Fusion Power Materials

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The selection and design of materials that can withstand the extreme conditions of a fusion power plant has been described as one of the greatest materials science challenges in history.

Materials for fusion power generation must withstand high temperatures, high levels of radiation damage, high production rates of transmutation elements, and high thermo-mechanical stresses. Materials for fission power clearly overlap with some of these requirements, but fusion materials present additional challenges.

The first is the copious amount of helium that is produced, both in the D–T (deuterium-tritium) fusion reaction and by transmutation reactions in the structure. Helium bubbles formed at vacancy clusters and grain boundaries cause swelling and embrittlement.

The second challenge unique to fusion reactors is associated with the 14 MeV neutron produced by the fusion reaction. This extremely high-energy particle penetrates deep into the structure and collides with the atoms, creating a high number of defects in the material. The accumulation of this damage in structural and diagnostic materials is one of the primary concerns for power plant design.

The ITER nuclear fusion experimental reactor will link current plasma experiments to a demonstration power plant by establishing the feasibility of a self-sustained plasma burn. The materials in the ITER design were selected for optimum plasma conditions and, as the total neutron fluence and helium production will be relatively low, the chosen materials are expected to survive for the lifetime of the experiment.

However, the conditions in a power plant will be much more demanding, as the neutron fluence and heat loads will be increased by an order of magnitude and the operating temperature will be higher.

This article reviews the conditions in the first wall, plasma facing materials, and in the divertor in a fusion power plant, and the materials that are currently thought to be best suited to these roles.

First Wall Materials

A schematic representation of a fusion power plant is shown in Fig. 1. The outer region represents the superconducting magnets that will confine the plasma. The intermediate region is the vacuum vessel. The inner region is the first wall, which includes the blanket system that will breed neutrons and extract power.

The first wall of a fusion power plant must contain the integrated blanket that plays the dual role of breeding the tritium fuel and capturing the useful power from the fusion reaction. Efficient designs would operate at high temperatures; therefore, good creep resistance and high-temperature strength are important criteria. First wall materials will be subjected to high neutron loads (approx. $8 \times 10^{14}$ neutrons/cm$^2$/sec) and they will experience up to 120 dpa (displacements per atom) over the lifetime of a power plant.

The neutron-generated radiation damage and its effect on mechanical properties will be a significant issue. Residual defects created by each radiation event evolve over time and form small clusters or dislocation loops, which will eventually reduce the fracture toughness of the material. Helium atoms, produced by the fusion reaction and by the decay of transmutation elements, become trapped in vacancy clusters, and this will...
cause swelling and embrittlement. The neutrons may also induce segregation. Alloy components in metastable solution could be driven towards equilibrium by radiation-enhanced diffusion, with a corresponding degradation in properties. Neutron activation of certain elements produces long-lived radionuclides, and alloy concentrations of such elements must be kept to a minimum to minimize waste disposal issues.

The main contenders for first wall structural materials are reduced activation ferritic/martensitic (RAFM) steel, vanadium alloys, and SiC fiber/SiC composite materials. Currently, ferritic/martensitic steel is the favored option, not least because of the vast amount of technological experience available. Austenitic steels have been ruled out because of the unfavorable radiation resistance of fcc metals and high nickel content. The requirement for only short half-life radioactive waste means that Ni and other high-activation elements such as Ti and Co are undesirable, and this has resulted in the development of a range of reduced activation steels targeted at fusion applications. Embrittlement and high-temperature strength remain open issues, as ferritic steels rapidly lose strength at temperatures higher than 550°C.

Experimental Alloys

**Oxide dispersion strengthened (ODS) steel:** Nano-scale oxide particles increase high-temperature strength. The insoluble particles play the dual role of defect sinks and dislocation barriers. Preliminary results on high-temperature stability and radiation resistance of the oxide nanoparticles are encouraging.

**Vanadium alloys:** Some advantages over ferritic/martensitic steels include superior high-temperature performance. Operating temperatures up to 700°C may be possible, which is higher than that anticipated for ODS steels. Vanadium alloys are the only low-activation alloys that would be compatible with liquid lithium; therefore, they would be essential if the liquid lithium coolant option were preferred. However, vanadium alloys lack a production infrastructure and have a relatively immature joining technology.

**SiC composites:** These have excellent high-temperature strength. SiC is a brittle material, but the fracture toughness of the composite can be improved by tailoring the fiber, matrix, and interphase material. However, performance of the fiber matrix interface under neutron irradiation is still an open issue. As with vanadium alloys, there is concern about the lack of manufacturing infrastructure, joining technology, and fabrication costs.

Table 1 summarizes the primary candidates for first wall structural materials. Early demonstration power plants are likely to use ferritic/martensitic steels, which means that the operating temperature would be somewhat restricted. Research into alternative materials that will maintain strength to higher temperatures will continue for future-generation thermo-nuclear power plants.

### Plasma-Facing Materials

Materials that face the plasma directly present additional challenges. Consideration must be given not only to the effect of the plasma on the material, but also to the effect of the material on the plasma. These materials experience high fluxes of both neutral and charged particles that escape from the plasma, and these sputter atoms from the surface of the wall. The sputtered atoms may enter the plasma and cause radiative cooling.

Low atomic weight (low Z) materials require less energy for ionization and therefore these are the preferred option for plasma-facing materials. Hence the choice of beryllium for the coating of the first wall in ITER. Low Z metals have low melting points (low binding energies) and high erosion rates; therefore, from the materials perspective...
tive, high Z metals are the preferred option. The high erosion rate and high toxicity of beryllium mean that it is unlikely to be the material of choice for a power plant design. Tungsten, because of its high melting temperature and thermal conductivity, may be a viable alternative.

**Divertor Materials**

The role of the magnetic field in a tokamak is to confine the plasma and prevent it from coming into contact with the vessel walls. However, in a burning plasma, it is necessary to remove the excess energy and fusion products (alpha particles) from the vessel. The magnetic field lines must come into contact with the vessel wall; in ITER, this is done using the X configuration such that the outer (open) field lines contact the wall around the base of the tokamak. Particles escaping the plasma are diverted along the field lines and contact the wall in a region known as the divertor.

Divertor materials experience the harshest conditions of all the materials in a fusion reactor in terms of both particle bombardment and the heat load, which is comparable to that of rocket nozzles.

Metals served as plasma-facing materials in early experiments, but graphite was found to increase the plasma temperature dramatically because of its efficient radiation properties. Graphite also has high thermal conductivity and low Z, both of which make it a suitable divertor material. However, graphite does have a major disadvantage—its high reactivity with hydrogen. Low-energy hydrogen that comes into contact with the divertor reacts with surface carbon to form volatile hydrocarbons that are re-deposited in a different part of the vessel. This would be a major problem for the tritium inventory because of both resource and safety issues. Tritium is a scarce resource and it is highly radioactive; therefore, it should be contained in the plasma.

Carbon remains in the ITER design, in the form of carbon fiber-reinforced carbon (CFC), only at the strike points of the divertor. In the remainder of the divertor, tungsten serves as a plasma-facing material because of its high melting temperature and thermal conductivity.

Diamond has been suggested as an alternative to graphitic carbon as a possible divertor material. Its exceptional thermal...
conductivity would be favorable for high thermal loads and its strong bonding should decrease its susceptibility to chemical erosion by hydrogen.

Tiles or components made from a range of materials, including tungsten or graphite, could be coated by microcrystalline or nanocrystalline diamond to produce a protective coating. Preliminary experiments on diamond-coated molybdenum, silicon, and graphite tiles have produced encouraging results and further experiments are planned. Some degree of arc-ing was detected, but this could be eliminated by doping with boron to increase the electrical conductivity. The microstructure of a microcrystalline diamond film, before and after exposure to a high-density H plasma, is shown in Fig. 2.

Graphitization and amorphization, caused by radiation damage and high thermal loads, may negate some of the advantage of diamond, but again, doping with selected elements could minimize this effect. We are investigating graphitization and amorphization of diamond under high thermal loads by classical molecular dynamics. Preliminary results demonstrate that passivation by H has a strong stabilizing effect.

In summary, the plasma-facing materials in general and the divertor in particular present the greatest challenge for materials selection in a fusion power plant. Table 2 summarizes the current contenders, but further materials development will be required for these exceptionally challenging applications.

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