Development of advanced tungsten and alternative materials through advanced manufacturing

L. Garrison1*, S. Babu2,1, R. Dehoff1, Y. Katoh1, A. Sabau1, R. Lowden1, S. Zinkle2,1, B. Wirth2,1, J. Blanchard3, C. Henager4, R. Kurtz4, R. Nygren5, M. Yoda6

1Oak Ridge National Laboratory
2University of Tennessee, Knoxville
3University of Wisconsin, Madison
4Pacific Northwest National Laboratory
5Sandia National Laboratories
6Georgia Institute of Technology
*garrisonlm@ornl.gov

1. Background

The plasma-facing components (PFCs) are a linchpin of a fusion reactor because they must handle the high heat flux (ReNeW Thrust 11), resist the plasma and neutron interactions (ReNeW Thrust 9 and 14), and also interface with the blanket materials (ReNeW Thrust 13). Although tungsten has been chosen as the main plasma-facing material (PFM) in ITER and is the leading candidate for future fusion reactors such as FNSF or DEMO, serious doubts remain as to if unalloyed tungsten will be able to withstand the necessary heat flux while experiencing temperature gradient stresses and property changes from simultaneous neutron bombardment and ion fluxes. A dedicated effort to design new hybrid materials1 for PFCs must be undertaken with input from the results of neutron, plasma, and high heat flux testing while taking advantage of the emerging advanced manufacturing techniques that can produce near-net components with unique combinations of form, function, and shape.

1.a. Progress since ReNeW

Originally, many possible PFM s vied for selection, but many have been ruled out for different failings, leaving tungsten as the only choice for ITER’s divertor2. With a lack of alternatives to select from, future designs such as FNSF and DEMO are depending on tungsten’s success. A large effort is ongoing to analyze tungsten’s microstructure and mechanical properties after neutron irradiation and is beginning to identify serious limitations of unalloyed tungsten3,4. Creative solutions beyond pure tungsten are essential to the success of future fusion reactors. Fortunately, since the ReNeW report, significant advances have been made in additive manufacturing and composite technology which can be leveraged to solve the engineering challenges of PFCs.

1.b. Opportunities, national/international context, scientific urgency

Pure tungsten has several non-ideal properties for use as a PFM. Its high DBTT temperature (~400-650°C), low recrystallization temperature (~1300°C), low fracture toughness, and brittle behavior under neutron irradiation could easily cause pure tungsten PFCs to fail when subjected to the extreme heat flux, temperature gradients, and possible off normal events present in a fusion power plant. In addition, the PFCs must withstand nanostructure formation induced by helium and hydrogen isotopes ion flux at least enough to prevent extinguishing the burning plasma, eroding so quickly that replacement is too frequent to be economical, or causing unacceptable levels of tritium retention.

With the US historical expertise in advanced materials development and recent advances in manufacturing science and technology, we have the right tools and knowledge to seize the opportunity and become the world leader in creating PFCs that can meet all the requirements of a fusion power plant. Because the road to qualifying a new material is long, especially for a nuclear application, the time to act is now, and the need is urgent. The investment in fusion neutron, high heat flux, and PMI simulation devices is crucial to understand the processes occurring at the plasma-wall boundary, but equally crucial is the need to have viable materials developed to test in those devices.
2. Specific proposal

Four interconnected focuses of research are identified to overcome the challenges of the PFCs: creating advanced tungsten based materials, exploring other high temperature materials besides tungsten, developing a transitional structure between the PFM and the structural materials, and utilizing advanced and additive manufacturing techniques to create the necessary complicated structures.

Tungsten-based materials should be developed that raise the recrystallization temperature of tungsten while also improving the ductility and fracture toughness. Many current approaches to create a tungsten based material with improved mechanical properties rely on the use of W fibers or foils to introduce crack deflection interfaces and/or use deformation processing to improve the mechanical properties\(^5\). Although the science basis for W fiber reinforced composites is well established, numerous practical manufacturing challenges need to be overcome. In addition to research on improved W alloys or composites, a parallel effort should be maintained to explore non-tungsten materials. For example, ultra high temperature ceramics with high thermal conductivity, such as ZrB\(_2\) are one possibility.

Beyond improving the material properties, the engineering challenge of connecting the PFM to the underlying structural and cooling components must be accomplished in a way that can survive temperature gradients and the thermal expansion mismatch of different materials and still ensure minimal thermal contact resistance. Functionally graded materials are being explored for tungsten to steel connections both to reduce the stresses induced by thermal expansion differences as well as to add fracture toughness to the tungsten. Possible routes to creating functionally graded components include roll-bonding, plasma spray, spark plasma sintering, and additive manufacturing\(^6\)\(^-\)\(^9\). Other methods for joining dissimilar materials, such as the Transient Infrared Processing technique, developed for joining tungsten armor to SiC and steels using a plasma arc lamp\(^10\)\(^,\)\(^11\), should be explored for PFCs.

Advances in additive manufacturing offer possible solutions to creating tungsten-based composites, functionally graded structures, and more complicated PFC structures with internal cooling or diagnostic channels that would not be possible with subtractive manufacturing. For one example, ORNL researchers have proven the concept of using ultrasonic additive manufacturing to produce metallic structures with embedded ceramics. These new flexibilities of advanced manufacturing component shapes could allow new design space to be explored for future PFCs. In addition, methods are being developed to locally control the microstructure of a component as it is being manufactured by using electron beam additive manufacturing processes\(^12\). This is crucial for PFCs where it has been shown that grains with different microstructures can cause 2-3 times increase in gas retention, for example.\(^13\)

Efforts must be coordinated between materials development, materials testing and characterization, and component design through topology optimization to create new and improved PFCs. Any new material resulting from the study must be fully characterized and have its performance validated through testing in high heat flux devices, PMI simulators, and neutron environments while moving toward progressively more complex testing conditions until the materials can be validated in prototypical fusion reactor conditions in a device such as FNSF. Results at each stage of testing need to be shared with the design community so PFC designs can be realistic and take advantage of the unique features of the materials. For example, any composite will have anisotropic properties that can be beneficial if anticipated in the design, or a part created through additive manufacturing can have a complicated internal structure that could influence the design of the cooling manifold system.

3. Anticipated results, impact

Having reliable PFCs that can withstand much harsher conditions than in today’s experimental fusion devices is absolutely essential for the success of fusion power. Pure tungsten is an important model system to gain understanding of the degradation mechanisms in the PFM environment, but it may not survive in future devices. The efforts to design improved, tungsten-based hybrid materials should draw on recent advances in additive manufacturing in the areas of joining dissimilar materials and creating complex internal channels. The anticipated results of this would be creation and validation of a new divertor material and structure that could be deployed in future reactors.
4. References


