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FUSION-8652; No. of Pages 9

ARTICLE IN PRESS

Fusion Engineering and Design xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

A new vision of plasma facing components

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HIGHLIGHTS

- New approach recommended to develop refractory fusion plasma facing components.
- Need to develop engineered materials architecture with nano-features.
- Need to develop PFCs with gas jet cooling with very fine scale for jet arrays.
- Emphasis on role of additive manufacturing as needed method for fabrication.

ARTICLE INFO

Article history:
Received 1 September 2015
Accepted 6 March 2016
Available online xxx

Keywords:
Plasma facing components
First wall
Divertor
Tungsten
Additive manufacturing

ABSTRACT

This paper advances a vision for plasma facing components (PFCs) that includes the following points. The solution for plasma facing materials likely consists of engineered structures in which the layer of plasma facing material (PFM) is integrated with an engineered structure that cools the PFM and may also transition with graded composition. The key to achieving this PFC architecture will likely lie in advanced manufacturing methods, e.g., additive manufacturing, that can produce layers with controlled porosity and features such as micro-fibers and/or nano-particles that can collect He and transmutation products, limit tritium retention, and do all this in a way that maintains adequate robustness for a satisfactory lifetime. This vision has significant implications for how we structure a development program.

1. Introduction

This paper advances a vision for plasma facing components (PFCs) motivated by our perceived need for a new approach to developing refractory plasma facing components for a fusion reactor. The high temperature coolant needed for efficient power extraction in a reactor drives the need for refractory materials. The ARIES Team's more recent DEMO studies [1,2] also have used refractory PFCs.

The EU power plant study of ~10 years ago [3] identified water cooling in one of four blanket systems of interest; and has now focused more aggressively on near term development of a water-cooled DEMO plus a second option for longer term development [4]. Also the US explored options for facilities for fusion nuclear science that includes D-T devices based on various confinement concepts and devices for testing PFCs [5–8], but effort in this area has decreased. And China had a strong program for developing a component test facility [9].

Several factors evolving in recent years point toward the need for a reactor PFC being an engineered structure. Among the issues of concern are:

a) mitigating brittleness in tungsten-based materials,
b) preempting deleterious effects from helium as the microstructure of tungsten-based materials evolve,
c) neutron-induced transmutations in tungsten and dimensional changes in graphite that lower their thermal conductivity and mechanical integrity, and
d) achieving higher efficiency heat transfer (to helium coolant), e.g., develop impinging jet arrays with much finer size than is currently used in fusion applications.

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[1] Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

http://dx.doi.org/10.1016/j.fusengdes.2016.03.031

Please cite this article in press as: R.E. Nygren, et al., A new vision of plasma facing components, Fusion Eng. Des. (2016), http://dx.doi.org/10.1016/j.fusengdes.2016.03.031

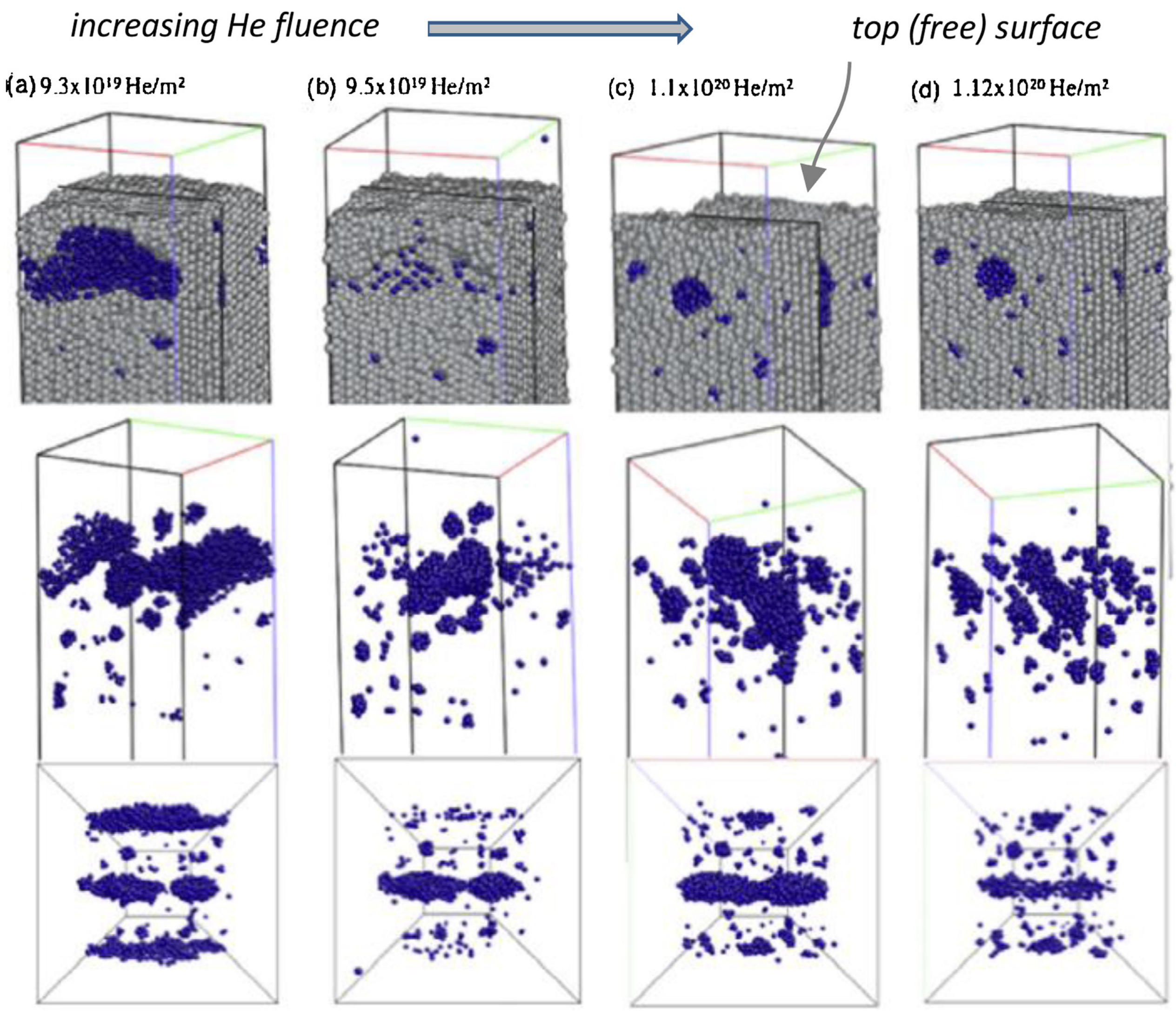

Fig. 1. Visualization of MD simulations of tungsten (light gray spheres) exposed to a 60 eV helium plasma implantation (blue or dark spheres are helium atoms), from Ref. [36] which gives a detailed explanation. (The web version of this article has a color figure.)

The first part of this paper expands upon the points above. The underlying theme is that the solutions for these issues will most likely come by developing materials and structures that have fine scale features such as nano-scale particles or small fibers as well as porosity in the PFM and fine scale coolant passages in the PFC substructure, and these structures may also require graded composition.

The underlying theme is the materials architecture and engineering structure that characterize these refractory PFCs. The second part of the paper discusses the directions in research and development that we believe are needed to make progress toward novel, engineered PFC solutions. Certainly progress is also necessary in confinement and power handling but these are not topics in this paper.

2. Plasma facing materials for a fusion reactor

Tungsten (W) or Carbon (C) are the leading choices for PFMs for FNSF and DEMO along with reduced activation ferritic steels (RAFS) for the first wall structure. With irradiation in a fusion neutron spectrum to 30 dpa, 10% of the W transmutes to Osmium. These transmutants, combined with the irradiation-induced defects produced, lead to significant tungsten embrittlement. Moreover the thermal conductivity, **k**, will drop by about half (based on irradiation data with Re) [10]. By 30 dpa, graphites begin to undergo significant dimensional changes with substantial swelling following the initial densification, along with a loss of mechanical integrity and decreases in thermal conductivity of as much as ~60%. Compared to nuclear graphite, the higher performance carbon fiber composites, which are typically considered for PFC applications will have significantly less lifetime, largely due to irradiation-induced dimensional instability [11]. With tungsten the threats of recrystallization and cracking are also concerns [12]. So the use of these materials in product forms in which they are currently available implies component lifetimes that would require replacement on a schedule that is unattractive for a commercial reactor.

The underlying constraints for this assertion about PFC lifetime are as follows and have been well summarized in the past [13–17].

1. The neutronics for tritium, specifically the fact that the flux of neutrons that transmute lithium to produce tritium decays rapidly with the radial distance beyond the first wall (FW), imposes a requirement that the FW in a breeding blanket are integral with the blanket structure rather than being a separately demountable structure.
2. Replacement of the FW requires removal of blanket modules and reinstallation of new modules.

Please cite this article in press as: R.E. Nygren, et al., A new vision of plasma facing components, Fusion Eng. Des. (2016), http://dx.doi.org/10.1016/j.fusengdes.2016.03.031