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15.8. Materials R&D strategies in the next decade
(Session Organizers: K. Abe, F.W. Wiffen, M. Victoria and M.I. Solonin)

Materials research and development strategy in the next decade

1. Organizer's intention

In order to make fusion reactors a competitive and safe energy source, it is necessary to make intensive progress in the development of materials system in the next decade. What strategies and international activities are crucial?

(1) Materials R&D master plan which substantiates the time frame of fusion reactor development, (2) Realization of fusion relevant neutron source (IFMIF and complementary facilities) and utilization of fission reactors, (3) International collaboration through multilateral and bilateral programs, based on current and potential activities in each party.

K. Abe: We, organizers, set three points to be included to discuss material R&D strategy in this session. First, we have to make a master plan based on the time frame of fusion reactor development. Second, we do need a fusion relevant neutron source. Third, we have to strengthen multilateral and bilateral international activities. The keynote will cover the first and second, and prepared discussions will talk about the standpoint from each party.

2. *K. Ehrlich*: Keynote on 'Long-term target of materials development for fusion reactors'

(1) *Assumption and replacement of first walls/blankets*: A commercial fusion reactor (CFR) has to be competitive with conventional power stations such as light water reactors, which operate with a lifetime of 30 full power years and with a thermal efficiency equal to or greater than 30%. Consequently, for a neutron wall loading (NWL) of 2 MW/m^2, an integrated NWL of 60 MWY would be expected for the first wall (FW) and blanket materials. For a ferritic–martensitic steel this would mean, without replacement, the displacement damage and gaseous transmutation of 600 dpa, 5600 appm He and 25 000 appm H, if the relation of 1 MWY = 10 dpa for Fe is used.

A more achievable approach is to do periodic replacement of FW/blanket components at levels of 100–200 dpa and 2–3 MW/m^2. This, we can do, based on experience with structural materials in nuclear technology in Europe. Fast breeder reactor technology showed that, at a temperature range of 360–600 (630)°C and with cooling medium of Na, austenitic stainless steels and ferritic–martensitic steels operated as cladding and wrapper materials up to about 150 dpa. Light water reactor experience showed that, at temperatures of 280–320°C with cooling medium of pressurized water, austenitic steels operated as core structural materials up to 50 dpa.

It should be the aim of a DEMOnstration reactor to show where the limits for different FW/blanket-concepts regarding structural and breeding materials are. Present EU concepts are those for 70 dpa (DEMONET) and 120 dpa (SEAFP). That is, in the case of replacement of FW/blankets, the goal limit for DEMO would be 100–200 dpa with 2–3 MW/m^2.

(2) *Master plan in EU*: Using DEMO to define the time frame for the master plan and considering ferritic steels as the primary choice for the intermediate term, we in EU have the following scenario of materials development.

Phase I (~2000): Alloy development of ferritic/martensitic steels, 1996–1998, and selection of one or two prime candidate alloy PCAs based on the assessment, 1999–2000.

Phase II (2001–2006): Development of database for selected PCA, 2001–2005, using MTR for 15–30 dpa irradiation and FBR for 100 dpa irradiation. Assessment of PCA, ~2006.

Phase III (2007~): Database confirmation and validation, based on irradiation under fusion-specific neutron conditions.

(3) *Irradiation facilities*: The following test facilities to study the effect of high-energy neutrons on structural materials are needed.

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- Fission reactors (MTR's and FBR's) to simulate high-fluence and dpa-dependent radiation damage phenomena.
- Light-ion irradiations to simulate transmutation reactions (He and H) and to perform in situ mechanical tests under irradiation.
- Development of an International Fusion Materials Irradiation Facility (IFMIF) for materials tests under real fusion conditions.

Why do we need IFMIF? Fission reactors provide sufficiently large irradiation volumes, good accessibility for irradiation rigs, high neutron flux and displacement rates, but low energetic neutrons. Irradiations with light ions (protons and He) provide high displacement rates and appropriate transmutation reactions, very good possibilities for in situ mechanical tests, but are limited to small volumes and low dose irradiations. D-T neutron sources like RTNS I + II have the 'right' 14 MeV neutrons, but a very small capacity of volume and an inadequately low neutron flux. ITER cannot be used for DEMO materials testing because fluence accumulation is restricted up to 30 dpa and the mode of operation is very different to DEMO (low temperature, strongly pulsed operation, etc.).

Even the best fission reactors produce inappropriate He/dpa by $\approx 10^2$, and have big discrepancy on PKA effects (leading to large uncertainties on radiation effects). IFMIF is to be on-line by 2006, in order to mesh with the Phase III target (data validation after 2007), since it will adequately simulate DEMO conditions, i.e. both in terms of (dpa, He/dpa, H/dpa) and PKA energies.

(4) *Recommendations*:

- A clear definition of the aims for a DEMO and CFR would be very helpful to develop a common strategy.
- The use of fast reactors and other high intensity material test reactors with appropriate irradiation devices (loops, rigs) is necessary for the next development phase.
- The quick decision for an intense neutron source is very desirable.
- The international collaboration has to be strengthened through all available channels (IAEA, IEA, bilateral).

2.1. Discussion on Ehrlich's presentation

M. Dalle-Donne: Can beryllium be irradiated in IFMIF to get data for DEMO blanket?

K. Ehrlich: Yes. It can be used to obtain data including transmutation effect.

S.J. Zinkle: Is it possible to cut costs by sharing IFMIF with other physics communities?

K. Ehrlich: No. It will mainly be a fusion machine because of too many issues for fusion materials alone.

Comment: IFMIF, with its high flux, is good to study sequential nuclear reactions (before radio-decay takes place).

K. Ehrlich: Agreed. Sequential reaction must be important also from the metallurgical point of view, for example, high transmutation cross section in V–Cr alloys.

B.N. Singh: We need to conduct "calibrated experiments" (even with IFMIF for DEMO) in order to gain the ability to properly model the effects.

K. Ehrlich: Agreed. For instance, creep/swelling are complex phenomena, then using only dpa as a means for extrapolation may be very dangerous.

3. *F.W. Wiffen*: Prepared discussion on 'US Strategy and IEA Activities'

What has changed in the US program since the last conference in Obninsk is that we no longer have time line driven program for fusion. The recent changes in the US program stress on an advanced plasma science, fusion science and fusion technology, that is, the knowledge base for an economically and environmentally attractive energy source for the nation and the world. Program goals are:

1. Understanding the physics of plasma; the fourth state of matter.
2. Identifying and exploring innovative and cost-effective development paths to fusion energy.
3. Exploring the science and technology of burning plasma, the next frontier in fusion research, as an international efforts.

US fusion budget is still about 1/4 of the world total, therefore collaboration with others is vital. This delineated the US–Japan (Monbusho, JAERI) and US–RF collaboration programs. (No current national collaboration with EU or China).

The following are what the International Energy Agency (IEA) provides. They play an important role in coordinating worldwide activities on fusion materials.

1. Agreement on fusion materials
    - Collaborations on materials research and development.
2. Agreement on fusion nuclear technology
    - The nuclear technologies of fusion reactors, including first wall, blanket, shield, tritium, processing and neutronics.
    - Provides a mechanism for implementing collaborative programs on work identified by the ITER Test Blanket Working Group.

3. Agreement on environment, safety and economics
   - Safety and health effects of tritium.
   - Activation product mobilization and transport.
   - Analytical tools to describe fusion from safety perspective.

The IEA fusion materials agreement covers a broad range of activities for coordination:

1. Structural materials:
   Theory and modeling or irradiation effects.
   Low-activation ferritic/martensitic steels.
   Vanadium alloys.
   Ceramic composites like SiC/SiC for fusion structures.
2. In vessel materials:
   Refractory metals and alloys for fusion.
   Radiation effects in ceramic insulators.
3. Blanket materials:
   Beryllium technology for fusion.
   BEATRIX experiments on tritium production.
   Ceramic breeder blanket interactions.
4. Irradiation facilities:
   BEATRIX experiments.
   IFMIF neutron source study.

3.1. Discussion on Wiffen's presentation

Question: Were plasma facing materials left out in the presentation?

F.W. Wiffen: No agreement under IEA specifically covers that topic which is strongly tied to ITER, otherwise ad hoc.

4. *L.D. Ryabev*: Prepared discussion on 'RF strategy'

Basic approach can transfer existing fission database to fusion research. It is related to extend lifetime and reliability of LWR and FBR. RF supports ITER and conceptual design of DEMO. Many fission reactors in RF can prepare irradiation capability of 25 dpa/year.

Research and development in RF covers the following areas:

- Structural materials referring developed cladding materials (ferritic steels) for FBR.
- Developing low-activation ferritic steels, vanadium alloys.
- Developing high strength Ti alloys, refractory metals (including mono crystals).
- Developing diagnostic systems, high heat flux components etc.
- Superconducting materials.
  - Increasing production scale to reduce cost.
  - Developing low-activation and high-Tc superconductors.
- Blanket materials and tritium technology.
  - New materials development such as porous Be and proposing new grades of Be.
  - Tritium extraction, developing breeding blanket.
- ITER
  - RF supports the next phase of ITER and wants to participate in all areas (first wall, divertor, blanket, limiter, in-vessel components, ceramics, superconductors).
- International collaboration.
  - RF participates in international collaboration ITER and IFMIF.
  - Promoting bilateral collaborative activity; RF–US, RF–Germany, RF–EU and RF–Japan.

5. *H. Nakajima*: Prepared discussion on 'Japanese strategy'

National strategies to develop fusion materials have been discussed by working group activities since April 1997. Major milestones of R&D for structural materials are considered to be Experimental Reactor (demonstration of burning and reactor technology), DEMO Reactor (demonstration of the electric power plant) – 2025, and Power Reactor (utilization to compare costs with other power systems) – 2050. It is based on the third phase basic program in 'National Policy for Promoting Fusion Research and Development' stated in 1992.

(1) *Materials selection*: Selection of candidate materials would be made from:

- Harmonization of R&D program for DEMO reactor (available to construction scheduled around 2025).
- Feasibility and potentiality based on the results obtained through basic research.
- Industrial background.

Therefore, candidate materials proposed in Japanese program are as follows:

- Primary candidate material – reduced activation: ferritic/martensitic (RAF) steel (including oxide dispersion-strengthened RAF steel).
- Alternative materials: Vanadium alloys and SiC/SiC composite.
- Others: TiAl intermetallic compound and high Cr–Fe–base alloys.

(2) *Time table for materials development*

- Attain high-fluence irradiation test for RAF by 2010.
- Complete fabrication technology base of alternative materials including vanadium alloys by 2010–2015.
- Development by means of existing test facilities, and evaluation after IFMIF construction.

To harmonize an overall fusion R&D program on the road to DEMO Reactor in the current time schedule, key technology development for a fusion neutron source like IFMIF has to be initiated within a few years.

5.1. Discussion on Nakajima's presentation

T. Kondo: I agree to select primary candidate materials and to concentrate short-term R&D efforts into those, but we have to develop more innovative materials for longer term goals. Let me show you one example of TiAl–V alloy, which has good strength and ductility, good corrosion resistance and tritium permeation based on recent results.

6. *Jin-Nan Yu*: Prepared discussion on 'Research status in China'

Emphasis is on hybrid reactor for the near-term, and pure fusion machine for the future. Conceptual design for the hybrid reactor is completed, which is composed of small tokamak and subcritical assembly. Fusion-related activities are as follows:

- First wall
  316 SS, low-activation SS, ODS (medium temperature), Vanadium alloys, SiC/SiC (high temperature).
- Plasma facing and high heat flux materials
  graphite, CFC, TiC coating, W/Cu, FGM.
- Tritium technology
  $LiAlO_2$, Al_2O_3, TiC, TiN as tritium barriers.
- Blanket materials
- Superconducting materials
  NbTi, High Tc materials.
- Modeling
  Using fission reactor data to predict fusion situation.
- International collaboration
  Ongoing collaboration with US, Japan, EU.

6.1. Discussion on Yu's presentation

A.I. Ryazanov: What is the size of fusion activity in China?

Jin-Nan Yu: Two institutes (Institute of Plasma Physics, Chinese Academy of Science, Southwest Institute of Physics) and 5–10 Universities.

7. *M. Victoria*: Prepared discussion on 'Basic radiation damage research'

Development of a long-term materials program needs knowledge on "basic" behavior. Basic but not academic study should be oriented to well-defined objectives. Examples of possible "mature" areas are role of spectrum effects and role of helium accumulation in the intermediate temperature regime. Some of the reasons focusing in this direction are decreasing funding, decreasing number of available irradiation facilities and future of 14 MeV neutron source.

- Approach:
  Science based,
  Well-defined objectives,
  Develop an ability to predict rather than to extrapolate (Example: LWR pressure vessel steel embrittlement).
- Framework:
  Under IEA program,
  Initial expert meet to define areas and laboratory interests.

8. General discussion

K. Tomabechi: In my view, time has come to make some hardwares to do experiments with, in addition to theoretical studies of paper works. The available scientific and technical database are sufficient *to build reasonable machines*, even though they should not be ideal machines. With those machines we will learn much more about the real performance of plasma as well as other characteristics of materials under fusion conditions. I would like to introduce one of my interesting experience to study fission power reactors. Before the construction of the first nuclear reactor, everybody believed that stainless steel must be cladding material for a reactor. In fact, the first nuclear reactor was built with the material. But afterwards one material scientist proposed Zircaloy for a cladding material. Due to this new material, present light water reactors are able to compete with other types of energy production. So I would like to propose building the useful hardware, which will give fusion scientists the opportunity to jump into the next phase.

E.T. Cheng: *Radioactivity issues* are very important for public acceptance. The long-term material R&D program needs to be planned with a clearly concentrated objective. The current objective appears to be the development of a safe, reliable and environmentally attractive fusion power reactor. I am afraid that too much radioactive waste will be produced by using stainless steel for near-term objectives. And also, the proposed innovative materials like TiAl should be screened from the viewpoint of activation before significant efforts are invested in their development.

H. Matsui: I would like to raise a new issue for building other kinds of *fusion neutron sources* of which the scale is smaller than IFMIF in the near future. We are planning to propose small-scaled D–Li type neutron source as one of such sources. As for our specific proposal, for instance, the deuterium beam current will be about 10 mA which is much smaller than IFMIF. It could be expected to be constructed in the near future. We can get IFMIF to test the materials which are selected based on data obtained by using small-scale neutron sources. Original idea was that we have to develop materials which have to survive in the fusion neutron irradiation environment. For instance, as for ferritic steels, we have no data about He generation which is relevant to fusion neutron irradiation condition. Another point is that real fusion environment is never steady, like varying temperature and so on. With alternating irradiation temperature, the resulting microstructure is very much different from the one irradiated at constant temperature, and the microstructure evolution in some case may be very much accelerated so that hardening and enbrittlement will be a much more significant issue.

P. Rocco: To be competitive with clean energy of the next century, the *activation level* characteristics should be such that it should be potentially possible to reduce them by material purification, i.e. activation should be mainly due to impurities.

K. Ehrlich (*written answer*): *Purification* may be envisaged in two ways: (1) Reducing the impurity content in the raw materials, and (2) Reprocessing of the irradiated material by elemental dilution of various nuclides.

F.W. Wiffen: Let me *summarize* this discussion session. We have heard quite a range of needs. We should not throw things out without some considerations. I sometimes wish I could find models good enough to extrapolate. At least there are wide range of needs in this program. We started with time line showing possible scenario that will get us to DEMO by about 2025, building from the work of ITER and the IFMIF. So we have explored in this last two hours quite a wide range of approaches that were chosen by no means. Now is the time to close the discussion on the strategy for fusion and the next fusion material in the next decade and beyond. It is good to get all these ideas out to open how we come to be close. In our IEA executive committee meeting to be held in next week, I think we will be discussing these topics. Since two or three years we have the need to do more definitive and careful planning on international bases. We will explore international strategy on how to get from where we are today to fusion power systems for the world.