMO plant | △ Reflection of achievements | | | △ universities | JAEA/ Industry/ Academic societies/ NIFS/ Universities |

Table 11 Sectors in charge and necessary facilities for "Availability and Maintainability"

| | ITER | BA | JT-60SA | Others | Not yet launched |
|---|---|---|---|---|---|
| Determination of maintenance method, reactor structure and parameters | | ○ Japan home team | | | |
| Investigation and selection of maintenance techniques and working process | | ○ Japan home team | | | ◎ DEMO design team (Reinforcement of framework) |
| Investigation and optimization of maintenance process, reactor shutdown period and back end | | ○ Japan home team | | | ◎ DEMO design team (Reinforcement of framework) |
| Handling of radioactive large components, hot cell, decontamination, inspection and repair of devices, detailed investigation on waste disposal, detailed design of equipment and building | ◎ Reflect investigation and design | | | | ◎ DEMO design team (Reinforcement of framework) |
| Technological accumulation of remote handling, inspection and maintenance | ◎ Reflect experience | | ○ | | ◎ DEMO design team (Reinforcement of framework) |
| Construction of database of failure rates. | ◎ Reflect experience | | ○ | | ◎ DEMO design team (Reinforcement of framework) |
| Development on large-scale maintenance techniques for DEMO. | | | | | ◎ JAEA (Development facility for large-scale maintenance techniques) ○ Industry, Universities |
| Development on functional materials and devices aiming for 200 MGy. | | | | | ◎ JAEA ○ Industry, Universities |
| Standard setting for disposal, reuse and clearance of radioactive wastes. | | | | | ◎ JAEA, Industry, ○ Universities |

Table 12 Sectors in charge and necessary facilities for "Diagnostics and Control Systems"

| | ITER | BA | JT-60SA | Others | Not yet started |
|---|---|---|---|---|---|
| To focus diagnostics to be applicable to DEMO and definitely needed for operation control | ○ | | | ◎<br>JAEA, NIFS | |
| To accumulate data of plasma response property for use of model validation | ◎ | | ◎ | ○<br>LHD, ITPA | |
| To define operation standard point and surrounding allowable operating regime | | | | ◎<br>JAEA, NIFS | |
| To develop diagnostics and their analysis codes using plasma experimental device | ◎ | | ◎ | ○<br>LHD, International collaboration | |
| To develop radiation-proofed components in parallel with evaluation of lifetime of diagnostics | ○<br>Reflect actual achievement | | | ◎<br>Irradiation test facility | |
| To show prospects for accuracy of equilibrium control under DEMO relevant electro-magnetic condition | ○ | | ◎ | | |
| To develop operational control simulator (offline) | ○<br>Reflect actual achievement | | ◎ | ○<br>JAEA, NIFS | |
| To develop real-time operational control simulator | ○<br>Reflect actual achievement | | ◎ | | |
| To validate simulator using experimental data | ◎ | | ◎ | | |
| To establish practical and reliable control logic | ◎ | | ◎ | | |