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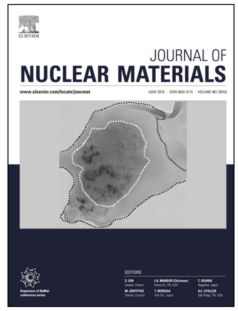

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Refractory Metals as Structural Materials for Fusion High Heat Flux Components

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Abstract

Tungsten is the favoured armour material for plasma facing components for future fusion reactors, but studies examining the use of tungsten or other refractory metals in the underlying cooled structures have historically excluded them, leaving current concepts heavily dependent on copper alloys such as copper chrome zirconium. This paper first outlines the challenge of selecting an appropriate alternative material for this application, with reference to historical selection methodology and design solutions, and then re-examines the use of refractory metals in the light of current design priorities and manufacturing techniques.

The rationale for considering refractory alloys as structural materials is discussed, showing how this is the result of relatively small changes to the logic previously applied, with a greater emphasis on high temperature operation, a re-evaluation of current costs, a relaxation of absolute activation limits, and the availability of advanced manufacturing techniques such as additive manufacturing. A set of qualitative and quantitative assessment criteria are proposed, drawing on the requirements detailed in the first section; including thermal and mechanical performance, radiation damage tolerance, manufacturability, and cost and availability. Considering these criteria in parallel rather than sequence gives a less binary approach to material selection and instead provides a strengths and weaknesses based summary from which more nuanced conclusions can be drawn.

Data on relevant material properties for a range of candidate materials, including elemental refractory metals and a selection of related alloys are gathered from a range of sources and collated using a newly developed set of tools written in the python language. These tools are then used to apply the aforementioned assessment criteria and display the results. The lack of relevant data for a number of promising materials is highlighted, and although a conclusive best material cannot be identified, refractory alloys in general are proposed as worthy of further investigation.

Keywords: fusion, high heat flux, divertor, materials, refractory

1. Introduction

1.1. The divertor problem

Energy from controlled nuclear fusion promises clean, safe, and abundant electricity and significant advances have been made in recent history, particularly in the field of magnetic confinement fusion, employing the tokamak reactor design. Significant technical challenges remain, however, and commercial viability has yet to be proven. One of the most significant challenges faced by designers of fusion power plants, whatever the technology used, will be extracting heat and exhaust gasses efficiently.

For the tokamak concept, a core element of the power exhaust system is the divertor, where magnetic field lines are directly incident on a region of the vessel wall (the divertor target) and which is subject to steady state heat fluxes in the form of radiation and high energy particles in excess of $10\,\mathrm{MW\,m^{-2}}$ with excursions due to off-normal events producing transient loads an order of magnitude higher. There is currently no divertor target design suitable for use in a demonstration fusion power plant, either due to insufficient heat handling capability, thermal efficiency, or component lifetime [1]. Significant effort is being spent reducing the heat and particle fluxes incident on the target by adapting the plasma geometry, e.g. [2, 3], but engineering requirements still exceed capability. When compared to designs used for ITER and other current machines, peak incident heat flux, surface material erosion, irradiation damage, and required coolant efficiency are all likely to be higher, in some cases considerably [4].

1.2. Divertor target state of the art

Away from exposed liquid or vapour-based proposals [5, 6] which have a number of significant outstanding technical and physics challenges, leading concepts broadly fall into two categories: water cooled pipes in tungsten monoblocks similar to the design used for ITER [7] and helium cooled thimbles or pipes employing jet impingement [8].

Figure 1 shows two example divertor target designs: one ITER-like and the other a helium-cooled alternative. The former consists of a water cooled CuCrZr pipe with twisted tape insert surrounded by tungsten "monoblocks" as armour and steel mounting blocks as mechanical support. The other uses a tungsten laminate pipe with

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