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Authors :

1. Takeo Muroga

National Institute for fusion Science, National Institutes of Natural Sciences,

Toki, Gifu, 509-5292 Japan

2. Hiroyasu Tanigawa

National Institutes for Quantum and Radiological Science and Technology,

Rokkasho, Aomori, 039-3212 Japan

Corresponding Author :

Takeo Muroga

National Institute for fusion Science, National Institutes of Natural Sciences,

Toki, Gifu, 509-5292 Japan

Tel : +81-572-58-2002

Fax : +81-572-58-2600

e-mail : muroga@nifs.ac.jp

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Japanese Fusion Materials Development Path to DEMO

Takeo Muroga[1] and Hiroyasu Tanigawa[2]

[1]*National Institute for fusion Science, National Institutes of Natural Sciences, Toki, Gifu, 509-5292 Japan*

[2] *National Institutes for Quantum and Radiological Science and Technology, Rokkasho, Aomori, 039-3212 Japan*

Abstract

This paper reports Japanese strategy for developing blanket structural materials for DEMO. In the Japanese program, the candidate materials are categorized into Primary Option (RAFM) and Advanced Options (V-alloy, SiC/SiC, ODS-RAFM etc.). A staged development is planned corresponding to the three decision-making points (DPs), DP1 : Intermediate check and review (C&R), DP2 : Decision of transition of research and development (R&D) focus to DEMO, and DP3 : Decision of DEMO construction. The near-term D-Li neutron source (A-FNS) and IFMIF are regarded as key facilities for the development. The strategy emphasizes “standardization” as an important step toward DEMO design qualification and licensing. The procedure to standard materials specifications by way of establishing structural design criteria and materials property requirements, and the procedure’s interaction with the schedule of irradiation data acquisition are discussed.

Key Words : fusion materials development, irradiation facilities, standardization

I. Introduction

Two documents were recently issued by “The Joint-Core Team for the Establishment of Technology Bases Required for the Development of a Fusion DEMO Reactor” (hereafter referred to as the Joint-Core Team, “joint” meaning collaboration of Japanese National Laboratories, Universities and Industries). These documents were entitled “Basic Concept of DEMO and Structure of Technological Issues” issued in February, 2015[1] and “Chart of Establishment of Technology Base for DEMO” issued in March, 2015[2], respectively. They were produced in accordance with the request of the Working Group on Fusion Research, the Nuclear Science and Technology Committee, the Ministry of Education, Culture, Sports, Science and Technology (MEXT). These two documents, hereafter referred to as “the Reports”, and their backgrounds were outlined in Ref. 3. Because the Reports were written based upon the extensive discussion in the fusion energy research and development community in Japan, including National Institutes for Quantum and Radiological Science and Technology (QST), National Institute for Fusion Science (NIFS), universities, industries, and other participants, it is thought that the Reports reflect the common understanding of the community.

In the Reports, “Material Development and Establishment of Codes and Standards” was selected as one of the eleven technological elements, and a chart, referring to a roadmap made by the community but not yet authorized by the Government, of the establishment of technological bases for DEMO was made for both Reduced Activation Ferritic/Martensitic steels (RAFM) and advanced materials, including the timeline of research and development (R&D) to resolve technological issues.

Then "Action Plan toward DEMO Development" (the Action Plan) was presented in March, 2016[4] by "The Task Force of Integrated Strategy for DEMO Development", established under the Fusion Science and Technology Committee in MEXT. This document was a follow-up of the Reports and included actions to check and ensure the progress in upgrading the project execution organizations.

Japanese DEMO development strategy is under reconstruction based on these documents. This paper reports and discusses Japanese strategy, timeline and plan of action for the development of fusion blanket structural materials, in accordance with the Reports and the Action Plan.

II. Decision-making Points Defined by the Reports and the Action Plan

The technical investigation of the Joint Core Team assumes that DEMO is of the Tokamak type with availability relevant to commercial reactors for commercialization and having sufficient tritium breeding to fulfil self-sufficiency[1]. It should be noted that this does not preclude a potential selection of non-Tokamak concepts for DEMO.

The Report defines three Decision-making Points (DPs) as follows[2,3].

(1) Intermediate check and review (C&R) (DP1)

The C&R is currently set for around 2020.

Here no major decision will be made but the result may influence partitioning of the efforts in the programs.

(2) Decision of transition of R&D focus to DEMO (DP2)

Tentatively scheduled ~2027 but subject to ITER schedule. The date was initially set near the projected time to start the D-T operation of ITER. With the delay of the expected D-T operation of ITER, the DP2 time may be shifted accordingly. This is under discussion.

(3) Decision of DEMO construction (DP3)

The time is not yet clearly defined, but is currently assumed to be during the 2030s. This may also be subject to the ITER schedule.

Many of the development plans toward DEMO were staged in accordance with the DPs.

III. Strategy for the development of fusion materials

III.A. Fundamental policy

The fundamental policies of the development of blanket structural materials of Japan are summarized as follows.

(1) Categorize the candidate materials into Primary Option (RAFM) and Advanced Option (V-alloy, SiC/SiC, ODS (Oxide Dispersion Strengthened)-RAFM etc.).

(2) Adopt staged development corresponding to DP1, DP2 and DP3.

(3) Position near-term D-Li neutron source (A-FNS[5], which is almost identical to DONES[6]) and the full-size IFMIF[7] (or equivalents) as key facilities for the development.

(4) Emphasize the necessity of “standardization” of materials specifications and test technology as a crucial step toward DEMO design qualification.

(5) Emphasize the necessity of establishing structural design criteria for the materials property requirements and standard specification of the structural materials.

III.B. Primary option and advanced options of candidate materials

It has been for many years the fundamental Japanese position that the candidate structural materials are categorized into Primary Option and Advanced Options with the former being RAFM and the latter including vanadium alloys, SiC/SiC composites and ODS-RAFM[8,9]. The two categories are in correspondence with the primary and advanced blanket options, the former using RAFM with water or He gas coolant and the latter using the advanced materials with high temperature He or liquid breeder (or their combination) coolants. Initial effort will be focused on RAFM and the RAFM-based blanket systems and the later efforts will shift to advanced materials and advanced high temperature blanket systems. This general strategy is common to Japan and EU[8]. Although the choice of Primary and Advanced materials options is interconnected with decisions regarding the blanket breeding and coolant options, the process for making such cross-cutting decisions has not yet been established. Weighting of the present advanced options has not yet been made either.

This paper focuses on the development of the Primary Option (RAFM), but some discussion will be presented for the advanced materials in Section IV.

III.C. Technical Base Chart and Research Plan for materials development

Figure 1 shows the Technical Base Chart (the Chart) and the Research Plan for RAFM development constructed based on the Reports and the Action Plan[1-4]. In the Chart, the three DPs divide the DEMO Reactor Design activities into Basic Design, Conceptual Design, Engineering

Design, and Construction phases. Two irradiation facilities, near term D-Li Neutron Source (A-FNS) and IFMIF, are listed in the Chart which closely interact with the materials irradiation test plan shown in the Research Plan. This strategy will be explained in Section III.D.

Fabrication technology of RAFM as listed in the Research Plan includes the technology for producing large scale materials and manufacturing blanket components, including joining technology. The technology is expected to be established before DP1. Before DP2, qualification of the technology will be made for installing the RAFM-Test Blanket Module (TBM) into ITER, which will be an important milestone for fabrication technology.

Establishing the structural design criteria and the materials property requirements are crucial steps toward standard materials specifications. In addition, timely standardization of materials test technology including Small Specimen Test Technology (SSTT) is necessary. These will be discussed in Sections III.E and III.F.

III.D. Irradiation facility options and strategy for irradiation testing

There has been extensive discussion on the use of irradiation test facilities for fusion materials development[10-12]. The fundamental Japanese position has been that the testing should be based on charged particle irradiation, fission neutron irradiation, and D-Li neutron irradiation[8,9]. In this subsection, the discussion focuses on the roles of neutron irradiation facilities in the materials development plan shown in Figure 1 including DP1, DP2 and DP3.

The roles and limitations of the neutron irradiation facilities are summarized in Figure 2. Fission reactors are presently available and should be used to select materials to be tested well before DP2. Considering that there now are a number of "candidate" RAFMs for DEMO in the world and that irradiation volume and the available period for the future irradiation tests by D-Li neutrons will be quite limited, it is essential to select a small number of candidate(s) well before the D-Li irradiation tests. Fission reactors will be the major tool for this purpose. Timely use of fission reactors is also valuable for constructing materials performance models to be validated later. It should be noted that, for the validation, fission reactors are not sufficient mainly because of the difficulty in simulating the He production rate in fusion reactor conditions.

Near-term D-Li neutron sources are being investigated in Japan (A-FNS[5]) and EU (DONES[6]). Their major role is to give low to medium fluence irradiation data contributing to DP2 and DP3. A schematic view of the A-FNS is given in Figure 3[5,13]. The A-FNS project plans to use an accelerator system to be established by the IFMIF/EVEDA Project which will be completed at the end of 2019[7]. The IFMIF/EVEDA accelerator system has a capability to accelerate deuterium ions to 9 MeV with a current of 125 mA. Although there previously were the options of the acceleration voltage of 26 and 40 MeV[5], the A-FNS project presently plans 40 MeV and 125 mA. As shown in Figure 1, the construction of A-FNS have to start around 2020 for the irradiation tests to contribute to DP2. This means that the decision to construct A-FNS should be made immediately following the conclusion of the IFMIF/EVEDA Project.

In addition, full-size IFMIF is considered to be necessary for DP3 and beyond.

Use of spallation neutron sources is not presently considered in the Japanese program. It is not intended in this paper to discuss in details regarding these options. It is to be noted, however, that these facilities can contribute to reinforcing the materials database once they are available through international collaborations. The component irradiation tests using plasma-based neutron sources are not on the table either, mainly because of shortage of time to accommodate the tests. Alternative or compensation activities of the component irradiation tests include miniaturized component tests in fission reactors, IFMIF and other irradiation means, thorough structural analysis and basic experiments for ensuring the structural integrity, and in-service surveillance tests of components during the DEMO operation in order to confirm the soundness of the components.

An example of the use of fission and D-Li neutron sources for quantifying the materials degradation in the fusion condition is schematically shown in Figure 4 (modified from Ref. 14). This figure shows the decrease in total elongation with dose, which is a common phenomenon for RAFM at relatively low temperature (<673K). Recent understanding is that neutron irradiation effects (hardening and loss of elongation) on RAFMs saturate at 10~20 dpa if He production rate is small (fission reactor condition)[15]. This model should be carefully inspected by DP1 based on the available fission irradiation data. For this model, verification to ~80 dpa is planned to be carried out by DP2 using extended fission reactor irradiations [2,4]. However, there is a Critical Dose at which the materials behavior under fusion neutron irradiation starts to deviate from that under fission neutron irradiation. This prediction is based mainly on ion irradiations and modeling efforts, and should be inspected minutely by DP1. In this case Critical Dose can be defined as the dose at which significant He effects emerge. It is of high priority to verify that the He effects are insignificant before the Critical Dose by low fluence (10~20 dpa) D-Li neutron irradiations by A-FNS, which is scheduled to be carried out by DP2 in the Research Plan. This step can be the rate-limiting for the transition from Conceptual Design to Engineering Design. Then D-Li irradiation to >50 dpa is expected either by extended use of A-FNS or construction and operation of IFMIF allowing for the validation of the model of He effects emerging after 10~20 dpa. The database to ~50 dpa will be necessary for DP3. IFMIF or its equivalent is also necessary for licensing the DEMO operation period by showing evaluated lifetime of the materials.

III.E. Structural design criteria and specification of materials

The materials property requirements highly depends on the structural design criteria. The structural design criteria is established based on the philosophy for ensuring plant safety. The options for the position of the blanket for the plant safety are as follows.

(1) Safety boundary (similar to the pressure vessel of Light Water Reactor (LWR))

(2) Failure below certain probability is allowed (similar to the cladding of LWR)

(3) No safety boundary but any failure is not acceptable

(In this case, the requirement is identical to (1))

As an example of the relation between the structural design criteria and the materials property requirements, Figure 5 illustrates the procedure to determine allowable ductile to brittle transition temperature (DBTT) limit for Reactor Pressure Vessel (RPV)[16], which is categorized into the plant safety boundary. The DBTT limit is determined according to the toughness of the materials evaluated by in-service surveillance tests, which include radiation effects, and the calculated transient stress applied to the material when cold water is injected in case of accident.

Because of complex shape and thin structure, a far more detailed stress distribution analysis is necessary for the first wall and blankets than for fission reactor RPVs. An example of the applied stress analysis is published for “In-Box LOCA” in water-cooled Test Blanket Module (TBM)[17]. In this case the stress is originated mostly from the pressure of the coolant as a result of its extensive ingress. The Finite Element Method (FEM) can provide stress distribution of the

TBM. The maximum stress can be compared with the allowable stress intensity supplied by the existing standard such as ASME-Boiler and Pressure Vessel Code (BPVC) Sec. III, Div.1[18].

However, this procedure has pronounced difficulties compared to the RPV case shown in Figure 5, because ASME-BPVD and the procedure to assure the structural integrity is not developed for the complex and thin structure such as the fusion first wall and blanket. In addition, the changes of materials properties by irradiation and the transient temperature and pressure are not incorporated. Because DBTT is not a good measure of the materials properties for the thin structure of the first wall and blanket, other materials properties which can incorporate radiation effects are necessary. This consideration clearly demonstrates that we have a long way to go toward establishing the structural design criteria and the materials property requirements for the first wall and blanket.

III.F. Standardization strategy and procedure

For the standardization of materials specifications, collaboration with academic societies etc. (ASTM, ASME, RCC-MR and others) is necessary. The following staged procedure is being proposed corresponding to the progress in the irradiation database.

(1) Standardization of materials specifications for non-nuclear application (by DP1)

(2) Standardization of materials specifications for licensing of ITER-TBM to ~3 dpa (by DP2)

(3) Standardization of materials specifications to the dose of DEMO initial operation (small He effect) for DEMO engineering design.

(4) Standardization of materials specifications for DEMO relevant condition (with He effect) (by DP3).

The staged establishment needs timely acquisition of radiation data. However, it should be noted that the standardization must be carried out in most cases without sufficient irradiation data.

The materials test technology including SSTT also requires standardization. The present standards of materials testing, such as JIS, ASTM, ASME, JSME and ISO, do not address the SSTT. Although the standardization is necessary before DP2 (start of D-Li neutron irradiation), the strategy and plan have not been established yet in the Japanese program.

The standardization again requires collaboration with academic societies. One of the few examples of establishing a standard in nuclear fusion field by an academic society is “JSME standard for superconducting magnets for ITER construction”[19], including materials standards[20]. Although the scope of the standards is very different from those for DEMO, this can be considered to be a good precedent of collaboration by the fusion community and an academic society toward standardization.

III.G. Materials development scenario toward DEMO licensing

The scenario of materials development toward DEMO licensing is summarized as follows and in Figure 6.

(1) Establishing a philosophy for ensuring safety of the plant.

For this purpose, fundamental design concept needs to be built.

(2) Establishing structural design criteria to guarantee structural integrity in in-vessel (heavy irradiation) environments.

This, however, must be carried out without sufficient irradiation data.

(3) Determination of materials property requirements based on the criteria.

(4) Establishing materials database which can convince that the candidate materials satisfy the requirements.

For this purpose, standardization of materials test technology including SSTT is necessary. Also necessary is the standard materials specifications in un-irradiated conditions (non-nuclear applications).

(5) Establishing standard materials specifications based on the irradiation database to be obtained (nuclear applications).

(6) DEMO design qualification, including materials and component qualifications.

As shown in the figure, execution of (5) and (6) based on (2) to (4) is staged by 1. TBM based on fission neutron irradiation, 2. DEMO construction and initial operation based on medium dose D-Li neutron irradiation and 3. DEMO operation extension to full specification based on high dose D-Li neutron irradiation. The bidirectional arrows in the figure means that they are interactive with each other. For example, irradiation data obtained can influence the materials property requirements and then the structural design criteria.

IV. Development of advanced materials

The Reports and the Action Plan do not address details of the development strategy of advanced materials but simply propose to extend their database and to continue investigation for their potential use in DEMO. These activities will be targeted at enabling decision on the use of the advanced materials for DEMO at DP2.

It is to be noted, however, that, this strategy is a part of the overall strategy for the advanced materials development. The target of the Reports and the Action Plan is for a relatively conservative DEMO aiming at early start of construction (~2030s). Advanced DEMO blanket systems must also be explored in a long-term view in order to increase the competitiveness of fusion energy relative to other energy options with regard to cost, safety and environmental benignity. Among the advanced materials, however, ODS-RAFM has a potential to be used in a limited manner in a conservative RAFM-based blankets at the positions where thermal load is locally high.

Development of non-magnetic advanced materials, such as vanadium alloys and SiC/SiC composites, is also meaningful in terms of risk mitigation by providing backups, considering that uncertainty still remains regarding the effects of ferromagnetic materials on plasma confinement.

Figure 7 shows the scenario of irradiation tests and development of primary and advanced candidate materials. The figure shows that although initial effort will be focused on RAFM and RAFM-based blanket systems for early realization of DEMO, subsequent efforts will shift to the advanced materials and advanced high temperature blanket systems, and thus toward development of advanced fusion systems. In more detail, the feasibility of advanced materials should be verified around DP2 for their potential use in ITER-TBM and DEMO blanket tests. Low fluence irradiation data should be available around DP3 for the design and construction of the DEMO advanced blanket test system. Medium fluence irradiation data should be available for starting the blanket tests in DEMO. Of course, the development of the blanket systems as well as materials qualification will take time. Therefore elaborate technological development strategies must be established for timely realization of the advanced blanket systems. As mentioned in section III.B above, the decision making process for the materials and blanket concepts together also remains to be established.

V. Summary

Recently, the Japanese fusion community issued documents on the strategy for technological development toward DEMO. Japanese DEMO development plan is under reconstruction based on these documents. Three decision-making points were defined allowing a staged development toward DEMO. These are DP1 : Intermediate C&R; DP2 : Decision of transition of R&D focus to DEMO; and DP3 : Decision of DEMO construction.

In the Japanese program, the candidate materials are categorized into Primary (RAFM) and Advanced (V-alloy, SiC/SiC, ODS-RAFM etc.) options and D-Li neutron sources are the key facilities for the staged development. The standard materials specifications are recognized as a crucial step toward DEMO design qualification and licensing. For this purpose, the materials property requirements to be derived by establishing the structural design criteria is necessary as well as establishing irradiation database.

The challenges in this process include that the reactor design must be carried out without sufficient materials irradiation data. Thus careful manipulation of the schedule in the development of irradiation facilities and the acquisition of irradiation data, and auxiliary basic and modeling research efforts are essential for accelerated materials development toward DEMO.

The development of advanced materials also must be enhanced, in the long-term view, for developing advanced DEMO blanket, and as potential backups of RAFM for risk mitigation. Although initial effort will be focused on RAFM and RAFM-based blanket systems for early realization of DEMO, later efforts will shift to the advanced materials and advanced high temperature blanket systems, toward development of advanced fusion systems.

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Figure Captions

Figure 1. Technical Base Chart and Research Plan for RAFM development constructed based on the Reports and the Action Plan[1-4].

Figure 2. Summary of the positions of neutron irradiation facilities for fusion materials development.

Figure 3. A schematic view of A-FNS[5,13]. Photographs of the facilities developed in the IFMIF/EVEDA Project are also shown

Figure 4. The role of fission and D-Li neutron irradiations for quantifying the loss of elongation of RAFM in the fusion condition. (Modified from Ref. 14.)

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Figure 6. Materials development scenario toward DEMO licensing.

Figure 7. Irradiation tests and development of primary and advanced candidate materials.

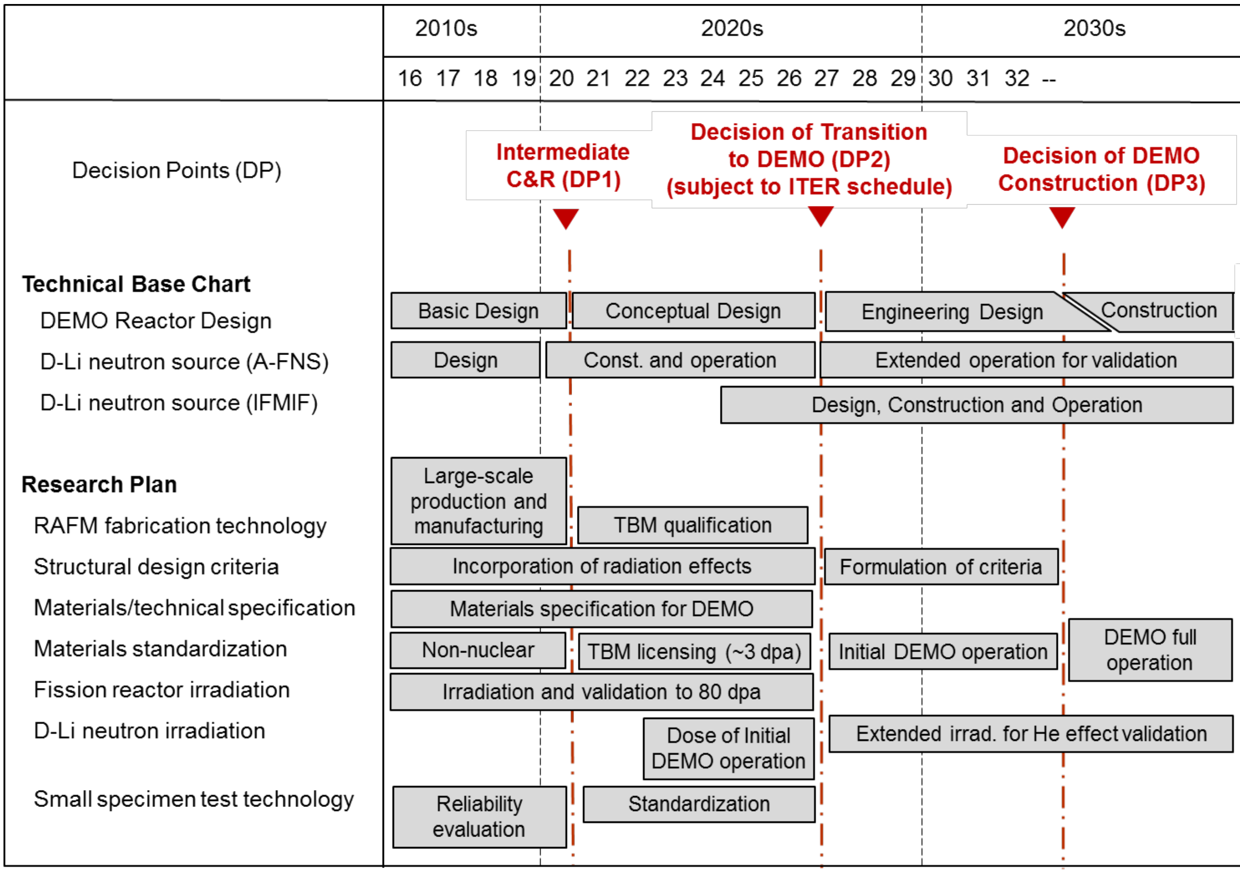


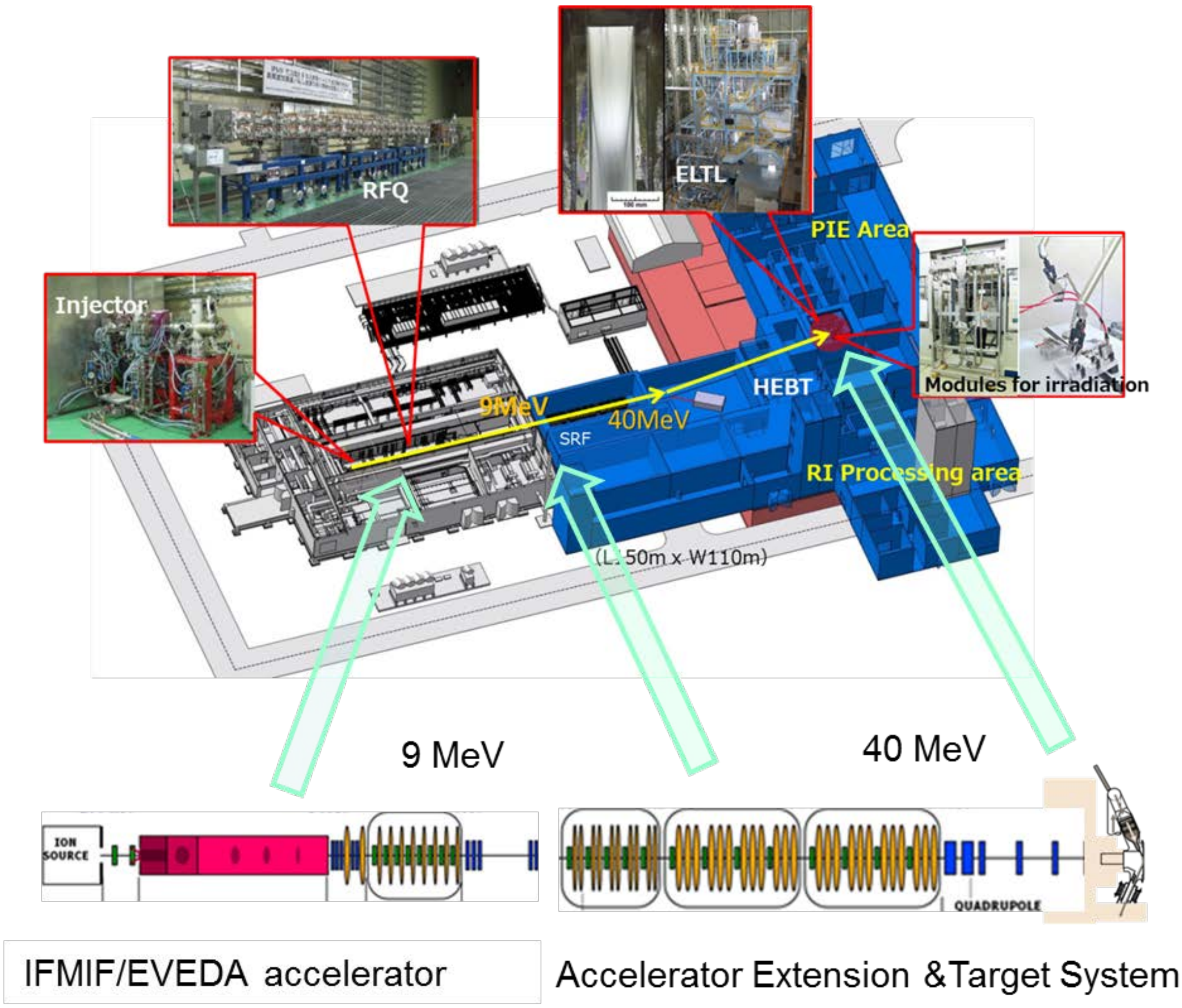
Figure 1. Technical Base Chart and Research Plan for RAFM development constructed based on the Reports and the Action Plan[1-4].

Purposes	Candidate Selection	Model Validation	Lifetime Evaluation
Required Characteristics	Timely availability	Precise Control	High Fluence
Fission Reactors	Timely use possible Difficult to simulate He effect	Difficult to simulate He effect	Difficult to simulate He effect
A-FNS	Limited timely use	Low fluence validation	Medium fluence evaluation
IFMIF	Not timely	Medium fluence validation	High fluence evaluation

DP1-DP2 emphasis DP2-DP3 emphasis Beyond DP3

DP1: Intermediate C&R DP2: Transition of R&D focus to DEMO DP3: DEMO construction

Figure 2. Summary of the positions of neutron irradiation facilities for fusion materials development.



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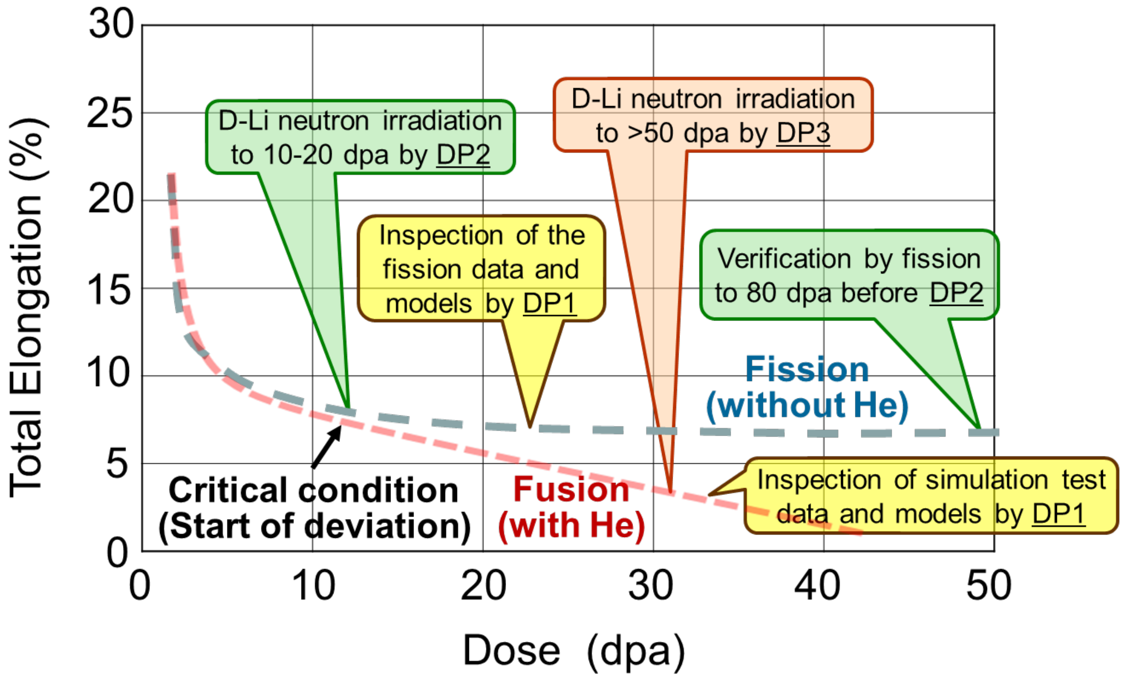

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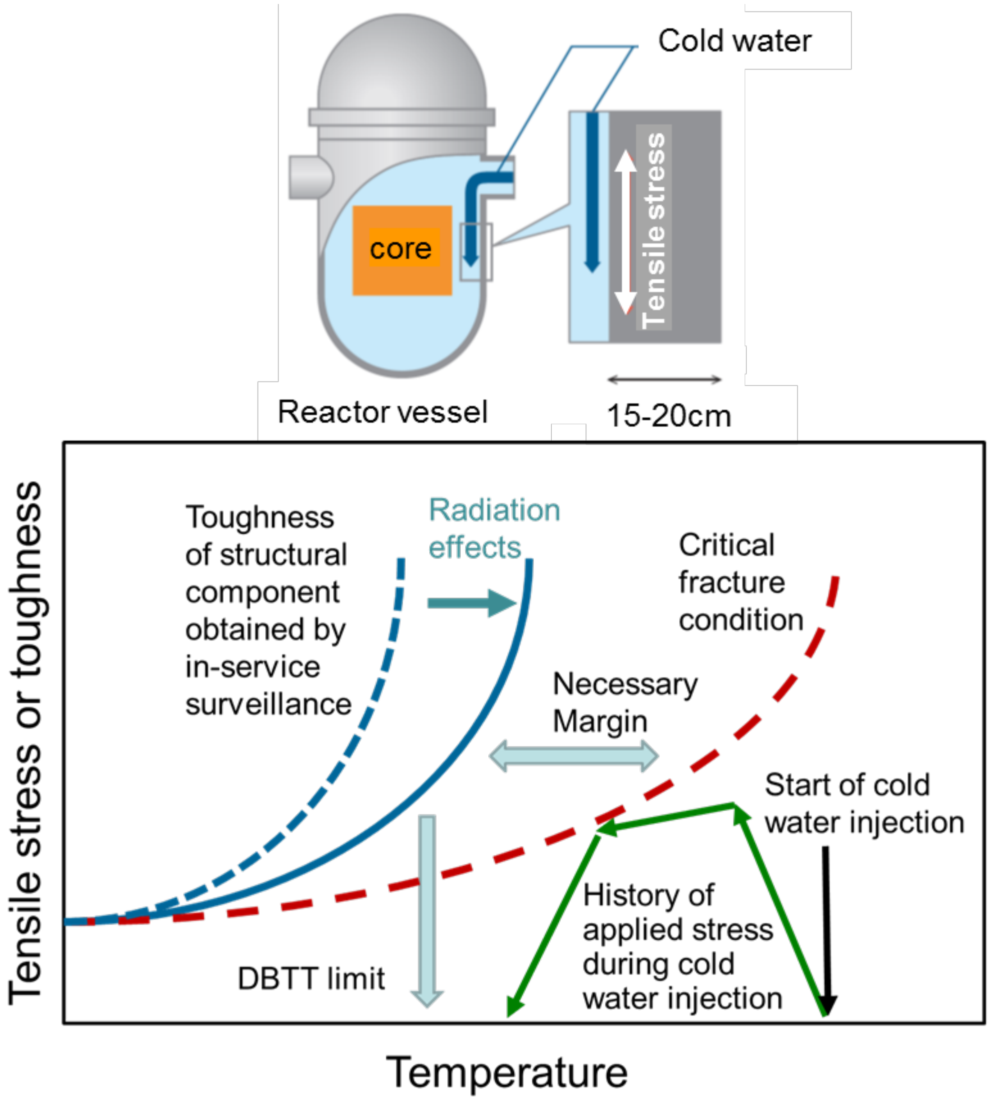

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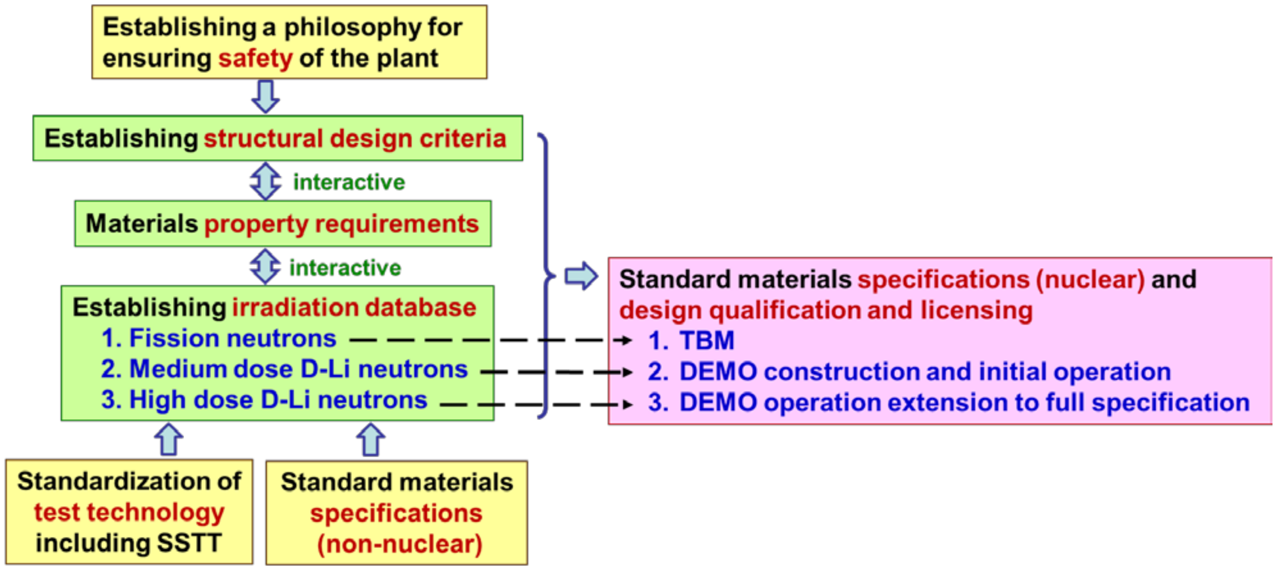

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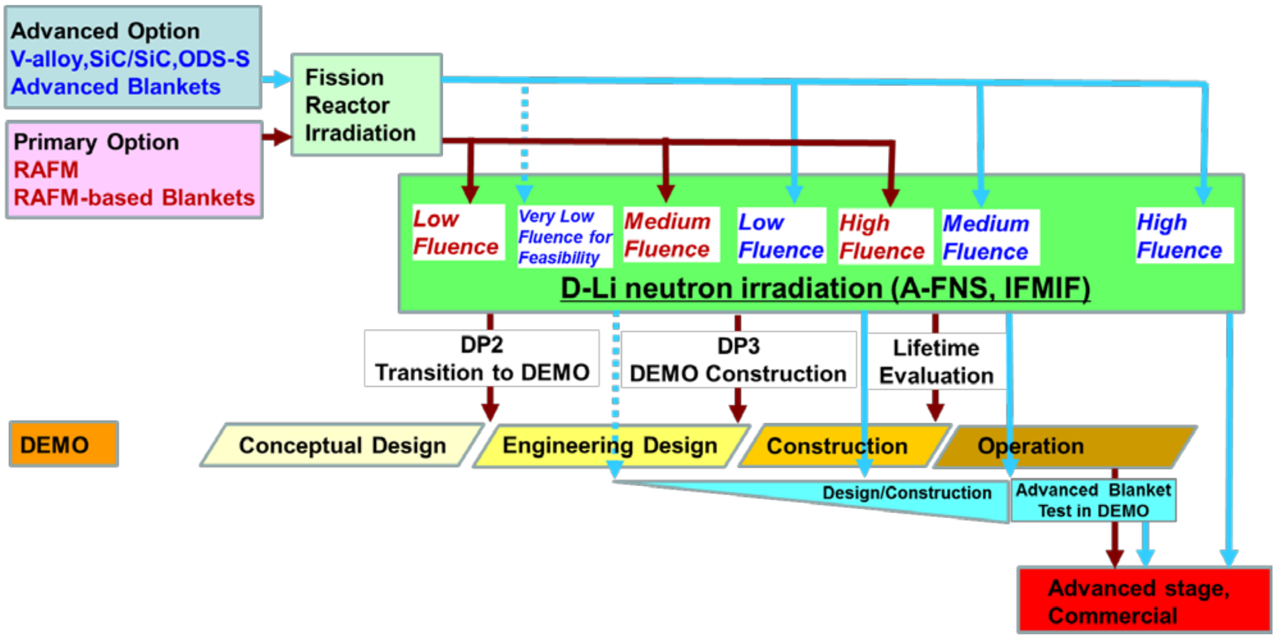

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