Research
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A REVIEW OF MATERIALS USED IN FUSION RESEARCH

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ADVANCED MATERIALS

AN INTRODUCTION TO FUSION ENERGY

Nuclear fusion, the process powering stars, holds promise as a sustainable and virtually limitless energy source.

However, replicating it on Earth requires overcoming immense technical challenges—confining plasmas at over 100 million Kelvin while withstanding intense neutron flux and radiation damage.

These extreme conditions place unprecedented demands on materials, requiring breakthroughs in durability, thermal conductivity, and radiation resistance to name a few. Progress in fusion research hinges on the interplay between innovative materials science and advanced reactor designs. This e-book explores how materials are meeting these challenges and shaping the future of fusion energy.

MATERIALS SCIENCE CHALLENGES IN FUSION

Materials used in fusion reactors face a multitude of critical issues stemming from the extreme operational environment. These challenges necessitate extensive research and development to identify and qualify suitable materials for future fusion power plants.

The main issues materials must face can be summarized as follows:

NEUTRON IRRADIATION DAMAGE:

Fusion reactions produce high-energy neutrons that bombard reactor components, leading to several forms of damage.

1. **Atomic Displacement:** Neutrons displace atoms from their lattice positions, creating defects that can lead to hardening and embrittlement of structural materials. This can significantly alter mechanical properties like creep resilience and the ductile-to-brittle transition temperature.
2. **Transmutation:** Neutron interactions can transmute atoms into different elements, causing compositional changes and the generation of gases like helium and hydrogen within the material. Helium accumulation can lead to embrittlement, especially at grain boundaries.
3. **Activation:** Neutron irradiation activates the reactor materials, making them radioactive and complicating waste management and disposal. The goal is to develop low activation materials that minimize long-lived radioactive waste.

EXTREME THERMAL LOADS:

Plasma temperatures are exceptionally high, resulting in significant heat fluxes on plasma-facing components like the first wall and divertor. Materials must withstand these high temperatures without degradation of their structural or thermal properties. Maintaining adequate cooling is crucial, and materials need excellent thermal conductivity.

PLASMA MATERIAL INTERACTIONS (PMIS):

The hot plasma interacts directly with the inner surfaces of the reactor, leading to:

1. **Erosion and Sputtering:** Energetic particles from the plasma can erode the surface of materials through sputtering and blistering, leading to material loss and plasma contamination.
2. **Fuel Retention:** Plasma-facing materials can trap and retain hydrogen isotopes (deuterium and tritium), affecting the fuel cycle and potentially leading to safety concerns. Efficient tritium management, including minimizing permeation, is essential.
3. **Mechanical Stresses:** Reactor components are subjected to various mechanical loads, including stresses from thermal gradients, magnetic forces, and operational cycles. Materials must possess sufficient strength, toughness, and creep resistance to withstand these stresses over extended periods.

COOLANT COMPATIBILITY AND CORROSION:

Many fusion reactor designs involve coolants (e.g., water, helium, liquid metals like PbLi, molten salts) to remove heat. Materials in contact with these coolants must be corrosion-resistant and compatible with the operating temperatures and pressures. For instance, liquid metals can cause liquid metal embrittlement in some alloys.

TRITIUM BREEDING AND EXTRACTION:

For a sustainable fusion power plant, the reactor must breed its own tritium fuel. Materials within the breeding blanket (e.g., lithium-containing ceramics, beryllium as a neutron multiplier) must function effectively under irradiation and allow for efficient tritium extraction. Research focuses on developing permeators for efficient hydrogen and tritium extraction from breeder materials.

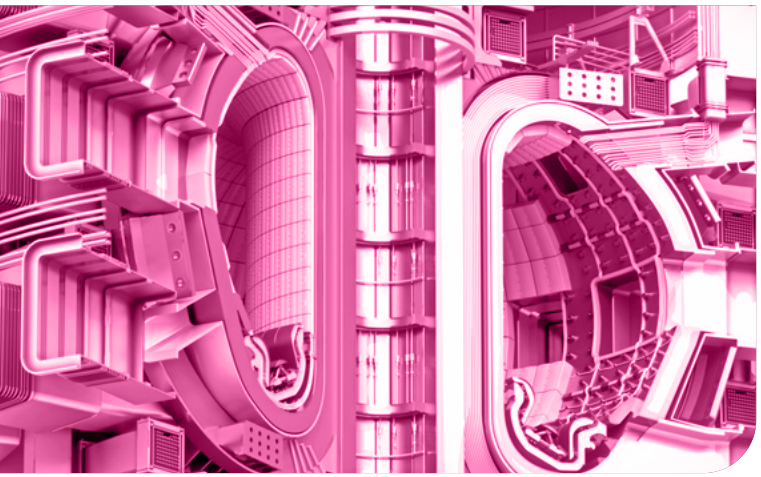
JOINING AND MANUFACTURING:

Developing reliable techniques for joining dissimilar materials (e.g., tungsten to steel, ceramics to metals) that can withstand the fusion environment is a significant challenge. Advanced manufacturing techniques, including additive manufacturing, are being explored to create complex components and potentially improve material properties.

LACK OF FUSION-RELEVANT NEUTRON SOURCE:

A major challenge in materials research for fusion is the absence of a readily available neutron source that perfectly replicates the spectrum and flux of a fusion reactor. This necessitates the use of surrogate irradiation facilities (like Materials Test Reactors with fission spectra) and advanced modelling to predict material behaviour under fusion conditions. Validation of these models through limited fusion-relevant irradiation data (e.g., from IFMIF-DONES when operational) is crucial.

Addressing these interconnected issues requires a comprehensive and integrated research program involving materials development, irradiation testing, advanced modelling, and engineering design. International collaborations and knowledge sharing are vital to accelerate progress in this challenging field.



PRIMARY RESEARCH FOCUSES CONCERNING HYDROGEN PERMEATORS

Hydrogen permeation has a crucial role in the fusion fuel cycle, specifically for fuel processing and tritium management. Key areas of investigation include:

DEVELOPING MATERIALS WITH HIGH HYDROGEN PERMEABILITY AND SELECTIVITY

This involves exploring various metals and their alloys.

PALLADIUM-BASED ALLOYS, particularly Pd-Ag has been extensively studied due to their high hydrogen permeability and reduced embrittlement compared to pure palladium. Research aims to optimize their composition and fabrication methods, such as coating porous ceramic tubes with thin metal layers using sputtering, electroless deposition, and cold rolling. Rolled Pd-Ag membranes have demonstrated complete hydrogen selectivity and stability required for fusion applications.

VANADIUM AND ITS ALLOYS are investigated as alternatives to palladium due to their superior hydrogen permeability. Research focuses on alloying vanadium with elements like Cr, Al, Pd, and Fe to enhance hydrogen diffusivity and mitigate hydrogen-induced embrittlement. Studies aim to quantitatively evaluate the effects of these alloy elements on hydrogen diffusivity and identify the most suitable compositions for hydrogen-permeable membranes. For instance, research suggests that Cr and Fe additions enhance hydrogen diffusivity in vanadium, while Al and Pd can decrease it due to blocking effects in the crystal lattice.

Other metals like **Tantalum (Ta)** are considered for applications requiring resistance to hydrogen embrittlement. **Tungsten-Vanadium alloys** are also explored to combine the durability of tungsten with the hydrogen permeability of vanadium for specialized applications.

DEVELOPING AND UNDERSTANDING MEMBRANE TECHNOLOGIES

for efficient hydrogen and tritium separation and extraction.

MEMBRANE PERMEATORS utilizing thin metal or ceramic membranes are a common approach. Research includes optimizing membrane thickness to maximize hydrogen permeation fluxes and reduce tritium inventory.

VACUUM PERMEATORS, which use a vacuum to drive tritium permeation through a membrane, are a promising technique for tritium extraction from liquid metal breeders like lead-lithium (PbLi). Experiments like the Tritium Extraction eXperiment (TEX) aim to test the vacuum permeator concept with materials like vanadium.

Research also investigates **ceramic coatings,** such as alumina (Al2O3) and aluminides, as hydrogen permeation barriers to prevent tritium contamination in fusion reactor components.

FOCUSING ON TRITIUM RECOVERY FROM VARIOUS SOURCES

This includes:

EXTRACTING TRITIUM FROM LIQUID METAL BREEDERS
(e.g., PbLi) using permeators. Research involves designing and modelling permeator systems for efficient tritium extraction, considering factors like PbLi flow rate, temperature, and permeator material.

RECOVERING TRITIUM IN ELEMENTAL FORM FROM TRITIATED WATER
using membrane reactors that couple a selective membrane (like Pd-Ag) with a catalytic bed for the water gas shift reaction. This approach aims to shift the reaction equilibrium towards hydrogen production by continuously separating the hydrogen.

UNDERSTANDING HYDROGEN TRANSPORT PROPERTIES
of permeator materials, including diffusivity, solubility, and recombination constants. Quantitative evaluations of hydrogen diffusivity in various alloy membranes are conducted to optimize permeator performance.

ADDRESSING CHALLENGES RELATED TO ISOTOPE SEPARATION
to selectively separate hydrogen isotopes (H, D, T) based on their different permeation rates. Research explores how co- and counter-permeation of different isotopes affect permeation fluxes.

DEVELOPING MODELS AND SIMULATIONS
to predict and analyse the permeation process, aiding in the design and optimization of permeator systems. These models consider factors like mass transport in liquid metals and permeation through metal membranes.

CONSIDERING SURFACE EFFECTS
on permeation, as surface oxides can reduce surface reaction rates, which are crucial for efficient hydrogen dissociation and recombination.

SCALING UP PERMEATOR TECHNOLOGIES
for industrial applications, including fusion reactors and other energy systems. This also includes considering the durability and stability of permeator materials under fusion-relevant conditions.

Overall, the research on hydrogen permeators is a multidisciplinary effort involving materials science, chemical engineering, and nuclear engineering, all aimed at enabling efficient and sustainable fusion power.

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