Advanced Materials to Enable Timely Deployment of Fusion Energy

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Recent scientific and technological advances in plasma physics and fusion technology, coupled with growing interest in large-scale deployment of sustainable energy options, have spurred a dramatic worldwide increased interest in accelerating the timeline for deployment of demonstration fusion energy systems. The two leading international reduced-activation alloy options for fusion energy structural applications are Fe-(8-9%)Cr-2%WVTa tempered ferritic/ martensitic steel (e.g., ORNL 9Cr-2WVTa, Eurofer97, F82H, CLAM) and V-4%Cr-4%Ti. Both alloy options exhibit good fabricability, acceptable mechanical properties, and attractive safety and waste disposal radiological behavior, along with documented resistance to radiation induced dimensional changes at intermediate temperatures.

Both of these reference reduced-activation structural alloy options are based on materials originally created in the 1980s. Advances in understanding of steel metallurgy during the past ~40 years has led to steady improvement in the high temperature strength of ~9%Cr ferritic/martensitic steels (e.g., ~50-100ºC increase in the upper use temperature based on thermal creep strength to ~650-700ºC for recently developed ferritic/martensitic steels). Similar enhanced performance in V alloys is now achievable compared to the international reference solid solution V-4%Cr-4%Ti alloy. However, there is a widespread perception that alloy development & optimization followed by obtaining code qualification and licensing of a new material (by the relevant national organizations responsible for ensuring public safety during operation of power plants) requires several decades of testing with an accompanying high cost. This has led to a very limited range of options for structural materials that are qualified for safety-related components in high temperature nuclear power plants. For example, there are only 6 alloys currently qualified for Class A high temperature nuclear reactor components in the relevant ASME Boiler &Pressure Vessel Code, all of which were initially created over 45 years ago and none of which meet the designation of a reduced activation material. The current lack of any ASME high temperature nuclear code-qualified fusion structural materials is arguably the most time-critical obstacle to commercialization of fusion energy.

Research performed within the broader materials science and engineering research community has demonstrated viable pathways to rapidly move from alloy design and fabrication to industrial utilization in very high-performance structural component applications. This so-called Materials by Design approach can be applied to a wide range of alloys to accelerate their insertion into demanding industrial applications, but to date has not been attempted for fission or fusion energy systems. The key steps in this process include the following: 1) identify the desired microstructural features in the alloy (e.g., thermally stable precipitates in the matrix and along grain boundaries to enable improved high temperature strength), 2) perform computational thermodynamic and kinetic modeling to determine the most promising chemical composition and thermomechanical or heat treatment conditions that will lead to the desired microstructures, 3) fabricate small laboratory heats of the new alloy and confirm via microstructure analysis and mechanical testing whether the desired functionality is achieved, 4) iterate with revised chemical compositions and heat treatment conditions as needed, 5) scale up to large sizes using relevant industrial alloy producers, and 6) perform comprehensive mechanical testing on the industry-produced alloy heats to obtain necessary data for reactor engineering design activities, qualification and licensing. Steps 1-4 can be performed rapidly (~weeks to ~2 months per step). Step 5 can take months to 1 year depending on the industry vendor workload. Step 6 has traditionally been the most time-consuming step due to the historic approach of assembling properties data to support lifetime reactor operation up to ~40 years. For high temperature nuclear reactor applications, complementary environmental effects testing (chemical compatibility with coolant, irradiation effects) on the base metal and joints needed for power plant licensing have also traditionally been very time consuming.

This presentation will summarize several recent successful examples of rapid design, small heat fabrication, and scaleup to large industrial production of novel high-performance fusion-relevant structural materials, and will outline a strategy for staged code qualification and prioritized environmental effects testing of these new materials. In particular, this approach has been demonstrated for the rapid development and scaleup of a precipitate-strengthened reduced-activation ferritic/martensitic steel. The new steel has ~50% increased tensile strength at low to intermediate temperatures, and ~10X improvement in the creep rupture lifetime at high temperatures (~650^{o}C) compared to international benchmark reduced activation ferritic/martensitic steels. The large increase in precipitate number density of the new steel is predicted to also impart improved radiation resistance compared to benchmark steels. Due to large current uncertainties on the accelerated degradation (cavity swelling, etc.) that might occur for deuterium-tritium fusion neutron irradiation conditions compared to fission test reactor conditions, improved radiation tolerance compared to benchmark ferritic/martensitic steels is highly desirable. Similar approaches to rapidly develop and deploy high performance precipitate-strengthened vanadium alloys and copper alloys will be presented. The potential to apply this methodology for rapid design and deployment of emerging materials such as ultra-high temperature ceramics (single or multiple cations), compositionally complex concentrated alloys (also known as high entropy alloys) including ductile refractory versions of these alloys, and W refractory metal matrix composites will also be summarized.

An analysis will also be presented on the impact of benchmark vs. advanced structural material options on fusion demonstration power plant deployment timelines, cost, and perceived mission risk. Collectively, efficient utilization of a modern Materials by Design approach is arguably the fastest and most scientifically robust pathway for the development of viable advanced materials, which in turn will enable more rapid deployment of fusion energy. For accelerated development of practical fusion energy (as envisioned by multiple startup companies), an acceleration in the cost-effective design and qualification of new high-performance materials options is considered to be an important foundational strategy.