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Fusion materials development program in the broader approach activities

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ABSTRACT

Breeding blankets are the most important components in DEMO. The DEMO blanket has to withstand high neutron flux typically 15–30 dpa/year under continuous operation. Therefore integrated and effective development of blanket structural materials and breeding/multiplying materials is essential in the blanket development for DEMO. In parallel to the ITER program, broader approach (BA) activities are initiated by EU and Japan. Based on the common interest of each party towards DEMO, R&D on reduced activation ferritic martensitic (RAFM) steels as a DEMO blanket structural material, SiC_f/SiC composites which have potential for use in DEMO blankets, advanced tritium breeders and neutron multiplier for DEMO blankets, and tritium technologies including tritium behavior studies in advanced materials for DEMO blanket applications will be carried out as a part of the BA activities.

1. Introduction

The world fusion community is now launching construction of ITER, the first nuclear-grade fusion machine in the world. In parallel to the ITER program, broader approach (BA) activities [1] are being initiated by the EU and Japan, mainly at Rokkasho BA site in Japan. The BA activities include the International Fusion Materials Irradiation Facility-Engineering Validation and Engineering Design Activities (IFMIF-EVEDA) [2], the International Fusion Energy Research Center (IFERC), and the Satellite Tokamak. IFERC consists of three sub projects; a DEMO design and R&D coordination center, a computational simulation center, and an ITER remote experimentation center.

The breeding blanket is the most important component in DEMO. Fig. 1 shows the schematic view of the typical pebble bed type blanket [3], which consists of the first wall and structure material, the tritium breeding pebbles, the neutron multiplying pebbles, and the cooling channels. The DEMO blanket has to withstand high neutron flux typically 15–30 dpa/year under continuous operation. Therefore an integrated and effective development of blanket structural materials and breeding/multiplying materials which can be used under the DEMO operational conditions is essential in the blanket development for DEMO. Fig. 2 shows the roadmap of the blanket material development toward DEMO. As a milestone for DEMO, the ITER test blanket module (TBM) program is the most important test bench activity in the blanket material development. According to the common interests of each party towards DEMO, R&D on reduced activation ferritic martensitic (RAFM) steels [4,5] as a DEMO blanket structural material, SiC_f/SiC composites, advanced tritium breeders and neutron multiplier for DEMO blankets, and tritium technology will be implemented through the BA DEMO design and R&D coordination center.

In the R&D on the RAFM steels, the fabrication technology, techniques to incorporate the fracture/rupture properties of the irradiated materials, and methods to predict the deformation and fracture behaviors of structures under irradiation will be investigated. For SiC_f/SiC composites, standard methods to evaluate high-temperature and lifetime properties will be developed. Not only for SiC_f/SiC but also related ceramics, physical and chemical properties such as He and H permeability and absorption will be investigated under irradiation. For the advanced tritium breeder R&D, Japan and the EU plan to establish the production technique for advanced breeder pebbles of Li_2TiO_3 and Li_4SiO_4, respectively. Also physical, chemical, and mechanical properties will be investigated for the breeder pebbles produced. For the advanced neutron

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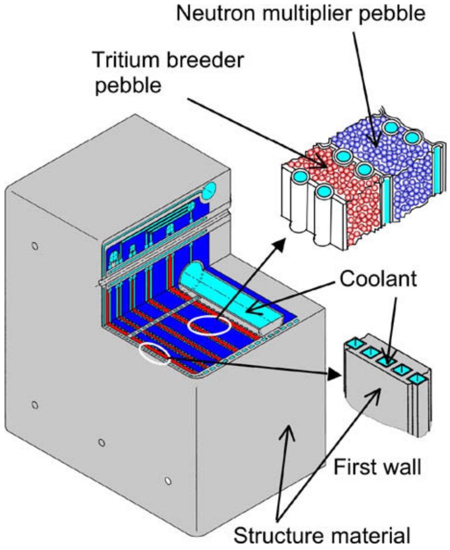

Fig. 1. Schematic view of the typical pebble bed type blanket.

multiplier, Japan and the EU will develop the fabrication technique of beryllide mother rods such as $Be_{12}Ti$ and $Be_{12}V$, and will try to produce pebbles from the mother rods by the rotating electrode method. For the tritium technology, tritium behavior in advanced materials to be used in DEMO, such as RAFM steels, SiC_f/SiC composites, and advanced breeders/multipliers, will be studied. This paper reports on the R&D plan to be implemented in the BA DEMO R&D activities.

2. R&D on reduced activation ferritic martensitic steels as a blanket structural material

The development of blanket structural materials is crucial on the path to fusion power. Experience is now well established for the development and characterization of reduced activation ferritic martensitic (RAFM) steels, such as F82H [6] in Japan and EUROFER [7,8] in the EU, which are now being considered as main candidate materials for structural applications in DEMO. For the manufacture and operation of DEMO, the timely availability of sound engineering bases, such as materials database, modeling/simulation/prediction methods of materials behavior and design methodology, have become indispensable elements in international fusion roadmaps. In particular: (1) the fabrication technology and the materials database must provide highly attractive properties, especially with respect to high thermal efficiency, availability, reliability, irradiation resistance, and reduced activation capability; (2) appropriate techniques must be defined to incorporate the fracture/rupture properties of the irradiated materials into an engineering procedure that allows one to ensure the integrity of the components for the safe operation of a fusion power reactor; and (3) methods need to be developed to predict the deformation and fracture behavior of structures under irradiation from materials databases by modeling/simulation of materials behavior.

2.1. Optimization of fabrication technology

Optimization of manufacturing technology of RAFM steels, such as melting, forging, rolling, milling, to obtain wrought products will be performed. Japan and the EU have experience of small-scale heats of RAFM steels. The next step in the development of RAFM steels also focuses on a further reduction of the irradiation-induced activation of large-scale heats (several tons). The long-term activation level is mainly determined by some minor alloying elements and by impurities. The aim is to define and fabricate a low activation material with recycling times much shorter than those for the 1st generation of RAFM steels. It is important to achieve this with industrial scale production technology and not only for lab scale production (<300 kg).

Optimization of joining technology of RAFM steels and dissimilar materials is also an important technology to be established for the DEMO blanket fabrication. DEMO blanket fabrication requires various welding techniques such as tungsten-inert-gas (TIG) welding, electron beam (EB) welding, YAG laser welding, and diffusion welding, and the weldments must be of the highest quality. In Japan, mock-ups of first wall and side walls for the water-cooled pebble bed type TBM were fabricated by hot isostatic pressing (HIP) using F82H to form a built-in cooling channel structure as shown in Fig. 3. In order to develop the DEMO specific welding technologies, mechanical restraint factors for the various welding methods, and metallurgy based investigation on hot cracking sensitivity will be performed to obtain basic information on RAFM welding.

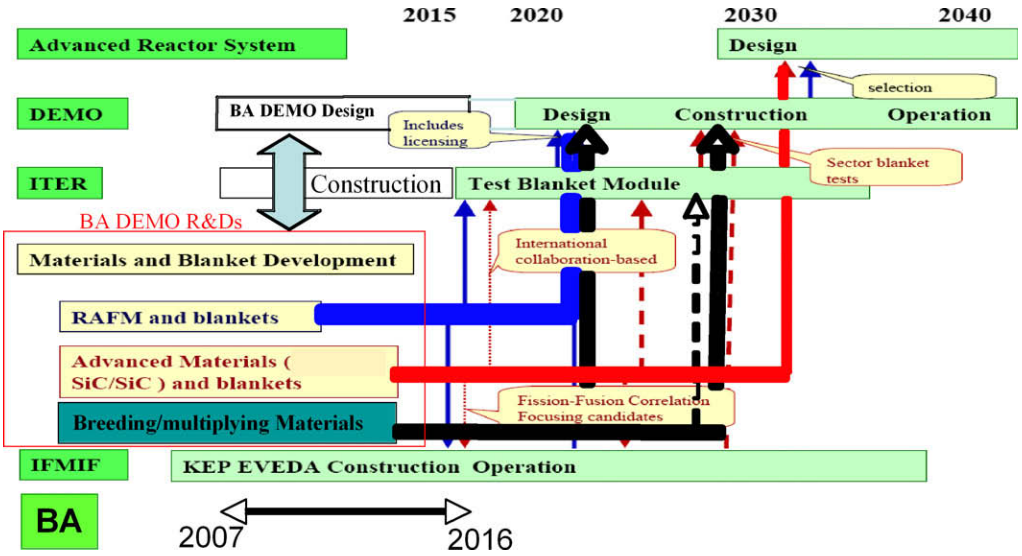

Fig. 2. Roadmap of the blanket material development toward DEMO.

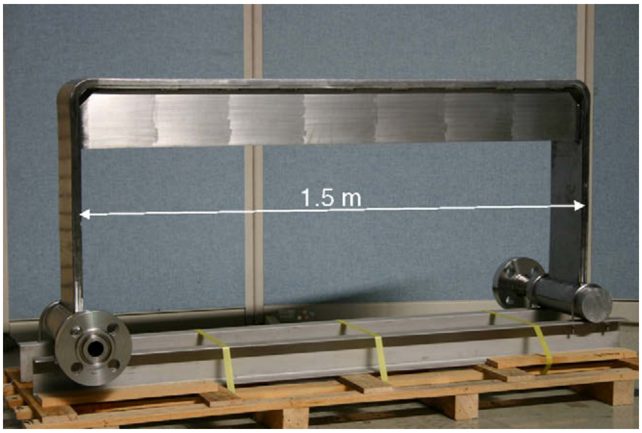

Fig. 3. Mockup of first wall and side walls for the water-cooled pebble bed type TBM fabricated by hot isostatic pressing (HIP) using F82H to form built-in cooling channel structure.

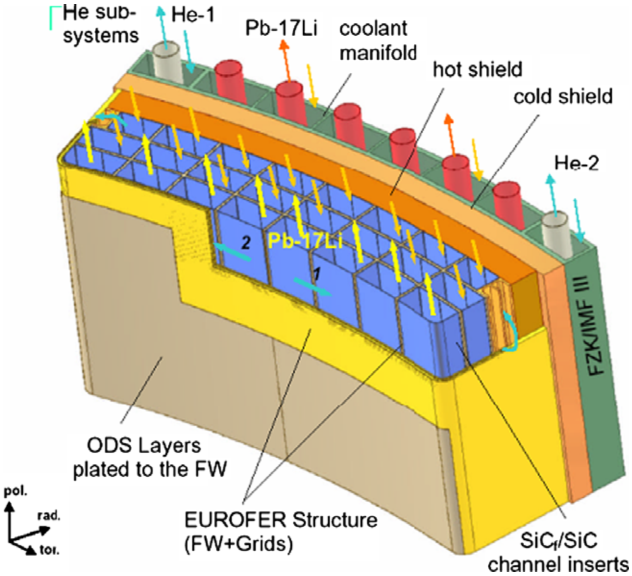

Fig. 4. Schematic view of the dual-coolant lead–lithium (Pb–17Li) liquid breeder blanket (DCLL) system.

2.2. Irradiation effects on mechanical properties and microstructure

Experimental investigation of mechanical properties will be performed using small specimen test techniques, in order to understand the micro-mechanisms of irradiation effects on the mechanical properties of RAFM steels. Not only experimental studies but also simulation will be carried out to characterize the irradiation effects and to quantify the specimen size and geometry effects on the mechanical properties. Fracture toughness, mainly focusing on the applicability of master curve methodology, and tensile tests will be carried out as well as post-test microstructural analyses and finite element modeling of unirradiated and irradiated RAFM steels.

2.3. Basic engineering for materials property and structural design interface

Empirical and theoretical models of the deformation behavior of irradiated RAFM steel structures will be proposed on the basis of detailed analysis of post-irradiation evaluation (PIE) data and on a minimum amount of irradiation experiments. The models are for short-term plasticity/ductile fracture properties (mostly derived from tensile tests), fatigue under irradiation and irradiation creep properties. Irradiated simplified component elements, such as thin plates, plates with holes, and tubes will also be used to evaluate the validity of the models and to prepare basic methodologies for structural design criteria under irradiation in fusion reactors.

3. SiC$_f$/SiC composites

Silicon carbide composites have, and are being developed as a candidate material for the high-temperature operating DEMO reactor aiming at high energy conversion efficiency [9–11]. A conservative but new concept supposes the utilization of SiC$_f$/SiC composites as flow channel inserts for thermal and electrical insulation in the dual-coolant lead–lithium (Pb–17Li) liquid breeder blanket (DCLL) system as shown in Fig. 4 [11]. In addition, recent progress of a new class of advanced SiC$_f$/SiC composites such as nano-infiltration transient eutectic phase sintering (NITE) SiC$_f$/SiC composites [12] has raised their potential for the structural applications in DEMO. Of particular importance is the result that the latest highly-crystalline and near-stoichiometric SiC$_f$/SiC composites have shown superior structural stability to neutron irradiation [13]. With the completion of the ‘proof-of-principal’ phase, the R&D on SiC$_f$/SiC composites is now shifting to the more pragmatic phase of material data-basing for engineering design of SiC$_f$/SiC components.

Critical issues still remaining are (1) development of component fabrication technology including mass production, joining and coating technologies, (2) environmental effects for lifetime evaluation, e.g., oxidation mechanism and compatibility with Pb–17Li, (3) irradiation effects including dynamic issue, i.e., irradiation creep, and synergetic effects of helium and hydrogen, and (4) development of design codes and test standards for the development of a material property database. In the BA activity on SiC$_f$/SiC composites, (1) R&D on mechanical properties of SiC$_f$/SiC composites and (2) R&D on physical/chemical properties of SiC$_f$/SiC composites and other functional ceramics are proposed, being of particular importance to develop practical engineering database for the DEMO design. These R&D activities are performed on plates, tubes, and various joints at high-temperatures and/or under harsh environments.

3.1. Mechanical properties of SiC$_f$/SiC composites

Standardization of testing methods is essential to establish a reliable and practical database for the engineering design of DEMO. However, the test methodologies to evaluate mechanical properties of advanced SiC/SiC composites are not sufficiently standardized for the practical use of design activities. Additionally, these conventional test standards are insufficient to apply for miniature specimens for irradiation study and high-temperature evaluation. For those purposes, it has been recognized that further improvement of the test methodology for SiC$_f$/SiC composites is strongly required. Establishing the test methodology on high-temperature/lifetime properties such as fatigue and creep must be one of the critical R&D items. Evaluation on the off-axial mechanical properties is another important issue due to the intrinsic anisotropy of the composites. Thus, the R&D on SiC$_f$/SiC composites primarily aims to develop small specimen test techniques for lifetime and strength anisotropy evaluation. In development of test standards, evaluation on composite failure behavior, i.e., matrix cracking, which may cause a loss of functionality and structural stability of the composites, is specifically emphasized (see Fig. 5). In parallel, comprehensive modeling of the macroscopic mechanical behavior of advanced SiC$_f$/SiC composites will be developed,

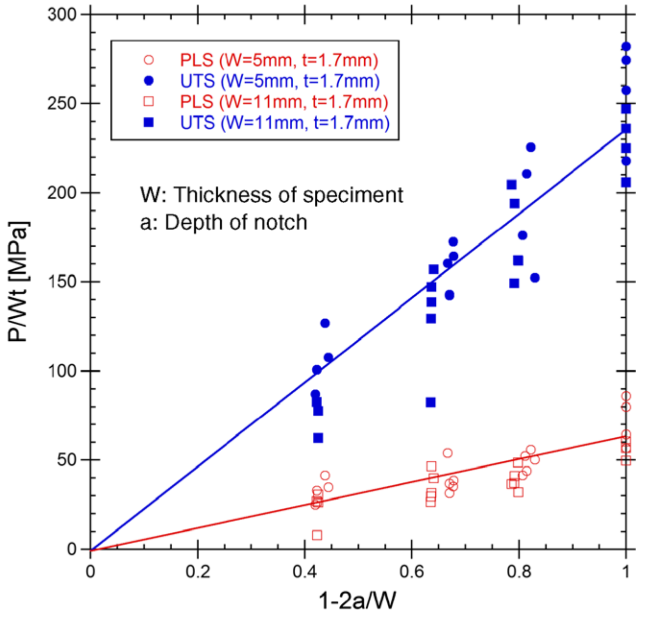

Fig. 5. Example of failure evaluation of advanced SiC/SiC composites by the double notch tensile test method, indicating notch insensitivity and very minor size effect on proportional limit tensile stress (PLS) and fracture strength (UTS).

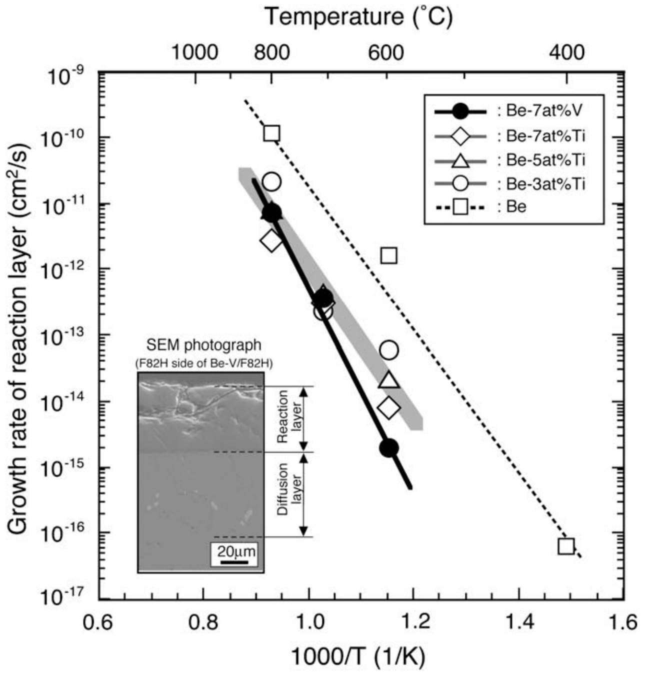

Fig. 6. Growth rate of reaction layer of beryllium and beryllium-based intermetallic compounds on F82H as a function of the reciprocal temperature.

also irradiation effects coupled with characterization of microstructural evolution and swelling behavior under irradiation are evaluated for structural modeling.

3.2. Physical/chemical properties of SiC$_f$/SiC composites and ceramics

Transportational properties of SiC$_f$/SiC composite are readily affected by irradiation depending on temperature and dose rate. The electrical conductivity and permeation of He and H isotopes during irradiation, and the possible detrimental effects on the microstructure of the composites due to displacement damage, He and H implantation will be studied as a part of the R&D items. It is worth noting that this study can readily be extended to functional ceramics other than SiC. It is also recognized that the compatibility between SiC materials and a Pb–17Li liquid metal is of particularly high interest and thus the erosion-corrosion behavior of SiC and SiC$_f$/SiC composites in Pb–17Li at high-temperatures will be studied.

4. Advanced neutron multiplier for DEMO blankets

A DEMO reactor requires ‘advanced neutron multipliers’ which have low swelling and high stability at high-temperature in the blanket design. Therefore, it is necessary to develop a real-size electrode fabrication technique for pebble fabrication by the rotating electrode method (REM) and evaluate characteristics of beryllium-based intermetallic compounds such as Be–Ti and Be–V.

In preliminary examinations, pebbles consisting of Be–Ti alloys were obtained by a small-scale REM [14]. Studies on mechanical and chemical properties and irradiation effects were performed for stoichiometric Be$_{12}$Ti (Ti content: 7.7 at.%) fabricated by HIP as well as for Be–Ti alloys with the αBe phase fabricated by arc melting [15]. As to compatibility between Be–Ti alloys (Ti content: 0–8.5 at.%) and structural material of F82H, the growth rate of the reaction layer on F82H decreased with increasing the Ti content up to 5 at.%. Both oxidation and steam interaction were about 1/1000 as small as those for beryllium metal. These results indicate a possibility to reduce a risk of a water or air ingress accident and to achieve a blanket with high efficiency of electric power generation.

Recently, compatibility studies between Be–V alloy and structural materials have begun with preliminary tests [16]. Fig. 6 shows the growth rate of the reaction layer on F82H as a function of the reciprocal temperature. The growth rate of the reaction layer on F82H was about 1/1000 as small as that of beryllium and was approximately the same as that of Be–Ti alloys.

A considerable challenge at present is the development of a technology that allows the fabrication of pebbles despite of the extreme brittleness of beryllides. It is therefore a common goal for both the EU and Japan to fabricate the beryllide pebbles and to evaluate characteristics of these beryllides in the DEMO R&D of BA. This R&D project consists of preparation of test facility, fabrication, and characterization of beryllides. The content of the joint proposal is to fabricate beryllides by using a similar process as presently used for the fabrication of Be pebbles. The critical steps are to develop fabricating processes that (i) master the extreme brittleness of Be-rich beryllides, and (ii) guarantee sufficient homogeneous alloy composition throughout the entire rod. Characterization of the fabricated beryllide samples is essential and will be performed in this project.

5. Advanced tritium breeders for DEMO blankets

DEMO reactors require ‘^{6}Li-enriched tritium breeders’ which have high tritium breeding ratios (TBRs) in the blanket designs of the EU and Japan. Both these parties have been promoting the development of fabrication technologies of Li_2TiO_3 pebbles by the direct wet process [17] and of Li_4SiO_4 pebbles by melt-spraying [18] including the reprocessing [19], and presently the EU and Japan are evaluating the properties of such tritium breeders, including ^{6}Li-enriched Li_2TiO_3 pebbles and Li_4SiO_4 pebbles.

However, the fabrication techniques of tritium breeder pebbles have not been established for large quantities. Therefore, a collaborative project has been launched for scaleable and reliable production routes of advanced tritium breeders. In addition, this project aims to develop fabrication techniques allowing effective reprocessing of ^{6}Li. The development of the production and ^{6}Li

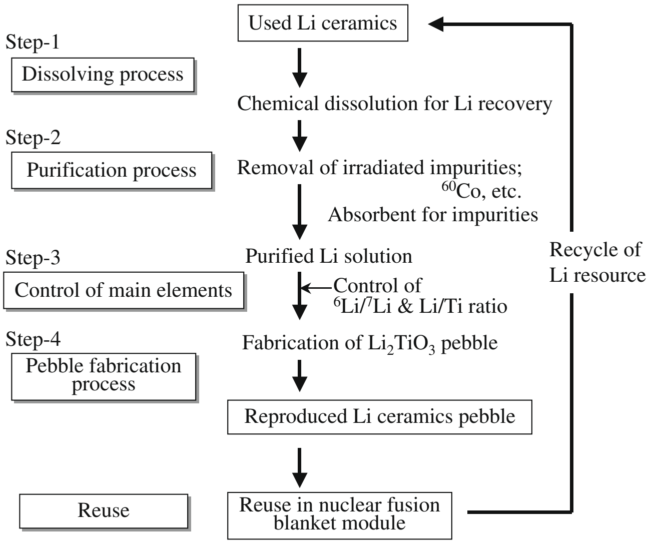

Fig. 7. Conceptual reprocessing process for tritium breeding materials.

reprocessing techniques includes preliminary fabrication tests of breeder pebbles, reprocessing of lithium, and suitable out-of-pile characterizations.

Fig. 7 shows a conceptual diagram of the lithium recovery process which is being studied in Japan [20]. Step-1 (dissolving process) and step-2 (purification process) were investigated so far in preliminary experiments. Lithium recovery of more than 90% was attained by an aqueous dissolving method using HNO_3, H_2O_2 and citric acid. Furthermore, decontamination efficiencies of ^{60}Co were 97–99.9% using a new chemical adsorbent, i.e., activated carbon impregnated with 8-hydroxyquinolinol. More details are given in Ref. [20].

In the BA activities, the experimental equipment for the advanced breeder production and characterization will be prepared at the starting stage of 2007–2011. Thereafter and in parallel, the following studies will be carried out;

(i) production of advanced Li_2TiO_3 and Li_4SiO_4 pebbles,
(ii) characterization of the advanced tritium breeder materials in physical, chemical, mechanical and other properties, such as stability of the advanced Li_2TiO_3 and Li_4SiO_4 pebbles as a function of temperature and exposure to purge gas atmospheres, and
(iii) reprocessing and re-use of tritium breeder materials, e.g., dissolution and removal of simulated radioactive products in the case of Li_2TiO_3 [20], and re-melting in the case of Li_4SiO_4.

6. Tritium technology

The tritium technology is one of the most significant subjects for fusion DEMO plants. A series of basic studies has been carried out to develop an advanced tritium recovery system for an ITER test blanket module. In contrast to ITER, a series of continuous operations is required for the main fuel and the blanket tritium loops for a DEMO plant. The R&D subjects for monitoring and analysis of tritium in these loops are required from the viewpoint of the control of the loops. In addition, the components of the loops in a DEMO plant are consequently exposed to tritium for a long period. Some new materials will also be used in a DEMO plant. Improvement of the basic tritium behavior database and demonstration of practical operation durability will enhance design, safety, and public acceptance for DEMO. Therefore not only R&D on the monitoring and analysis techniques of tritium but also tritium behavior studies in advanced materials to be used in DEMO will be carried out in the BA activities.

It is required to obtain basic data for the relation between tritium and materials from the viewpoint of the estimation of the amount of tritium permeation. The above basic data should also contribute to enhance safety designs and public acceptance for a DEMO plant. A basic tritium behavior database must be developed containing information such as solubility, diffusivity, permeability, characteristics of trapping, release, replacement, reaction etc. for advanced materials in DEMO. Tritium will be introduced into advanced material samples by various methods, such as thermal absorption, ion (plasma) implantation, etc. Tritium permeation and/or release experiments will be performed using the above samples and the basic characteristics of tritium behavior will be evaluated with the analysis of residual tritium amount in the material. The influence of impurities and traps on the tritium behavior in advanced materials will be also investigated. Also advanced tritium permeation reduction layers (permeation barriers) will be developed. To improve the physical stability of the barrier, oxidation layers for glass materials will be evaluated by the permeation reduction factor (PRF) measurement and alternative barriers with self-repairing function will be investigated. Durability tests for the barrier will be performed by measurements of PRF before and after irradiation or exposure under fusion reactor conditions.

7. Summary

In the planned broader approach (BA) activities, R&D on a reduced activation ferritic martensitic (RAFM) steels as a DEMO blanket structural material, SiCf/SiC composites, advanced tritium breeders and neutron multiplier for DEMO blankets, and tritium technology will be carried out. In the R&D on the RAFM steels, the fabrication technology, techniques to incorporate the fracture/rupture properties of the irradiated materials, and methods to predict the deformation and fracture behaviors of structures under irradiation will be investigated. For SiC_f/SiC composites, standard methods to evaluate high-temperature and lifetime properties will be developed. Not only for SiC_f/SiC but also related ceramics, physical and chemical properties such as He and H permeability and absorption will be investigated under irradiation. For the advanced tritium breeder R&D, Japan and the EU plan to establish the production technique for advanced breeder pebbles of Li_2TiO_3 and Li_4SiO_4, respectively. Also physical, chemical, and mechanical properties will be investigated for produced breeder pebbles. For the advanced neutron multiplier, Japan and the EU will develop the fabrication technique of beryllide mother rods such as $Be_{12}Ti$ and $Be_{12}V$, and will try to produce pebbles from the mother rods by the rotating electrode method. For the tritium technology, tritium behavior in advanced materials to be used in DEMO, such as RAFM steels, SiC_f/SiC composites, and advanced breeders/multipliers, will be studied.

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