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Journal of Nuclear Materials 283–287 (2000) 20–27

journal of nuclear materials

www.elsevier.nl/locate/jnucmat

Interactions between fusion materials R&D and other technologies

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Abstract

The importance of interactions between fusion materials research and development (R&D) and other technologies is emphasized to make attractive and realistic fusion technology integration activities. The focuses are on: (1) materials design and processing, (2) safety issues relating to materials and (3) material performance evaluation methodologies, including 14 MeV neutron source utilization for fusion material R&D. As typical examples, material design activities on reduced activation ferritic steels, vanadium alloys and SiC/SiC composite materials are provided. The safety assessment of reactor systems and reactor design code consideration including prediction methodologies of materials performance are also discussed. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

Fusion research is currently faced with many different and difficult demands worldwide. Thus each national fusion program is changing priorities and moving in near-term directions. These make the future of ITER unclear. As it was presented by Professor of Inoue, Chair of fusion council, Japan [1], the Japanese fusion program is rather stable and is trying to keep a balance in a wide range of fusion research. Japan is at the third phase of its basic program that is directed at developing fusion as a viable energy option for the future. Ignition and long-burn (steady state operation) are goals of the program. Therefore, construction of an experimental reactor has the highest priority and serious discussions are on-going in support of a decision on ITER construction. In parallel, Japanese programs are studying various concept improvements in plasma confinement, as well as materials development and reactor technology. Reactor technology improvements include safety improvements, low activation materials research and development (R&D) and reactor relevant technology R&D. Throughout many international and domestic strategy discussions, the importance of knowledge sharing and technology transfer with the non-fusion community has been stressed [2,3]. In addition, it is necessary to present a realistic R&D scenario to develop fusion as an attractive future energy option. Here, high performance, low activation materials and related reactor technology development are well known as the key issues. In order to accomplish the many difficult tasks to meet fusion R&D goals with available resources, reliance on advancements from non-fusion technologies is requisite. On the contrary, to get support from the non-fusion community, spin-offs from fusion technologies to non-fusion applications is very important. Hence, interactions between fusion R&D and other technologies have to be well managed.

This paper tries to identify possible paths whereby such interaction can be fostered. This paper will also try to answer the question; ‘Is it feasible to make low activation materials?’ which can be divided into the following questions:

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PII: S0022-3115(00)00156-2

1. Does material cost become sufficient to make economically attractive fusion energy?
2. Does material performance become sufficient to make attractive fusion power plants?
3. Do low activation properties become satisfactory for the public?

2. Impact of material on fusion energy cost

There are many impacts of material related costs on the total cost of fusion energy. Construction cost is one, where materials and component fabrication costs are known to be the major components. Operating costs are strongly dependent on operating conditions and component lifetimes, thus material performance as well as cost have a strong impact. Through plant efficiency (conversion efficiency of thermal energy to electricity), operating conditions strongly influence the cost of electricity (fusion energy cost); thus materials, which can operate at high temperature, improve plant efficiency and lower costs. Maintenance cost depends on accessibility for maintenance and applicable processes, thus low activation and resistance to degradation reduces costs. Also, decommissioning and waste management are important cost components in the fusion material lifecycle, and the major part of this cost is dependent on the activation characteristics of the materials. At the same time, the cost of fusion energy is dependent on the fusion reactor concept and design. Therefore, it is very difficult to precisely evaluate the impact of materials on energy cost. As an example, the cost estimate of ITER construction is shown in Fig. 1 [4]. The magnet cost comprises nearly 1/3 of the total cost, while magnet materials cost (excluding magnet structural material) is only about 7%. Divertor and blanket material costs are about 1% each, mostly for non-structural material costs, the major costs coming from Be and high heat flux materials. The vacuum vessel and cryostat material costs are about 0.5% each, mainly from structural material cost. The important conclusions from the figure are: (1) extensive cost reduction and material performance improvement are urgent for magnet materials, Be and high heat flux materials, and (2) the cost of 316 stainless steel is a small fraction of the system cost and may serve as a good target for other materials R&D.

Although it is very difficult to predict material cost reduction quantitatively, based on available data a very rough estimate is made, as shown in Fig. 2. In making this estimate the important assumptions were:

1. A large cost reduction could be made by technology improvement and by the introduction of large-scale production. This is strongly supported by past experience. For example, SiC/SiC cost reduction is based on the history of C/C price reduction.
2. R&D activities leading to improvements will be supported by the non-fusion community in expectation of spin-offs from fusion.

Fig. 2 indicates that low activation ferritic steels, like JLF-1 and F82H are within a factor of three of the cost of ITER grade 316SS and 9Cr-steel.

Vanadium alloys are more than two orders of magnitude more expensive than 316SS, and a projected cost reduction still looks to be more than one order of magnitude higher cost than that of 316SS. A potential further cost reduction of vanadium alloys might be associated with an extended use of vanadium in hydrogen storage and recovery from industrial wastes, which will be promoted in the future by environmental policy. This will be discussed later.

The price of SiC/SiC should come down to 10% of the current price by large-scale production. Still the reduced cost will nearly be the same as the current vanadium cost. The price of SiC fibers might be expected to come down to within a factor of 10 of the price of 316SS based on the cost reduction history of the C fiber. The innovation of new SiC/SiC fabrication processes will be required to get the price of SiC/SiC to be very close to that of 316SS.

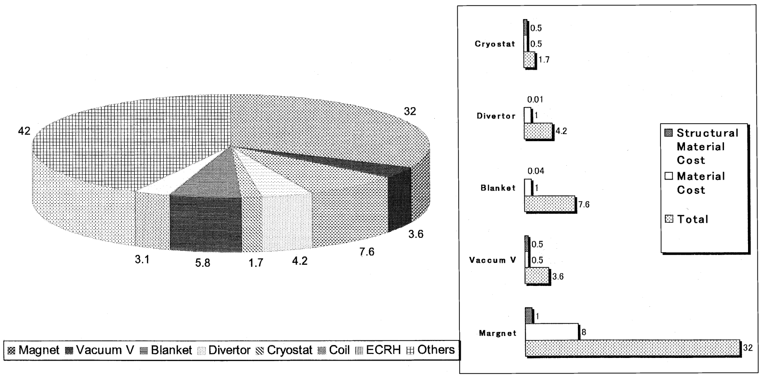

Fig. 1. Cost estimate of ITER construction – from ITER FDR –.

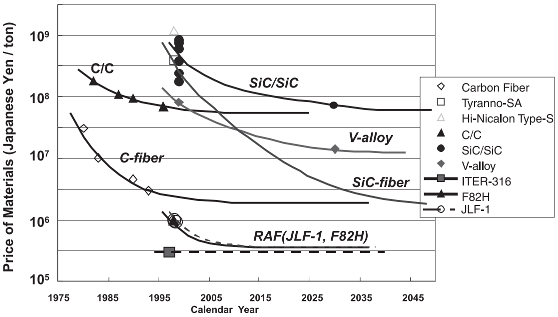

Fig. 2. Cost estimate of fusion materials.

In order to make a fairer comparison of the material cost, an ‘equivalent materials cost (EMC)’ is proposed as Equivalent materials cost = Price of material × Plant efficiency/specific strength (at the operating temperature).

The EMC gives the materials cost to produce equivalent electricity. However, in an EMC-based comparison, low activation ferritic steels and SiC/SiC composite materials are still more than one and two orders of magnitude lower, respectively, in cost than V-alloys. This estimate is very close to values shown by Zinkle at ISFNT-5 [5]. This result indicates the strong need for a breakthrough on cost reduction and performance increase of vanadium alloys and SiC/SiC composites which may be enhanced by a strong interaction with non-fusion activities.

Another important issue for attractive fusion reactors is to make advanced blanket systems with sufficient plant efficiency. Fig. 3 compares an advanced blanket systems to produce low cost electricity. ITER and near term fusion reactors are designed to use water cooled solid blanket systems and saturated steam turbines to make electricity. In this case, austenitic stainless steels and low activation ferritic steels can be used as structural materials resulting in a plant efficiency about 33%. However, this cannot produce competitive low cost electricity against other currently available energy options. To make competitive electricity from fusion, other higher plant efficiency blanket systems are currently under development. These are super-critical pressurized water-cooled solid blanket systems, self-cooled liquid blanket systems and gas-cooled solid blankets, where potential plant efficiencies are about 40%, 45% and 50%, respectively. In these designs, low activation oxide dispersion strengthened (ODS) ferritic/martensitic steels, vanadium alloys and SiC/SiC composite materials are considered to be used. The baseline properties of these advanced materials principally satisfy design requirements. But the materials performance in fusion environments is currently quite limited, and materials performance in blanket systems is little known. This requires systematic R&D activities on materials in support of fusion blanket development, as well as strong interaction with non-fusion activities.

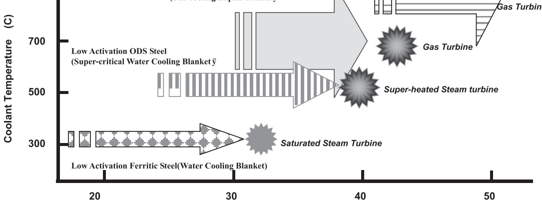

Fig. 3. Attractive fusion energy with advanced blanket systems.

3. Low activation ferritic steel R&D

The recent progress of low activation steels has been considerable [6–8], and F82H and JLF-1 are being considered for application to an ITER test blanket module [1]. Still it will be difficult to meet the ITER blanket goal, unless the large industrial scale low activation ferritic steel production is supported by the steel industry. The current report by the Iron and Steel Institute of Japan, 12 May 1999 [9], ‘R&D Strategies of the Japanese Steel Industry – Science and Technologies of Steel for the 21st Century –’ clearly defines four future tasks in R&D of iron and steel as:

1. Highly efficient and environmental-friendly ironmaking.
2. New steel products that contribute to a recycling-oriented society.
3. New steel applications that are conducive to an ecologically friendly society.
4. Comprehensive and basic support technology. Here, the following are emphasized:
    - high-performance, ultra high-purity, low cost steel R&D;
    - reuse and recycling process development;
    - energy production and energy conversion materials R&D;
    - advanced analysis and evaluation technology R&D.

These are consistent with low activation ferritic steel R&D, and the Japanese steel industry will continue this effort to support low activation ferritic steel R&D for fusion.

Another important activity in Japan is the national program ‘Creation of Ultra-Steel for the 21st Century’ at the National Research Institute for Metals under the Science and Technology Agency [10]. The first phase of this project is from 1997 to 2001 and the second phase will be started from April 2002 to March 2007. As one of the research tasks, the 'Advanced Ferritic Steels for 650°C USC Boilers' program is now collaborating with the low activation ferritic steels R&D for fusion. The primary objective of this study is to develop high-Cr, ferritic steels for ultra-supercritical (USC) steam boiler operations at 650°C and 350 times atmospheric pressure. The R&D concepts are quite similar and the major feature of the current research is stabilization of the tempered martensitic steel microstructure for long times at 650°C to guarantee creep strength.

As is well known, ferritic/martensitic steels exhibit good dimensional stability (low swelling and creep) in intense neutron environments at temperatures below 500°C. This is one of the reasons that these alloys have been developed for fast breeder reactor (FBR) applications. Strength of the alloys at high temperatures is, however, not high enough for application in a liquid metal cooled energy system with high thermal efficiency. Moreover, loss of fracture toughness (associated with a DBTT shift) by irradiation at low temperatures is significant. At temperatures higher than 400°C, the effect of irradiation on DBTT is rather small. Therefore, the irradiation induced DBTT shift may not be a problem for the gas or liquid metal cooled blanket concept operated above 400°C. On the other hand, the DBTT shift seems to be one of the largest problems for a blanket cooled by pressurized water near PWR conditions. A pressurized water cooling concept is suitable for a blanket concept with high wall loading, and has been chosen for the blanket concept of the prototype reactor steady state Tokamak reactor (SSTR) in JAERI. A high wall loading capability is beneficial for the reduction of reactor size and cost, although the thermal efficiency of the water-cooled blanket concept for cost-competitive electricity is not satisfactory, as was discussed previously. This upper temperature operation boundary issue is the next target for the low activation ferritic steels R&D. Improvement of high temperature strength is not only beneficial for the improvement of plant efficiency, but also beneficial to reducing the damage by high heat flux during plasma disruption. Improvement of high temperature strength by the dispersion of nanometer sized oxide particles in the reduced activation steels by mechanical alloying techniques (reduced activation ferritic/martensitic ODS steels) is a current intense R&D effort. The utilization of knowledge and information on ODS development in FBR programs is very important, and knowledge sharing and technology transfer have been initiated.

4. Vanadium alloys R&D

Vanadium alloys potentially have very attractive overall performance as fusion reactor structural materials. There are, however, a number of outstanding R&D needs, mainly because this class of material has never been used in large scale structural applications. On the laboratory scale, melting, fabrication to a variety of product shapes, welding, etc. are relatively easy, provided that impurity pickup from the environment is effectively avoided. On a larger scale, the feasibility of these processes has yet to be demonstrated, since the procedure to avoid impurity pickup is usually not a trivial task. The second major issue is the development of an insulator coating necessary to decrease MHD loss in self-cooled liquid metal blanket concepts. The third issue would be to assess the irradiation resistance of these materials in a fusion-relevant neutron environment. This is more or less common to all candidate structural materials. Since the technical details of the R&D needs for V-alloys have been addressed in another paper in this conference [11], the general strategy of vanadium alloy development is described here. In the current effort to produce a large heat at NIFS, reduction in interstitial impurity content is the first priority. This campaign will be highlighted below.

Within the budget constraints, accomplishing all the tasks listed above solely in fusion programs would be difficult, and it appears necessary to utilize resources outside fusion programs. Seeking applications of vanadium alloys in other industries is important not only because of the potential to share R&D tasks, but also in reducing product costs.

One of the issues raised in the last few years is the rather significant ductility loss of vanadium alloys after irradiation at and below 400°C. This finding is primarily the result of extensive irradiation tests focusing on relatively low temperatures because of the interest in possible application of vanadium alloys in ITER. The real advantage of vanadium alloys is in their high temperature performance, and the ductility loss after relatively low temperature can be avoided at the higher temperature. However, it would be nice to have a wider design temperature window. In recent studies [12], it has become clear that reducing interstitial impurity content, especially oxygen, can significantly mitigate this ductility loss. Thus, in the campaign to produce a large heat of vanadium alloy in NIFS, emphasis is on reducing the content of interstitial elements. The first step is the utilization of low cost industrial wastes, which would be promoted in the future by environmental policy. Vanadium can be extracted from Bayer sludge generated during recovery of alumina from bauxite and oil by-products. In Japan, crude oil residue and oil fired ash are extensively used for extraction of vanadium. The total production rate is comparable to that of imported ores. About 90% of the vanadium imported as an oil component is, however, disposed of presently. In the future, the availability of vanadium will increase with enhanced use of low-grade petroleum. It should be noted that these industrial wastes are more suitable than ores for production of high purity vanadium because they contain very limited kinds of impurities. High purity raw vanadium is essential for producing high-quality vanadium alloys for fusion applications. Assuming a large incentive for using industrial wastes, the cost of vanadium alloys could be reduced to 5% of the present level.

Another attractive feature of vanadium is its high hydrogen storage capability. Recently, increasing attention has been paid to vanadium alloys as hydrogen storage materials, and alloy optimization has been pursued for maximum hydrogen storage capacity [13]. However, oxygen impurities are known to reduce diffusivity and the effective strage capacity of hydrogen [14]. Thus, reduction of the oxygen level is a critical issue for developing vanadium alloys for hydrogen storage materials. This is also a common issue to their development for fusion applications. Accordingly, it is expected that the reduction of impurity levels recently carried out by NIFS and Japanese industry [11] will be applied to the development of vanadium-based hydrogen storage alloys. This sort of mutual benefit will promote vanadium alloy development both in fusion and in non-fusion application areas. It will be important to encourage such a bi-lateral flow of information and resources.

5. SiC/SiC composite materials R&D

Since silicon carbide possesses excellent thermal properties, oxidation resistance, strength and low activation, recently there have been many research efforts to develop silicon carbide-based advanced composites for use in energy conversion systems, aviation and aerospace systems [15–17]. One of the good examples is the Japanese project on ‘Advanced Materials Gas-Generator’ known as the AMG project [15]. The first stage was 1993–1998. The second stage is going to be during 2003, where 20% and 50% reduction in fuel consumption and in engine weight, respectively, are the goals. A 70% reduction in NO_x emission is also a goal. R&D of a ceramic matrix composite (CMC) combustor and turbine are the important tasks. As a result of the first stage efforts, combustors and turbines made with SiC/SiC were successfully developed. Under collaboration with the AMG project, the CREST-ACE program [16] is developing many fabrication processes for SiC/SiC and SiC fibers. SiC fiber development is an important activity, where polymer-derived fibers have been developed; and further efforts to develop new polymers and polymer and particle blending schemes are underway. There have been many improvements in both processing and concepts of interfacial coating, and multiple coating with SiC and C layers have helped successfully achieve excellent mechanical properties. A new production method of SiC/SiC, the polymer impregnation and pyrolysis (PIP) method with poly-vinyl-siran (PVS) and PCS-type SiC fibers, provides excellent mechanical properties with sufficient fiber pull-out without a fiber coating [18]. The transfer of the reaction sintering (RS) process from the AMG project to the CREST-ACE project provides a good example of technology transfer. High thermal conductivity (120 W/m K) SiC developed for the combustor liner by a modified RS process with optimized process parameters has improved the three point bending strength from 300 to 1000 MPa. This was done by a reduction and fine dispersion of the remaining Si phase in SiC. This technology has been applied to the semi-conductor industry, and is a good example of spin-off from fusion activity. This process is now under further improvement to make SiC/SiC for fusion. Another example of a spin-off is the oxide filler addition to the matrix [19], where the tensile strength of PIP SiC/SiC has been improved from 300 to 500 MPa at room temperature and from 150 to 400 MPa at 1400°C. This material is ready for non-fusion applications.

Fig. 4 shows improvements of tensile strength retention after high temperature heat treatment of polymer driven SiC fibers. From Nicalon fiber to Tyranno-SA fibers, the temperature at which degradation of fiber strength begins in air after 1 h has been improved from about 1000°C to more than 1800°C. This improvement was made, as shown in the lower figure in Fig. 6, by reduction of the remaining free oxygen by oxygen-free electron curing of the precursor polymer followed by the reduction of excess C to stoichiometry by de-carburizing. This process improvement at Nippon Carbon was made at the expense of a price increase. However, the new process at Ube for the production of Tyranno-SA neither requires electron curing nor de-carburizing processes, thus the fiber cost is unchanged. The improvement in high temperature resistance opens wider capabilities in production process options. By using Tyranno-SA fibers in PIP SiC/SiC production with a final process temperature at 1600°C, high thermal conductivity SiC/SiC has been successfully produced [18].

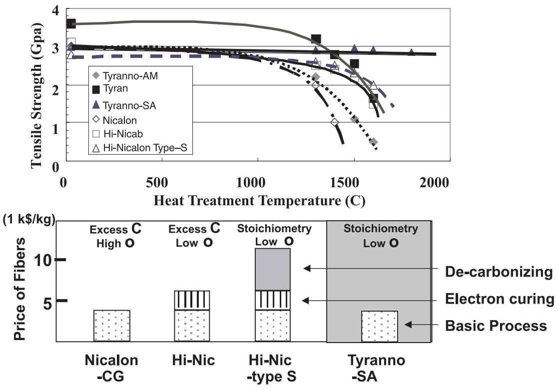

Fig. 4. SiC fiber development and price change.

6. Technology exchange in the field of safety

Safety, including the reduction of radioactive wastes, is an essential issue for nuclear power to become acceptable to the public. For the safety of fusion reactors, containment of tritium is one of the major factors. The containment is expected to be achieved by multiple barriers: the blanket, the vacuum vessel, the cryostat and the building [20]. The vacuum vessel is recognized to be one of the most important barriers to tritium leakage. For the integrity of the vacuum vessel, development of a structural design methodology is an important first step.

Fig. 5 indicates materials database and design code development related to ITER from non-fusion activities and anticipated spin-offs from ITER related design activities. Major inputs from non-fusion activity to ITER are from currently existing databases and design codes, such as ASME sec. III, MITI-501, RCC-MR and others. These have been partly modified to accommodate ITER conditions – e.g., fusion structure design (FSD) subcommittee activity in Japan – and are applied to the ITER vacuum vessel and other major components. Although irradiation induced mechanical property changes in the blanket of the prototype reactor will be significant, the current methodology of structural design may not be enough to cope with the large material property changes induced by irradiation. (The irradiation effects for first wall and blanket of experimental reactors are expected to be rather small.) FBR core components are exposed to intense neutron irradiation to a high fluence level. The structural design methodology for core components of FBRs, and LWRS takes into account the loss of elongation and the change of deformation mode by irradiation [21]. The loss of elongation (or loss of work hardening capability) is taken into account in the ITER structural design criteria (ISDC for ITER). Codes for blanket and in vacuum vessel components have been made based on codes for FBR fuel elements, such as the Monju internal code. The important modifications tried to include fusion neutron irradiation effects, but observations of these effects have been limited to very low neutron fluence levels. Throughout the final design activities and construction/operation of ITER, important outputs for prototype and DEMO reactors are anticipated. Together with data from the international fusion materials irradiation facility (IFMIF) and fission reactors, more accurate and generic inputs to a spallation neutron source design, to the IASCC issue in light water reactors, and to high temperature gas reactor and FBR design code issues should be possible.

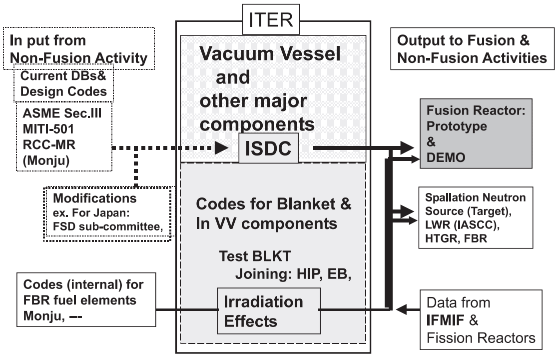

Fig. 5. Materials database and design code development.

To decrease the amount of radioactive-waste, reduction of induced activity in structural materials by modifying their composition is another important contribution. Requirements on the reduction of induced activity depend on the radioactive-waste management plan. Scenarios of recycling and shallow land burial after 50–300 years have been proposed. Based on Japanese regulations for radioactive-waste from fission reactors, the maximum permissible levels of impurities in fusion reactor blanket structural materials after operation to a fluence level of 10 MWa/m^2 have been estimated. The results indicate that the critical elements for reduced activation ferritic/martensitic steels are N, Mo and Nb; and their levels need to be lower than 20, 5 and 1 wtppm, respectively [22]. A heat of F82H was melted using a commercially available vacuum arc melting facility and with commercially available electro-refined raw materials (iron, chromium, tungsten, etc.). The content of Nb in the heat was reported to be 0.7 wtppm [23]. As the heat was not melted in a manner to reduce the Mo content, the level of 20 wtppm for Mo did not satisfy the requirement. However, it is quite possible to reduce Mo content lower than 5 wtppm under the current technology. Reduction of N is rather difficult compared to Mo and Nb; however, the requirement for N is not severe and does not seem to be a difficult problem to overcome with current commercially available processes. There may not be a serious difficulty in satisfying the requirement for each element, independently. It is suggested that the use of high purity raw materials for reducing impurity levels should be effective. It would be quite reasonable to achieve impurity levels 1–10 wtppm simultaneously in the prototype reactor development program. In Fig. 6, the electricity produced at the point induced activity reaches levels for shallow land burial scenario is shown against first wall and blanket life. The estimates in the figure are for the required life for the first wall and blanket of a prototype reactor with F82H low activation steel for SSTR, vanadium alloy for ARIES-RS and SiC/SiC for DEAM. Fig. 6 indicates that materials with high impurity control (low activation ferritic steel, vanadium alloy and SiC/SiC composite) can be attractive low activation materials with sufficient potential for application to electricity production while satisfying the Japanese shallow land burial requirements. These targets, while not easy, would be realistic and within reasonable material cost.

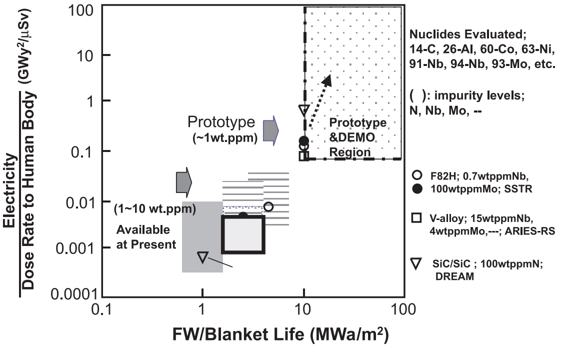

Fig. 6. Electric power vs. radioactive-waste relation (shallow land burial).

7. Material performance evaluation methodology R&D

Reduced activation ferritic/martensitic steels and vanadium alloys would suffer from serious irradiation embrittlement at low temperatures in prototype and DEMO reactors. Also, the low ductility and toughness characteristics of SiC/SiC composites would be further degraded in these reactors. Moreover, precise knowledge about fracture mechanisms under fusion conditions is not well established. To maintain structural integrity of LWR pressure vessels, chemical plants and gas tanks, advanced fracture mechanics and improvements in flaw inspection are recognized to be important for reduction of excess margins and to rationalize inspection methods. Thus it is important to take advantage of this progress to establish the structural integrity of the first wall and blanket structure of a prototype fusion reactor. To establish an underlying database on the effects of irradiation on structural materials in a fusion environment, an intense 14 MeV neutron source and fission neutron/charged particle irradiation technologies are essential. To meet the current Japanese fusion R&D scenario, fission/fusion neutron and charged particle irradiation should be used in a complementary approach. The urgent needs of an intense 14 MeV neutron source have been stressed now for more than a decade, and IFMIF activities are still on-going. However, a clear decision to construct IFMIF or an IFMIF-like facility has not been made yet. Recently, IFMIF cost reduction and a staged construction approach has been assessed for accelerating IFMIF construction under joint international efforts [24]. As shown in Fig. 7, even the reduced cost IFMIF and staged approach will rely on inputs from previous efforts to make 14 MeV neutron sources like FMIT, ESNIT and APT. Needless to say, small specimen test technology (SSTT) will be required and supporting R&D should be promoted for the test facility design and utilization of IFMIF. From the IFMIF activities, many valuable lessons, which can provide a basis for advanced intense accelerator technologies, should result as outputs. These could serve neutron science and industrial and medical applications.

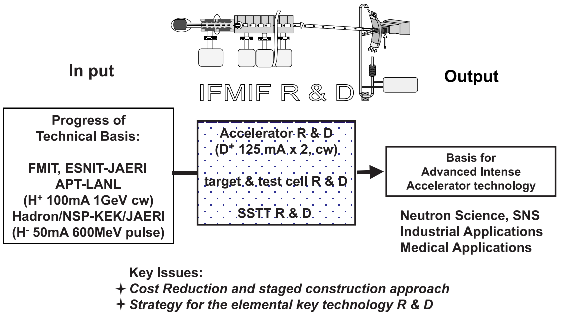

Fig. 7. Intense 14 MeV neutron source R&D.

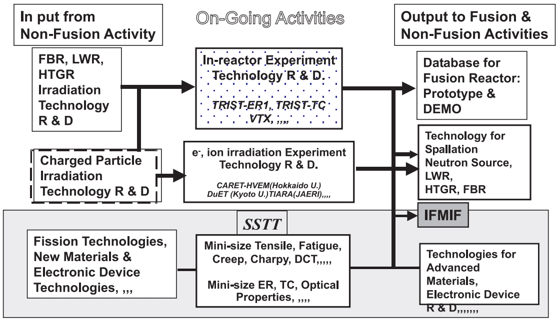

Fig. 8. Fission neutron and charged particle irradiation technologies and SSTT developments.

Fig. 8 briefly indicates the history and future prospects for fission neutron and charged particle irradiation technologies. The recent Japanese emphasis on charged particle irradiation technologies supports not only fusion R&D but many non-fusion efforts as well. The CARET facility (Hokkaido University) [25], TIARA (JAERI) facility and DuET facility (Kyoto University) [26] support electronic devices, biomass management, ultra high temperature materials R&D and others, but they also support fusion activities. On the other hand, SSTT R&D activities for fusion research have both been utilized and are under active consideration for non-fusion applications. This knowledge sharing and information exchange is very important in keeping fusion engineering R&D efforts more efficient and more economical.

8. Conclusions

The current status and future prospects of interactions between fusion materials R&D and other technologies have been reviewed and their importance to one another has been emphasized.

The focuses have been on: (1) materials design and processing, (2) safety issues related to materials and (3) material performance evaluation methodologies, including 14 MeV neutron source utilization for fusion materials R&D. As typical examples of fusion materials R&D, efforts on reduced activation ferritic/martensitic steels, vanadium alloys and SiC/SiC composite materials have been reviewed. The safety assessment of reactor systems and reactor design code consideration, including prediction methodologies of materials performance, has been discussed. The urgent needs of an IFMIF type intense neutron source and fission neutron/charged particle irradiation facilities are apparent.

ITER and IFMIF construction should have the highest priority in fusion engineering development, where knowledge sharing and technology transfer are keys for success.

Acknowledgements

This work was partly supported by Japan-US collaborative JUPITER program on fusion materials research.

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