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EUROPEAN FUSION DEVELOPEMENT AGREEMENT

Advanced Materials for Fusion Devices: towards Safety, Efficiency and Protection of the Environment

The construction of future fusion power stations is the ultimate goal of an international research and development programme involving many disciplines. One of these is research into materials suitable for the operating conditions and the safety requirements in a fusion reactor. Particularly important are advanced materials with low activation properties and high thermo-mechanical performance under irradiation. The development of such materials will be a key factor in realising full operational safety, low environmental impact and economic viability of fusion power.

Fusion is an attractive option for future large-scale energy production due to the abundant quantities of the basic fuels - deuterium and lithium - as well as to its inherent safety features and to waste production that will not be a long-term burden for future generations. Moreover, fusion offers the possibility of an environmentally friendly energy supply due to the absence of greenhouse gas emissions.

In the sun and other stars, huge gravitational forces compress the nuclei of hydrogen atoms close together to overcome their mutual electrical repulsion. The nuclei then fuse, releasing the energy that lights and warms the universe. A gas consisting of a mixture of hydrogen isotopes (deuterium and tritium) is heated to a temperature high enough to strip the electrons from the atoms. The resulting medium consists entirely of charged particles. This is called "plasma". The plasma is electrically conducting and therefore can be confined by strong magnetic fields. When heated to temperatures around 100 million degrees, energetic collisions between the plasma ions produce fusion reactions.

Why are the operating conditions of a fusion reactor so demanding for the structural materials? There are two reasons. First, a fusion power plant will generate heat, which is then converted to electricity, just as in a conventional power station. The heat generated by the fusion reactions must pass through the surrounding vessel. This large heat flux generates high thermal stresses within the structures. At the same time, the fusion reactions produce high-energy neutrons. These cause activation of the surrounding materials and degradation of their thermo-mechanical properties. The development of suitable structural materials is essential for the optimisation of future fusion reactors from the points of view of safety, environmental friendliness, and economics.

For example, to minimise the cost of maintenance, decommissioning, and waste management, low activation materials will be needed. Maximum plant availability will depend on the development of materials highly resistant to radiation damage.

Fusion roadmap

Most fusion research is carried out on a type of machine called a Tokamak. This has a toroidal (doughnut) shape. The plasma is initially formed and heated by an electric current (induced by a transformer) which flows around the torus. The plasma is heated to fusion relevant temperatures by ohmic resistance and by radio frequency waves or beams of high-energy neutral particles.

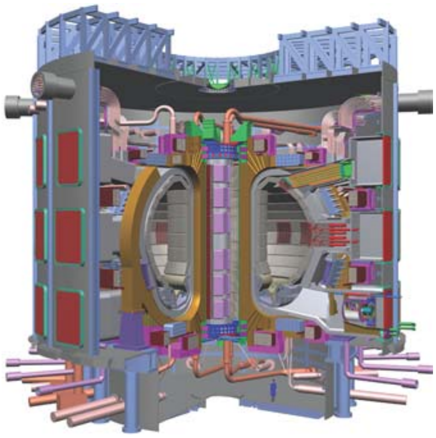
The development of fusion into a viable energy source is a stepwise process. The current generation of devices such as the Joint European Torus (JET) - presently the world's largest fusion experiment - should be followed by a "Next Step" machine with the objective of demonstrating the scientific and technological feasibility of fusion power production. This aim is being pursued in the framework of an international collaboration (involving Canada, the EU, Japan, and the Russian Federation) to design the ITER experimental reactor, which would produce 500 MW of fusion power in pulses lasting up to 500 s. The design of this device was completed in mid-2001, and a period of negotiations on the organisation, the legal framework and the site will precede any decision to go ahead with construction. This decision may be taken in late 2002. A duration of about 8-10 years is foreseen for ITER construction which would be followed by 15 years of operation. ITER can be built with existing materials since the overall loads on the materials are still moderate. In a fast-track fusion development vision the full exploitation of the ITER design flexibility would allow readily a modest upgrading over its lifetime. Based on the main results of ITER, a reactor, with both Demonstration (DEMO) and

The thermo-mechanical resistance of materials for fusion applications are tested in experimental facilities in some EU laboratories. One example is the plasma simulator in the Association Euratom-IPP-Berlin.

Prototype (PROTO) characteristics and capable of producing significant quantities of electricity could be built providing a credible model for a power producing fusion reactor although not fully technically and economically optimised. This device would probably have a fusion power of 2000 MW and its structural materials would be subjected to a substantial neutron load. This reactor should therefore be built with advanced materials. While ITER is planned to be a Tokamak like JET, conceptual designs for the prototype power plant may deviate from the present Tokamaks following conceptual optimisations, derived from configurations such as the Stellarator, which are currently being studied. A prototype commercial power station could become operational before the middle of the 21st century. In the DEMO/PROTO device the materials issues will be important because significant amounts of fusion power will be generated. The levels of heat and neutron fluxes through materials will be essentially the same as in a power plant, and the materials will need corresponding further development.

Materials for fusion

A fusion power plant will need a diverse array of materials. Depending on the location and function of an individual component, different materials will be needed to serve a wide range of functions: supporting mechanical forces, conducting heat, breeding the fusion fuel tritium, carrying large currents (superconductors), transmitting light or radio frequency waves, acting as dielectrics and electrical insulators. Among these the structural materials (i.e. those withstanding large forces) are the most critical because they become activated and their characteristics have a great influence on plant performance. Much research has already been done, and three major material groups have been identified as the most promising for the reactor inner structural components. These are steels with a ferritic/martensitic structure, vanadium alloys and ceramic composites based on silicon carbides. Some of these alternatives are more developed than others, but all of them require further development and investigation in certain critical areas. Exploratory studies on



A cut-away drawing of the ITER tokamak, showing the D-shaped vacuum vessel surrounding structures, and the 24 m high cylindrical cryostat, which forms one of the safety barriers.

other material groups, such as chromium and titanium alloys and the high strength tungsten alloys may show that these alternatives are also worth consideration. As has been clearly demonstrated by experience in conventional power systems, the optimisation and qualification of commercially available or new materials for fusion applications requires intensive co-ordination of R&D and continuing efforts over decades. This is the reason why, although advanced materials will eventually be needed only for DEMO, substantial research and development effort is already being undertaken. To support this effort, the construction of a large-scale materials test facility, where an intense source of high-energy neutrons will reproduce fusion-specific irradiation conditions, will be necessary.
Within the last year an assessment aimed at preparing the guidelines for the future materials development activities in EU have been made. The properties and future potential of various materials have been assessed.

Overview of a fusion reactor

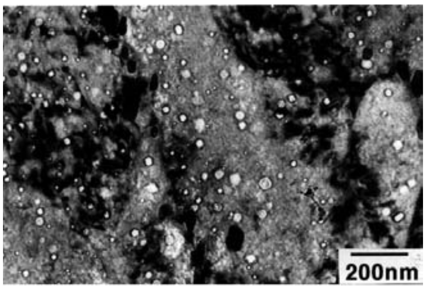
In a fusion power device of the Tokamak-type, the plasma would be isolated from the surrounding atmosphere by a vacuum vessel. Its internal components are mounted and protected by a "first wall" which is subject to electromagnetic radiation and low energy particles from the plasma, and is hit by high energy neutrons originating from fusion reactions. Behind the first wall is located a neutron-absorbing "blanket" acting as shield and breeding the required tritium as well as systems to heat and fuel the plasma. Superconducting coils, located outside the vacuum vessel, provide the required strong magnetic field. The vacuum vessel internal components absorb most of the radiated heat and neutron energy thus protecting the coils and other external systems from excessive nuclear radiation.
The structural materials issues are mostly associated with those components in the proximity of the plasma such as the first wall, the divertor, the limiter and the blanket. The first wall is the physical-structural interface between the plasma and the machine and is protected by beryllium. The highest thermal loads, up to ~20MW/m^2, act upon the divertor, whose target plates come in direct contact with the plasma edge where most of the particles escaping the plasma are collected. The ITER choice for the divertor armour plates is tungsten alloys, and carbon based composite materials for the targets. This is due to the high thermo-mechanical performances. Tungsten has also the advantage of low erosion. As the first wall limiters are also protected by beryllium, while tungsten is a possible alternative. The breeding blanket serves the dual function of converting the neutron energy to heat (which is extracted for the generation of electricity) and of regenerating tritium needed as fuel for the fusion plant. This results from reactions between the fusion neutrons and lithium. The tritium is extracted from the blanket, and after processing and storage is injected back into the vacuum vessel together with deuterium. Different blanket designs are being evaluated, each concept with a specific combination of different functional materials. In particular, candidate materials for the blanket are solid or liquid lithium-based materials such Li_2TiO_3 ceramics or Pb-Li17 eutectic (for tritium breeding) and beryllium (for neutron multiplication). Water or helium are the options for cooling. The structural materials for the first wall and blanket are foreseen to be low activation steels, vanadium alloys or silicon carbides based composite materials.

The thermal and radiation environment

A fusion reactor generating about 2 GW of thermal power will experience an average heat load on the first wall of about 1 MW/m^2. This figure is comparable with the wall load in the combustion chamber of a gas fired power station or the core heat flux in a fast breeder reactor, so would at first sight not seem to present a particular problem. However, the heat load is not evenly distributed. Moreover, materials must meet some stringent requirements such as compatibility with high vacuum and mechanical stresses. As for the radiation environment, the principal source of damage is the flux of high-energy (14 MeV) neutrons created by fusion reactions. This flux should be in the range 5-30 x 10^{18} n/m^2s, with a corresponding thermal load on the wall of about 2-3 MW/m^2. The development of structural materials able to sustain this level of neutron flux over a sufficiently long component lifetime will be essential for the economic attractiveness of a fusion reactor.

Irradiation damage mechanisms

What happens when high energy neutrons interact with matter? The long-term effects of radiation on a polycrystalline material (such as a metal) are numerous, and the magnitudes of these effects depend on the crystal structure and its previous history and on both irradiation level and temperature. A variety of purely physical effects are caused by atoms being displaced from their original positions in the crystal lattice, creating vacancies and interstitial atoms within the structure. Structural changes can occur in the crystal, sometimes accompanied by swelling of the material. The mechanical properties can change (for example loss of elasticity and ductility with increased hardness and brittleness) and the heat conductivity and electrical resistivity can be modified. At the same time, nuclear reactions may occur. In the case of fusion, the emission of one reaction product leads to a helium atom being trapped in the material. This atom acts as a defect, causing hardening and swelling. Neutron interactions can also lead to the material becoming radioactive. The average number of displacements experienced by each atom in a sample



Micrograph showing an example of material swelling under irradiation. Voids have been formed in a low activation steel (F82H) leading to 1% swelling.

of material (the "dpa") in a given time is one method used to quantify the level of exposure of a component. At the same time scale, the introduction of large He and H content by transmutation process contributes to additional damage. This combined effect cannot be simulated with the existing devices and justifies the needs of an intense source of high-energy neutrons with relevant fusion feature. Over the 30 years lifetime of a fusion plant the first wall will be subjected to hundreds of dpa, which is beyond the level that any material can sustain. To minimise the number of times the most affected components will need to be replaced, further development of advanced materials is required. From present design values of about 80-100 dpa a reasonable intermediate target is 150 dpa, which is similar to the level experienced in fast breeder reactors.

R&D on Structural Materials

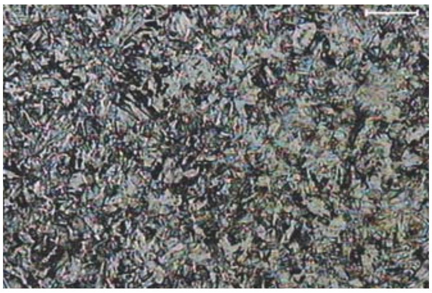
The challenge is to develop structural materials which maintain high performance during prolonged exposure to high thermal and radiation flux. In addition to their structural properties, they may need chemical compatibility with coolants and be relatively easy to manufacture. The thermo-mechanical properties must not degrade significantly due to damage and activation by 14 MeV neutrons. Heat conductivity should be maintained as well as low swelling and void formation, despite high levels of helium and hydrogen production. Weldability after irradiation should also be considered in order to allow rewelding after the maintenance operation. They should also have low levels of nuclear self-heating after irradiation and low activation to ease both maintenance and recycling of material.

In the sixties and seventies the high temperature advantage of refractory alloys (based on molybdenum, tungsten, and vanadium) gave impetus to their development for fusion applications. Their major drawback was their embrittlement after irradiation.

Therefore, in the late seventies attention shifted to low activation alloys and the development of vanadium-alloys was emphasised. Work was started on reduced activation austenitic steels where elements with high neutron induced activation (like nickel) were replaced by elements (such as manganese) with similar overall properties, but low activation. These steels fell into disfavour due to their poor phase stability and the complexity of fabrication. In the early nineties the study of low activation ferritic-martensitic steels started. The track record of conventional chromium steels exposed to high neutron fluxes in fast breeder reactors encouraged the investigation of ferritic-martensitic steel. The present decade has seen attention broaden to high temperature SiC/SiC composites. Some attention has been devoted recently to titanium and chromium alloys but these are still at an early stage of development.

Ferritic-martensitic steels.

These alloys have the most advanced technological and industrial development due to the experience acquired in fossil and nuclear energy technology. They show reasonably good thermo-physical



Magnified images of the microstructure are a common working tool for material scientists to investigate their material samples, in this case of EUROFER 97.

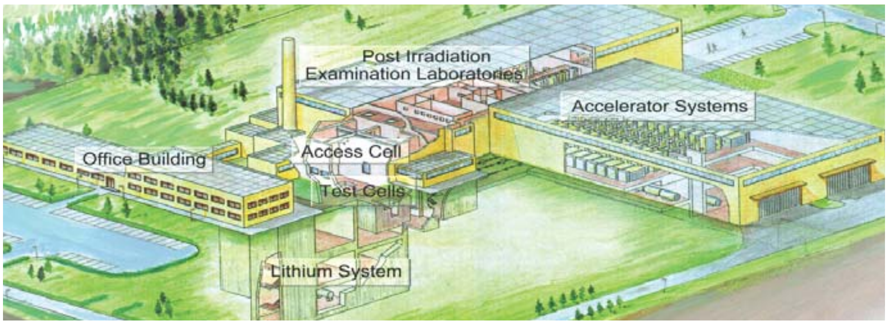
and mechanical properties, adequate resistance to radiation-induced swelling and helium embrittlement, and good compatibility with major cooling and breeder materials. Moreover, industrial batches have already been produced such as the F82H-mod in Japan and the Eurofer '97 in Europe and further studies towards super-clean steels are in progress. Development is required in several critical areas. Material with further reduced activation is needed, their radiation-induced hardening and embrittlement in a fusion relevant environment needs to be better understood. To enlarge their range of application to higher temperature, possible improvements using the technique of oxide dispersion strengthening is under investigation.

Vanadium-based alloys.

They have moderate high-temperature strength, adequate ductility above room temperature, and low long-term induced radioactivity. They show good resistance to high heat loads and allow high operational temperatures. The maximum operating temperature is limited by thermal creep while the low temperature limit is set by irradiation hardening. A major drawback is the high solubility of interstitial elements like oxygen, nitrogen and carbon having the potential to lead to unacceptable embrittlement. Therefore measures have to be taken to control and prevent their pick-up during manufacture and operation.

Fibre-reinforced composite materials based on silicon carbides.

These materials have been conceived and developed mainly for aerospace applications due to their potential for high temperature operation, which allows thermodynamic efficiency to be maximised. In addition for use in fusion, they exhibit very low short and medium term induced radioactivity and afterheat. The key issues to be addressed include the irradiation performance, the scaling up of fabrication techniques for large components, the lack of suitable techniques for joining parts since welding is not possible, the effect of matrix porosity and micro-cracking on coolant hermetic sealing capacity, the need for standardisation and (at present) the high cost.



Artist's impression of the International Fusion Materials Irradiation Facility (IFMIF).

The future

A major issue for the further development of all the structural materials is the need to submit them to neutron fluxes and energies close to those of a fusion reactor. Since no neutron source reproducing fusion-specific conditions presently exists, materials performance is mainly studied using fission reactors and ion accelerators, where fusion conditions can be only partially simulated. These experiments provide valuable information regarding specific radiation damage effects but they only allow a preselection of promising materials and a not complete characterisation and optimisation. Moreover, there is a need to further validate existing data coming from numerical simulation for meaningful extrapolation to the conditions in a fusion reactor. The ITER device would provide a powerful source of 14 MeV neutrons, but is not sufficient for all the materials testing required, being the fluence too low. Plans are well advanced for a dedicated test facility, the International Fusion Materials Irradiation Facility (IFMIF), using an accelerator-based D-Li source. It would produce neutrons with a suitable energy spectrum at high intensity and sufficient irradiation volume to allow all the necessary material tests with high flexibility and the capability of accelerated irradiations (up to about 50 dpa per full power year) with simultaneous helium production equivalent to conditions in a fusion power plant.

The development of low activation structural materials that can withstand the high-energy neutron flux environment expected in fusion reactors is one of the key challenges on the road to commercial fusion power.

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