Study of degradation of materials by radiation damage in Nuclear Fusion Reactors.

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Abstract: This research discusses the critical challenge of materials in the context of nuclear fusion reactors, with focus on mitigating radiation damage and enhancing overall reactor performance. Investigating the complex interaction between high-energy neutrons and structural materials, the study aims to identify extreme radiation conditions faced by the materials. By integrating studies of materials science, including nanomaterials and advanced alloys, the research seeks to discuss the resilience and longevity of critical reactor components under these conditions. The paper also took previous studies done by the IFMIF for better results. The outcomes of this study not only introduce the challenges associated with radiation damage but also towards the contribution of fusion energy technology.

Keywords: Fusion Reactors, Nuclear Energy, Material Science, Radiation Damage, Energy Efficiency, Nuclear Science.

Introduction: Recent advancements in nuclear technology have let to development of nuclear fusion reactors. These reactors or systems aims to harness plasma by electromagnetic conditions and create nuclear fusion. In which the immense kinetic energy possessed by the plasma particles will be transferred or better to say converted to thermal energy. Certain corporations and countries are developing this technology, it is promising for energy generation but still poses a wide list of challenges.

The reactors work on the principle of fusion where the hot plasma preferably at or around 150 million degrees Celsius [1]. The plasma at this temperature creates extreme conditions under the reactor as at such high temperatures intense neutron flux and radiation can corrode or degrade the materials used.

This extreme temperature is essential for initiating and sustaining the fusion process. However, the creation of intense conditions under the reactor, where the materials used are exposed to a combination of variables. These conditions pose a formidable challenge as they have the potential to corrode or degrade the materials over time. The study of material degradation due to radiation damage in nuclear fusion reactors becomes necessary for further research in addressing these challenges and ensuring the longevity and efficiency of the reactor components.

The paper is made in sections discussing the materials and the effect of such high electromagnetic induction for better understanding.

The Background: Fusion power is a proposed and under development form of power generation that would generate electricity by using heat from nuclear fusion reactions [(2)]. In a fusion process, two lighter atomic nuclei combine to form a heavier nucleus, while releasing energy [(3)(4)]. Devices designed to harness this energy are known as fusion reactors. Research into fusion reactors began in the 1940s, but as of 2023, devices like TRENTA by Helion aims to reach the net power [(5)]. A more detailed mechanism of fusion power generation is described below.

Fusion reactions occur when two or more atomic nuclei come close enough for long enough that the nuclear force pulling them together exceeds the electrostatic force pushing them apart, fusing them into heavier nuclei. For nuclei heavier than iron-56, the reaction is endothermic, requiring an input of energy [(6)]. The heavy nuclei bigger than iron have many more protons resulting in a greater repulsive force. For nuclei lighter than iron-56, the reaction is exothermic, releasing energy when they fuse. Since hydrogen has a single proton in its nucleus, it requires the least effort to attain fusion, and yields the most net energy output. Also, since it has one electron, hydrogen is the easiest fuel to fully ionize. As for energy capture multiple approaches have been proposed to capture the energy that fusion produces. The simplest is to heat a fluid. The commonly targeted D-T reaction releases much of its energy as fast-moving neutrons. Electrically neutral, the neutron is unaffected by the confinement scheme. In most designs, it is captured in a thick "blanket" of lithium surrounding the reactor core. When struck by a high-energy neutron, the blanket heats up. It is then actively cooled with a working fluid that drives a turbine to produce power.

Another design proposed to use the neutrons to breed fission fuel in a blanket of nuclear waste, a concept known as a fission-fusion hybrid. In these systems, the power output is enhanced by the fission events, and power is extracted using systems like those in conventional fission reactors [(7)].

Designs that use other fuels, notably the proton-boron aneutronic fusion reaction, release much more of their energy in the form of charged particles. In these cases, power extraction systems based on the movement of these charges are possible. Direct energy conversion was developed at Lawrence Livermore National Laboratory (LLNL) in the 1980s as a method to maintain a voltage directly using fusion reaction products. This has demonstrated energy capture efficiency of 48 percent [(8)].

Material used in a Fusion Reactor: Materials that can survive the high temperatures and neutron bombardment experienced in a fusion reactor are considered key to success [(9)(10)]. The principal issues are the conditions generated by the plasma, neutron degradation of wall surfaces, and the related issue of plasma-wall surface conditions [(11)]. Reducing hydrogen permeability is seen as crucial to hydrogen recycling [(12)] and control of the tritium inventory [(13)]. Materials with the lowest bulk hydrogen solubility and diffusivity provide the optimal candidates for stable barriers. A few pure metals, including tungsten and beryllium, and compounds such as carbides, dense oxides, and nitrides have been investigated [(14)].

- Superconducting Materials: In a plasma that is embedded in a magnetic field (known as a magnetized plasma) the fusion rate scales as the magnetic field strength to the 4th power. For this reason, many fusion companies that rely on magnetic fields to control their plasma are trying to develop high temperature superconducting devices. In 2021, SuperOx, a Russian and Japanese company, developed a new manufacturing process for making superconducting YBCO wire for fusion reactors. This new wire was shown to conduct between 700 and 2000 Amps per square millimeter. The company was able to produce 186 miles of wire in nine months [(15)].
- Containment Considerations: Even on smaller production scales, the containment apparatus is blasted with matter and energy. Designs for plasma containment must consider a heating and cooling cycle, up to a 10 MW/m2 thermal load. Neutron radiation, which over time leads to neutron activation and embrittlement. High energy ions leaving at tens to hundreds of electronvolts along with Alpha particles leaving at millions of electronvolts. Electrons leaving at high energy and light radiation (IR, visible, UV, X-ray). Depending on the approach, these effects may be higher or lower than fission reactors [(16)].

IFMIF: Further information was obtained from the International Fusion Materials Irradiation Facility, also known as IFMIF, which is a projected material testing facility in which candidate materials for the use in an energy producing fusion reactor can be fully qualified. The materials are qualified on the basis of how they react with the input and output elements or energies or gases. The accumulation of gas in the material microstructure is intimately related to the energy of the colliding neutrons. Due to the sensitivity of materials to the specificities in the irradiation conditions, such as the α-particle generation/dpa ratio at damage levels above 15 dpa per year of operation under temperature-controlled conditions, material tests require the neutron source to be comparable to a fusion reactor environment.

In steels, the 54Fe(n,α)51Cr and 54Fe(n,p)54Mn reactions are responsible for most of the protons and α-particles produced, and these have an incident neutron energy threshold at 0.9 MeV and 2.9 MeV respectively [17][18]. Therefore, conventional fast fission reactors, which produce neutrons with an average energy around 1-2 MeV, cannot adequately match the testing requirements for fusion materials. In fact, the leading factor for embrittlement, the generation of α-particles by transmutation, is far from realistic conditions (actually around 0.3 ppm He/dpa) [19]. Spallation neutron sources provide a wide spectrum of energies up to the order of hundreds of MeV leading to potentially different defect structures, and generating light transmuted nuclei that intrinsically affect the targeted properties of the alloy. Ion implantation facilities offer insufficient irradiation volume (maximum values of a few hundred μm layer thickness) for standardized mechanical property tests. Also, the low elastic scattering cross section for light ions makes damage levels above 10 dpa impractical [20].

Material Degradation Mechanism: The mechanisms in nuclear fusion reactors are complex and multifaceted, primarily driven by the extreme conditions to which reactor components are exposed [21]. High temperatures, a fundamental requirement for initiating and sustaining nuclear fusion, pose a significant challenge to materials. The intense heat can lead to

- thermal stresses,
- thermal fatigue,
- diffusion of elements within the materials.

Furthermore, the constant bombardment of high-energy neutrons generated during the fusion process contributes to radiation damage. Neutron irradiation can induce displacement of atoms within the material lattice [22], leading to

- structural defects,
- embrittlement,
- changes in material properties.

The cumulative effect of thermal and radiation-induced damage can compromise the structural integrity and performance of reactor materials over time [(23)].

Radiation damage in fusion reactors is not solely confined to the impact of neutrons. The accompanying flux of charged particles, particularly energetic ions, also contributes to material degradation. Ion bombardment can result in sputtering [(24)]. Where material is ejected from the surface, and can lead to erosion and surface modification.

Additionally, the accumulation of helium and other transmutation products within the material can further exacerbate degradation mechanisms.

Results: The results derived from studying the references and prior knowledge are best to be presented in concise form for further research and development.

1. Elevated Temperatures: Through the studies it was found that high temperatures in fusion reactors contribute to thermal stresses and fatigue in materials.
2. Neutron Impact: Intense neutron flux induces displacement of atoms, causing structural defects along with severe embrittlement.
3. Radiation-Induced Changes: Cumulative radiation damage leads to alterations in materialistic properties over time.
4. Ion Bombardment: Energetic ions contribute to sputtering, erosion, and surface modification in reactor materials.
5. Helium Accumulation: Transmutation products, including helium, accumulate within materials, exacerbating degradation.
6. Structural Compromises: The combined effects of thermal and radiation damage compromise the structural integrity of reactor components.
7. Surface Erosion: Ion bombardment and sputtering contribute to surface erosion in materials exposed to fusion reactor conditions.
8. Material Modification: Radiation-induced changes alter the microstructure and mechanical properties of reactor materials.
9. Embrittlement: Neutron irradiation induces embrittlement, impacting the mechanical strength and ductility of materials.
10. Transmutation Effects: Neutron-induced transmutations lead to the formation of new elements within reactor materials.
11. Mitigation Challenges: Developing strategies to mitigate material degradation poses significant challenges.
12. Advanced Materials: Ongoing research focuses on the development of advanced materials with enhanced radiation resistance.

13. Material Testing Protocols: Experimental methods and testing protocols play a crucial role in assessing material performance under fusion reactor conditions.
14. Future Directions: Identifying avenues for future research to address and overcome material degradation challenges in nuclear fusion reactors.

Conclusion: In summary the paper studied basic effects of fusion power generation on the materials used in general. It was found that the radiations and heat can interfere with the materials in many aspects from structural lattice defects to transmutation of new elements increasing further complexity. The paper tried to provide a clear concise understanding towards these effects and list all the possible results for further research and development.

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