The Case for Helium-Cooled Refractory PFCs

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Areas of Critical Need: Power conversion systems for DEMO will require helium-cooled refractory heatsinks for plasma facing components that can operate at high temperatures as part of a highly efficient closed Brayton cycle. Plasma facing components (PFCs) must endure peak heat fluxes in excess of 10 MW/m^2 at the divertor. Tungsten heatsinks require inlet temperatures greater than 600 ^oC (DBTT) and must operate at the highest outlet temperatures possible (~1000 ^oC) for higher efficiency, but stay below the re-crystallization temperature (~1100 ^oC). Thermal-aerolic studies including thermomechanical modeling and high heat flux testing and substantial upgrades to test facilities are necessary to evaluate these components. Further refractory materials development, innovative fabrication techniques and clever thermal engineering coupled with power-relevant testing will provide reliable high performance heatsinks for DEMO PFCs. Currently, the Technology Readiness Level (TRL) for helium-cooled components is about a 3. Much further development is required to reach the level required for DEMO (9-10). A lack of investment in refractory materials research and the limited capabilities of our present test loops and equipment to operate at the required high temperatures and pressures with sufficient helium mass flow have stymied progress. Unless the community addresses this need, helium-cooled components cannot advance past TRL 3.

Background: Helium cooling has many advantages in a nuclear system due to its inherently safe, inert chemical properties, lack of corrosion, vacuum compatibility, single-phase heat transfer without the possibility of critical heat flux (CHF), lack of neutron activation, and easy separation from tritium. Most importantly for DEMO, helium is the fluid of choice for a highly efficient, high temperature Brayton cycle exhibiting minimal wear and corrosion of gas turbines.

One disadvantage of helium is its low thermal mass, ρC_p, that is less than 1% of water. This necessitates the use of greatly enhanced heat transfer area and turbulence promoters for efficient heat transfer. Tremendous progress occurred in this regard during the last fifteen years, and helium cooling now can be as effective as water. Other disadvantages for helium and the Brayton cycle include the nature of a compressible gas working fluid, that requires higher pumping or blower power and larger supply and return piping compared to liquids and the large amount of stored energy in high pressure systems.

U.S. research efforts on helium-cooled heatsinks applications began in 1994 on copper devices [1-7]. These efforts were funded almost exclusively through the OFES SBIR program. Small businesses such as Creare, Thermacore, Plasma Processes and Ultramet, as well as larger concerns such as General Atomics and Rockwell, fabricated helium-cooled heatsinks with various enhancement techniques including microfins, jet impingement, plasma-sprayed, sintered or brazed porous media, and metal foams. Refractory heatsink development started in 1998 on pure tungsten and continues today with lanthanated tungsten, tungsten-rhenium alloys and molybdenum [8]. Several of these devices exhibited record heat flux handling capabilities with heat transfer coefficients as high as 30,000 W/m^2K.

U.S. industry was instrumental in developing low-cost, near-net-shape fabrication techniques for our present day helium heatsinks. The technology is now evolving to include large area (0.3m x 0.3m), multiple channel components with integrated manifolds and a minimum of joints. Further scale-up is required. Another possibility is the creation of monolithic PFCs consisting of refractory heatsinks and refractory armor such as tungsten rods or lamellae with no joints or thermal expansion mismatches. In other cases, diffusion bonding may be appropriate. The Japanese recently demonstrated diffusion bonding of tungsten to reduced activation ferritic steels (RAFS) for high temperature blanket applications.

Research Thrusts: We propose a small research thrust in the $2-3M range for development and testing of refractory heatsinks. This includes ductile refractory materials development, thermomechanical modeling, and HHF testing of large panel, helium-cooled heatsinks with integrated manifolding and diagnostics. This will enable researchers to carefully evaluate the influence of mass flow rate, operating pressure, residence time, and parallel flow instabilities due to non-uniform heating on the thermal performance and reliability of these heatsinks. In addition, the test results can validate the thermal modeling and identify failure mechanisms. Both porous media, like the Ultramet porous foam concept [9,10], and jet impingement devices, like the helium-cooled modular divertor (HEMJ) [11,12] or the ARIES CS Tee-Tube [13], are prime candidates for consideration.

Since, the current level of development has out-paced the capabilities of DOE to test the devices under DEMO-relevant power and flow conditions, we must link a larger thrust to this smaller effort. Any larger thrust on testing facility upgrades should include new or improved helium flow loops in the US to test PFCs and blanket components. This will require an investment at the $10-30 M level. DEMO-relevant helium flow loops should be capable of high temperature operation (~1000 ^{o}C), 10 MPa of operating pressure and provide mass flows on the 500 to 1000 g/s level.

Importance to MFE: In 2008, the International Energy Agency (IEA) Nuclear Technology of Fusion Reactors (NTFR) accepted, with DOE concurrence, a new international collaboration between the EU, RF, JA, IN and the US for the exchange and testing of porous media and jet-type helium-cooled refractory heatsinks to support DEMO. This includes US participation in the HEMJ collaboration now ongoing between FZK and Efremov. Currently no funds outside the PFC base-program are allocated to support this endeavor. This new research thrust would provide support to US industry for mock-up fabrication and cover the cost of HHF testing in existing facilities such as Sandia’s PMTF [14]. The thrust would support porous media and jet model development for heat transfer and stress analysis at a multitude of universities and laboratories, as well as provide for improved high temperature diagnostics, e.g. m-dot, stress, ΔP, and calorimetry, for testing and RAMI, and test procedures for use on upgraded facilities.

Ultimately, the testing must progress to higher temperature (~1000 ^oC), higher mass flow rates (>500 g/s) and higher pressures (8-10 MPa) to realize DEMO-relevant conditions.

This research thrust also allows the US to maintain the leadership role in helium-cooled refractories nurtured in the PFC base-program during the last fifteen years. Failure to adopt this strategy will relinquish that lead to the EU and RF.

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