2.8.4. Comparison with U.S. and Japan

A strong competition exists between the laboratories and industries in the EU and those in U.S. and Japan. Each region has different centres of gravity, but that similar trends can be observed:

- *Bi(2223) tapes:* Bi(2223) multifilamentary tapes are actually the only product being already on the market, in U.S. (market leader), EU and Japan. This conductor is still far from being optimized: new efforts have started, in several laboratories and industries of EU, and Japan.
- Y*(123) coated conductors:* For certain applications, Y(123) coated conductors are superior to Bi(2223) tapes (higher field tolerance, expected lower production costs). In this field, European laboratories (in collaboration with industries) have thus developed a strong activity, and their level is at least equivalent to that in U.S. and in Japan.
- *HTS electronics:* The industrial engagement is much higher in U.S. and Japan, which explains that the volume of this activity in the EU is somewhat smaller. However, this subject should be highly funded, also due to the implication of miniaturized devices in promising future applications, in telecommunication, but also in medical applications.

2.8.5. Conclusions

Breakthroughs in the field of superconductivity are intimately related to the progress in material research. The fundamental aspect of material research, and in particular also the search for new approaches, must be intensified in order to maintain the contact with U.S. and Japan in this field. Developments in the field of applied superconductivity imply a great variety of material aspects, reaching from the study of bulk materials to the development of long conductors with filaments (or coatings) of sizes down to ≤ 1 µm. The fabrication of devices (used in many fields, including medical applications) requires the technology for local material control at a scale of a few nanometres.

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2.9. Materials for Fusion

H. Bolt | Max-Planck-Institut für Plasmaphysik, 85740 Garching bei München, Germany

2.9.1. Introduction

Materials issues are of vital concern for the development of fusion energy into a sustainable source of energy supply. Advances in plasma physics and thus in fusion device performance have been flanked by an increasing understanding of the environment to which materials are exposed in fusion devices and by the development and application of new materials. In Fig. 2.17 the progress of the plasma performance is shown as triple product of plasma density, plasma temperature and energy confinement time. These data are related to the introduction of new materials for plasma facing applications. The Q=1 line indicates the break-even condition at which fusion power output equals the external power input into the plasma. Near-break-even conditions in present fusion devices (JET, JT-60U) have been reached with the help of surface and materials sciences. Now the emphasis is on power-producing fusion systems and the related materials research.

In this respect, the next step in the world-wide fusion programme, ITER [1], Fig. 2.18, has to be the main aim allowing the calibration of operational requirements with materials performance in terms of chemical, thermophysical and thermomechanical properties. At the same time materials development for fusion has to be pursued aggressively. On one hand an intense neutron source has to be built and operated to qualify base line materials for fusion reactor applications. On the other hand intense basic research into new materials is needed to offer fusion as an attractive and competitive energy system to society.

2.9.2. State of the Art of Materials Research for Fusion Technology

The requirements and thus also the materials themselves depend strongly on the specific application in a fusion reactor, Fig. 2.18. Here, a distinction is made between "structural material", "breeding material" (not being treated in this article), "plasma facing material", and other materials for special applications.

(a) Structural materials

In most exposed locations the structural materials of a fusion reactor would be subjected to neutron-induced atomic displacements of up to 30 dpa (displacements per atom) per operational year. This is accompanied by volumetric heat deposition and by the strongly material dependent bulk production of gas atoms (especially H, He).

The baseline development covers ferritic-martensitic steels with tailored elemental composition for reduced neutron activation. The latest development is the EUROFER alloy in which elements with high cross sections for activation by fusion neutrons have been substituted by more benign elements, e.g. Mo has been replaced by W; Nb by Ta and V. The Cr content has been adjusted to optimize corrosion resistance and low embrittlement under neutron irradiation. The long standing research and development in this field resulted in a material which is expected to withstand neutron fluxes up to 150 dpa and which allows an operational temperature range of 300°C to 560°C. Thus a structural material would be at hand to build DEMO, a power-producing demonstration reactor after ITER [2].

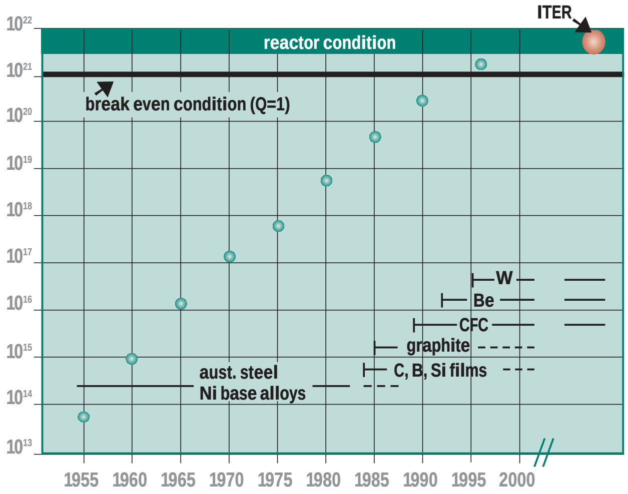

Fig. 2.17. Progress of the fusion triple product of plasma density, temperature and energy confinement time ($nT\tau$) Q=1 means fusion power output equals external energy input. The field "reactor condition" marks the operational field of fusion reactors. ITER is the international next step in fusion development. The plasma facing materials applied for high heat flux components are indicated.

Exploratory work is being performed on dispersion-strengthened steels, which would allow for operation at higher temperatures.

Materials, which are extremely attractive in terms of their low activation under neutron irradiation, are vanadium alloys and ceramic composites (SiC-SiC). Current knowledge hints that for these materials intense basic research is needed to allow for the application in fusion.

(b) Plasma-facing materials

Of the total fusion power in a reactor at least 20% will be deposited on the surface of the plasma-facing components. The divertor surface will see local heat loads of the order of 10 MW/m^2. Transient heat loads in present devices can be much higher, but intense research effort in plasma physics is being invested into the development of control mechanisms against such operational transients.

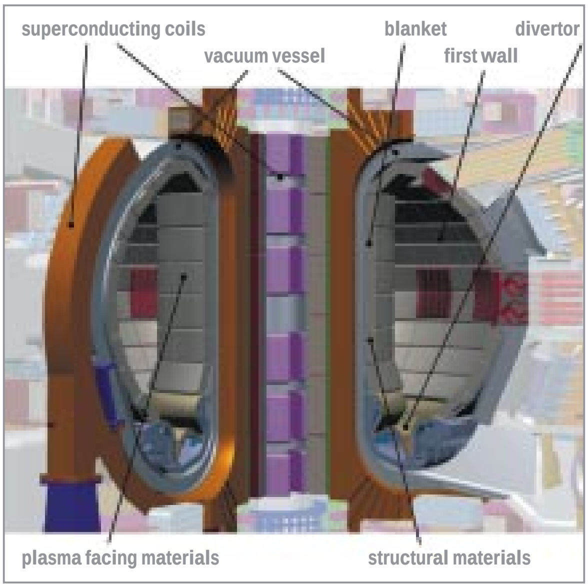

Fig. 2.18. Main components and materials for ITER.

Components and materials for plasma-facing applications have seen very fast progress during the last years. The growing understanding of plasma-material interaction processes has allowed the choice of applicable materials to be widened and has resulted in the selection of Be for the first wall, carbon fibre reinforced carbon (C/C) composites and W for the divertor of ITER [3]. Recent milestones in the field were

- understanding of transport processes and materials migration in fusion devices ("erosion and redeposition"),
- successful use of low Z composite materials and films during the operation of near Q=1 plasmas,
- development of dissimilar material bonds to remove steady state surface heat fluxes up to 30 MW/m^2.

In addition to these major activities in structural and plasma-facing materials advances were made with special materials for critical applications, e.g. the use of 10 cm diameter diamond windows for 1 MW microwave power transmission.

Finally, it has been shown that materials for the superconducting coils are mature and ready for reactor grade application.

Europe and Japan are presently leading the field of fusion materials science. U.S. efforts have severely suffered as funding for fusion research has been cut, because the need for a long term supply of sustainable energy is not being regarded as a high priority within the U.S.

Japan has a wealth of research activities in this field with mainstream development of fusion materials being carried out by a national research institute (JAERI) and strong basic research in the field of radiation effects and material studies being carried out by universities. Subjects include low activation steels, vanadium alloy development on industrial scale, and pace making work on advanced SiC/SiC composites

In Europe the member states of the EURATOM programme perform co-ordinated research in the fusion materials field with participation from mostly non-university institutions. The materials programme, which is being carried out under the European Fusion Development Agreement (EFDA), mainly supports application-oriented research. Most of the effort is dedicated to low activation steels, exploratory work being done on dispersion strengthened steel and other alloys as well as SiC/SiC composites.

2.9.3. Expectations and Needs for the Next ten/twenty Years

ITER will be the centre piece of the European fusion programme. Regarding materials issues, during operation of ITER the boundary conditions for the use of materials in a reactor relevant environment will become precisely known. Plasma-material interaction processes should be understood and the heat flux removal technology should become mature.

The steady development of structural materials, especially of steels with low activation properties should result in a qualified material for building a first generation power reactor. For this and for the testing and qualification of any other fusion reactor material a 14 MeV neutron source is definitely needed. This facility will provide a neutron environment very similar to that in a fusion reactor, however the local neutron flux density will be higher and thus allow accelerated irradiation. The planning of this “International Fusion Materials Irradiation Facility”, IFMIF is being carried out internationally under an agreement of the International Energy Agency, IEA. Expected costs to be shared internationally are 600 M€ [2].

In parallel to this evolutionary process of materials development and qualification, basic research in the field of materials science is urgently needed. Here the aim is towards a breakthrough in new materials with which fusion can be offered to society as a highly attractive and competitive energy system. Regarding such new materials the most important questions are:

(a) To which performance can advanced low activation materials be developed?

Directions are to increase the operation temperature for optimum energy conversion efficiency and to further improve the low activation properties of the materials. Possible paths are oxide dispersion strengthened steels, metal matrix – ceramic fibre composites, SiC/SiC composites, and possibly vanadium base alloys [3-5], Fig. 2.19.

Break through and success in this field would permit the highly loaded components in a fusion reactor to be furnished with materials having high strength also at temperatures well above 560°C (900°C in the case of SiC/SiC) and having highly favourable low activation properties. This would allow the thermal efficiency of a fusion power plant to be increased well towards the 50% mark. The behaviour under neutron irradiation is critical with such complex advanced

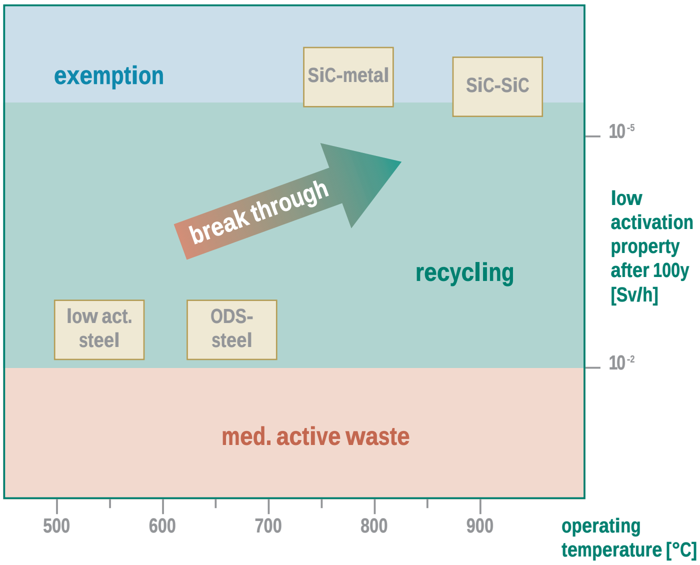

Fig. 2.19. Aiming at a breakthrough in structural materials. High temperature materials, which can be easily recycled or exempted after reasonable time, will underpin the attractiveness of fusion as an energy system.

materials and needs to be understood from the atomic scale to the mechanical property level of the materials.

(b) To which degree can thin films reduce the tritium uptake of structural materials?

The tritium uptake of the structural materials and the migration into the coolant should be reduced as far as possible in a fusion reactor in order to minimize the tritium quantity, which could be accidentally released.

The advances in atomic thin film deposition by plasma-assisted methods and the possibility to tailor the nanostructure of these films during deposition open a new horizon in the development of permeation barrier coatings. Together with an evolving understanding of the atomic interface and the migration physics, a new generation of tailored barrier materials could be developed.

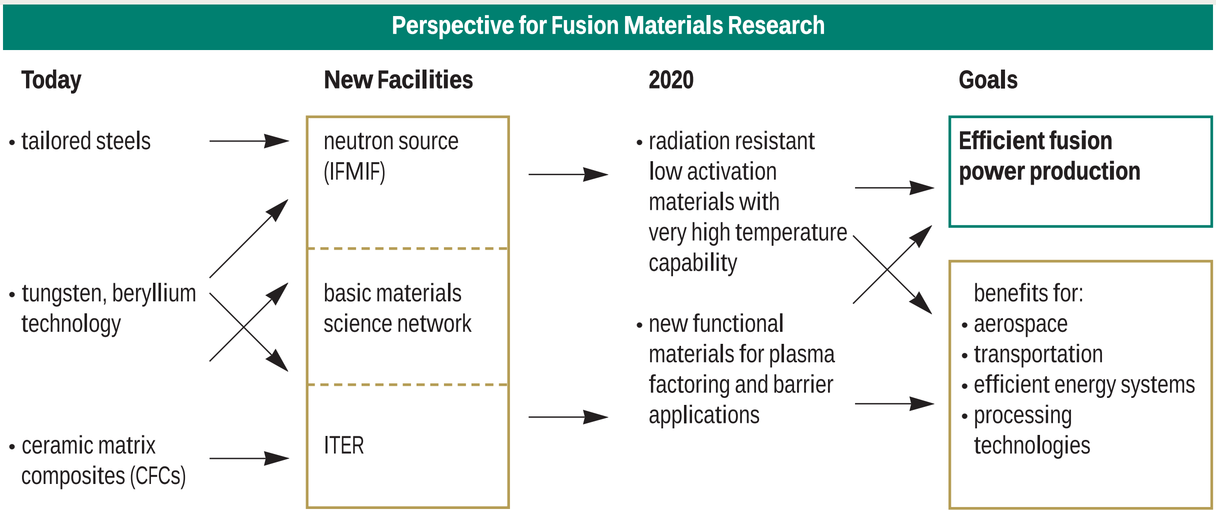

Fig. 2.20. Perspective of fusion materials research.

(c) Can plasma-facing materials with maximum lifetime be developed?

The use of high atomic number materials like tungsten would possibly allow to drastically increase the lifetime of the plasma facing components. However, the interaction of such materials with the plasma is extremely complex and needs to be controlled. If research in this field would be successful, the lifetime issue of the plasma facing material could be resolved. Work on ITER will show whether such plasma operation windows can be established, and perhaps even enable medium Z materials to be used. The thermal gradients in the plasma facing components, which are exposed to a surface heat flux of the order of 10 MW/m^2, will require advanced reinforced composite materials [6,7].

A further subject of intense research concerns the joining technology of the plasma facing material to the heat sink, such that the high heat flux from the plasma can be removed.

In order to proceed along this path, the following *key* technologies are essential and have to be strengthened:

- Advanced metallurgy (e.g. compositionally tailored alloys; metal matrix composites) and joining technologies.
- High temperature ceramic composite processing (e.g. SiC/SiC).
- Thin film technology (e.g. permeation barrier coatings).

It is obvious that these three fields also are closely related to other advanced materials applications and that the results of this research will be highly valuable to other sectors, e.g. fuel cell and hydrogen technology (hydrogen permeation barriers); aerospace and transport technology (composites); plasma technology (advanced materials processing), Fig. 2.20.

2.9.4. Actions Proposed

A new initiative on basic materials science issues related to fusion is strongly needed and would be excellently placed within a EC materials science programme. It would directly enhance the performance of the EURATOM programme for the development of fusion energy.

Important actions within the EC materials science programme should be:

- New alloys and composite materials for high temperature applications.
- Thin film processing - ceramic films with barrier functions.
- Understanding and control of radiation effects in complex materials.
- Facilitating the construction and exploitation of an intense neutron irradiation facility (IFMIF).

Integrating the competence of research laboratories (e.g. from fusion, aerospace, materials science), universities and industry into a "*network of excellence*" for the basic science issues of fusion materials would be the most appropriate step towards the aim of attractive and commercially viable fusion energy.

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2.10. Materials for Transportation

C.R. and W. E. Owens | UniStates Technology Corporation, LLC, Medford Massachusetts 02153-0101, United States

2.10.1. Introduction

Rising energy prices and heightened environmental concerns are intensifying the global push for quantum gains in materials performance. In all major industries, there is an acceleration of the longstanding unfulfilled demand for lighter, stronger, and more affordable materials. The lack of a leap forward in materials performance continues to be a brake to progress in many industries, but no industry is constrained more by the long absence of a breakthrough in materials performance than the transportation industry.

Other industries have been spurred by breakthroughs and are making rapid progress towards goals once considered to be at the outer limits of their technological potential. For example, the Internet has revolutionized the telecommunications industry, and the emerging map of the human genome promises extraordinary progress in medicine and biotechnology. But, the materials industry has not achieved a comparable breakthrough. No outsized gains have been made in materials engineering in the past 50 years, and a revolution in transportation remains an apparition.

As a consequence, the transportation industry is increasingly reliant on composite materials. But, composites lack precision in their makeup and sufficient predictability in their performance, and their greater costs exceed their margins of performance versus traditional materials. As an alternative, materials scientists have explored foam technologies. But, like composites, foams lack precision and predictability, and the costly processes for producing foams fail to realize a balance between density and porosity. Thus, the long-awaited breakthrough in material performance remains elusive.

State-of-the-Art Materials in Transportation

Steel
High strength steel

Aluminium
Plastics
Ceramics
Magnesium
Titanium alloys
Advanced aluminium alloys
Nickel alloys
Single-crystal nickel-base alloys
Aluminium lithium alloys
High temperature resin

Polyimides

Glass-fibre reinforced polymers
Graphite-fibre reinforced polymers
Polymeric composites
Metal-matrix composites
Polymer-matrix composites
Ceramic-matrix composites
Structural composites
Intermetallics
Super alloys
Microtextured materials
Self reinforcing liquid crystals
Carbon-reinforced thermoplastics
Liquid crystalline thermosets

Fig. 2.21. In an effort to make products lighter, stronger, and more affordable, the transportation industry is relying on a wide range of increasingly more complex, scarce, and expensive materials.