Elements of a US R&D Plan to Develop Fusion Nuclear Materials

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In addition to plasma physics challenges, demonstration of the scientific feasibility of fusion energy requires development of high-performance materials that can sustain the long-pulse fusion reaction, harvest the fusion power, and regenerate the tritium fuel. Fusion Nuclear Materials encompass the corresponding 3 functional areas: (a) plasma facing materials (PFMs), (b) structural materials, and (c) in-vessel blanket materials.

PFMs define the earthly boundaries with the burning plasma and are subjected to extreme radiation, particle and surface heat fluxes from the plasma. Their feedback of impurities to the plasma core must be mitigated by appropriate choice of materials and management of the plasma's edge parameters. In addition, tritium retention must be minimal for safety and operational reasons. Plasma facing components (PFCs) often combine a PFM as armor with a high-performance structural material as a heat sink. Structural materials must be resistant to property degradation for multiple years of operation in an environment with an order of magnitude higher displacement damage, ~10,000x more transmutant helium (He), and 2-3 times the absolute operating temperatures compared to the fuel cladding in current nuclear power plants. The fusion breeding blankets must simultaneously regenerate the tritium fuel via neutron-induced transmutation reactions and enable the efficient extraction of the fusion volumetric heating for electricity generation. The tritium fuel regeneration requires simultaneous achievement of the competing requirements of easy tritium extraction from the breeding medium and minimal permeation of tritium into surrounding components; both solid and liquid breeder concepts are under consideration internationally. A 2012 FESAC Report [1] highlighted key scientific challenges and proposed several high-priority research directions.

The subject of fusion nuclear materials overlaps with the topics for scientific community papers #6 *Plasma-material interactions & divertor* and #8 *Tritium fuel cycle*. [2,3]. This paper focuses on structural materials with some discussion of PFMs and blanket materials. Novel tailor-designed materials, new classes of advanced engineering materials, and advanced manufacturing are emerging innovations that could provide a major beneficial impact on resolving the materials science grand challenges associated with demonstrating practical fusion energy.

Benefits

The extreme operating conditions for fusion energy systems will require materials with extraordinary thermophysical properties and resistance to radiation damage degradation. Having viable options for PFC materials is critical to fusion energy development beyond ITER. Structural materials already developed for demanding environments such as aerospace or nuclear fission power plants are insufficient for the high thermomechanical stresses, displacement doses, and transmutant He associated with fusion energy applications. The US fusion program is leveraging R&D in the broader materials science & engineering (MSE) community to develop new materials and novel materials that can handle higher temperatures, harsher operating environments, and multiple functional requirements. With no committed timeline for a DEMO, the US fusion program is uniquely positioned to risk exploring new and more attractive fusion materials while efficiently identifying unsuitable options (e.g., due to unacceptable tritium retention, poor radiation resistance, or poor coolant compatibility).

Adopting new innovative approaches and cutting-edge tools for designing and evaluating materials will significantly advance fusion blankets and PFCs. Advanced tools such as computational thermodynamics, atomistic modeling and simulations, and computational micromechanics present opportunities to improve the current candidate fusion materials in a steady or possibly a disruptive manner.

Novel materials and advanced manufacturing (AM) technologies offer a potentially transformational advance for fusion energy by improving fusion plasma and engineering subsystems. Innovative materials are being developed in MSE community and emerging as industrial materials. Some of these materials present game-changing opportunities for fusion, such as 1) to extend the upper temperature limit for PFMs by up to ~1000°C over tungsten (W), 2) to achieve outstanding high temperature performance similar to SiC but without irradiation-induced thermal conductivity decreases, or 3) to simultaneously achieve exceptional radiation resistance, high strength and high ductility.

AM collectively represents rapidly developing capability to manufacture geometrically complex and/or multi-functional components. AM can enable fabrication of component shapes that were inaccessible by conventional manufacturing processes. Moreover, AM has diverse potentials to produce novel materials, composites, and inhomogeneously structured components due to use of non-conventional and highly transient fabrication processes [4-9]. A full implementation of AM's capability would likely radically change how we would design a fusion reactor. Examples of AM's potential applications to fusion include 1) serpentine micro-channel passages for ultra-high performance coolant and/or tritium recovery media through first wall and breeding structures and 2) functionally graded materials (FGMs) for PFCs. Serpentine coolant passages could replace the current approach (e.g., in ITER) of linear gun-drilled channels with end plugs. Serpentine passages are well suited for odd-shaped in-vessel components where the coolant must pass through all regions to remove nuclear heat. Another example is breeding structures. Unlike the conventional approach, AM could radially grade the mix of solid breeder, multiplier and coolant channels to optimize the breeding neutronics. FGM components could resolve the challenge associated with bonding of dissimilar materials in PFCs. AM is suitable to custom-fabricate functionally graded PFCs based on the computationally optimized thermo-mechanical designs for the maximum performance, service life, and reliability.

Given our current understanding of how to produce and sustain burning plasmas, the primary remaining fusion energy feasibility challenges beyond ITER are establishing viable technologies to operate fully functional blanket and associated fuel cycle and power extraction in a way that is commercially and environmentally acceptable. Without materials that can function reliably in real components, and not only as small test specimens, fusion energy will not be realized as a viable power source. A successful R&D path for fusion will include attention to the practical aspects of fusion engineering, such as how we integrate subsystems and understand critical phenomena that might cause them to fail. Their behavior is highly complex and design-dependent. Such a "materials-design interface" approach is based on strongly coupled investigations of the mechanical and functional behavior of materials within a design context. Our knowledge grows from studies with sufficient depth that constraints on subsystems can be analyzed and likely failure mechanisms identified and mitigated. ITER, as a design-to-build project, has been extremely informative. However, the functional operating requirements for the PFCs and blanket of a DEMO will greatly exceed those of ITER which does not have high temperature walls or integrated breeding blankets. In order to successfully design, construct and operate a DEMO, enhanced interactions amongst materials researchers and systems-level design teams will be beneficial to propel the development of innovative technologies.

Current Status

Sustained research in the US and internationally has led to high-quality reduced activation materials such as reduced-activation ferritic/martensitic (RAFM) steels, SiC/SiC composites, and W. Strong domestic program and international collaborations are both very important. Among the lessons in developing fusion nuclear materials is the evolving nature of these materials in response to the driving force of damage from neutrons (and ions for PFMs) and the evolution of microstructure due to transmutations. For example, the transmutations produce large amounts of He that can form He-filled cavities that degrade mechanical properties or cause intolerable volumetric swelling. Tailored adjustments of the composition of alloys have been made to forestall deleterious effects for exposure levels up to ~1 to 5 MW-yr/m^2. We seek to understand what drives the evolving microstructures and to adjust the composition and manufacturing methods so that the evolving microstructure can preserve adequate performance of the components for DEMO lifetime fluences that may exceed 10 MW-yr/m^2.

RAFM steels and W are leading candidates for structural and PFM applications, respectively. Today's RAFM steels' performances limit attractiveness of fusion energy due to upper operating temperature limits near 550^{o}C and moderate radiation resistance to the anticipated fusion reactor environment. Advanced nanostructured steels present attractive features of improved radiation resistance and higher operating temperatures that come with penalty of higher cost and limited fabricability. The low cost Castable Nanostructured Alloys (CNAs) currently being developed in the US program rely extensively on computational thermodynamics-based design. The early CNA achieves significant advantages in high temperature capability, toughness, and radiation resistance over the current standard RAFM steels with little additional manufacturing cost [10].

W is identified as the PFM material of choice in the ITER divertor and in many fusion reactor designs because of its high sputtering threshold and refractory properties. However, irradiation in a fusion neutron spectrum to 30 dpa induces transmutation of up to ~10% of the W to Re, Ta, Os.. This combined with irradiation-induced defects lead to severe embrittlement in commercial bulk tungsten, and the thermal conductivity drops by about half. [11] However, using the latest atomistic modeling tools to design W alloys and minimize irradiation embrittlement is considered possible [12]. Moreover, tailor-designed structural composites are rapidly gaining ground as the new way of utilizing brittle materials for demanding structural applications [13].

Innovative classes of materials being developed and deployed by the MSE community as advanced engineering materials are being explored for fusion applications. Among these are ultra-high temperature ceramics (UHTCs), MAX-phases, and high entropy alloys (HEAs), each of which incorporates unique chemical compositions and/or microstructures. Some UHTCs have very high thermal conductivities and have other significant advantages over W in high temperature stability (adequate strength at >2000°C), neutron absorption, and safety features [14]. In some MAX-phase materials the decrease in thermal conductivity after neutron irradiation is minimal in addition to their favorable properties overall [15]. HEAs may have significantly superior radiation tolerance over existing alloys and steels [16]. More broadly, a wide range of fiber reinforced composites and self-healing material concepts pioneered by the worldwide MSE community are being considered for fusion applications.

The conventional and innovative materials discussed above also present opportunities to develop novel composite materials that may be tailor designed by using latest scientific tools. Advanced computational tools are already commonly used to design the current ceramic composites and components. Properly designed composites can turn brittle materials (SiC, W, UHTC) into reliable, predictable, and damage-tolerant components. In fact, the brittle (SiC) matrix composites are now used for components for which reliability is uppermost important, such as passenger aircraft engines and passenger car brake systems. Moreover, AM is becoming available as an emerging tool to expand the production of composite materials to unconventional domains of material combinations.

AM is leading a revolution in materials manufacturing capabilities. Its most common use is to produce geometrically complex components from 3-D models typically in layer-by-layer "builds." Some 3-D printing processes use lasers or electron beams to melt each layer. Direct Write (DW) processes may be used to build a fragile "green" preform that can be machined easily and cured later to gain its finished properties. AM enables novel and complex engineered material architectures with features such as controlled porosity, micro-fibers and/or nano-particles incorporation, transitions in materials and integral robust coatings that can be important in developing solutions for fusion. It is being introduced for aerospace, electronics, bioengineering and medical applications. Current use of AM in fusion is small and for specific projects (e.g., an RF antenna with internal cooling, or a divertor module). Similar limited pioneering studies to use AM in commercial fission reactors are being launched.

Power handling, tritium self-sufficiency, and new compact reactor concepts [2, 17, 18] will require innovations in materials physics and technology that are guided by systems-level fusion power plant design studies. ReNeW [19] notes this legacy of valuable information on nuclear fusion technology and plasma-surface interactions. For successful design of a DEMO fusion reactor, we need to leverage ITER physics and technology experience and expand our competencies in fusion power plant design. Potential post-ITER design targets include the US Fusion Nuclear Science Facility (FNSF) [20] and the Chinese Fusion Engineering Test Reactor (CFETR) [21]. These proposed D-T devices for testing fusion nuclear systems with high availability could address most of the integration challenges of the first fusion reactor.

Programmatic Context

The US is the international leader for fusion materials research on SiC/SiC and is well positioned for leadership on advanced steels and PFMs by leveraging connections to world-leading broader US materials R&D activities, along with access to premiere U.S. research tools such as neutron irradiation facilities and linear plasma devices for PFM testing. Fusion nuclear materials R&D has two historic main thrusts, 1) structural materials and radiation damage and 2) PFMs and plasma-surface interactions (PSI), and successfully leverages major U.S. materials R&D and international fusion collaborations. An important decision to resolve current uncertainties regarding D-T fusion neutron radiation damage processes will center on obtaining access to an intense fusion neutron source within the next decade, most likely located outside the U.S. .

Strengthened research on PMI issues would reduce uncertainties on heat loads, the erosion of the wall, the retention of tritium and ultimately the plasma performance that we can project for a fusion energy demonstration device. R&D investment on PFMs and PSI divides primarily between a) R&D that supports the physics missions in existing and near-term devices, and b) research with longer term goals such as the survival of W in a reactor relevant environment and the development of dual structures that combine reactor relevant PFMs and high performance He-cooled heat sinks. A “cross-over” is R&D on liquid plasma facing surfaces [2]. It will be important to utilize toroidal and linear plasma devices (international and U.S.) to resolve whether solid vs. liquid surfaces in the divertor and other demanding plasma facing regions are the most appropriate pathway to practical fusion energy.

Novel high temperature, high performance materials should be evaluated for fusion divertor, first wall, and blanket structure applications. For example, certain UHTCs offer the potential to increase the maximum PFC operating temperature by 1,000°C over tungsten’s limit. HEA and MAX phases could potentially fill the service temperature gap between the PFC armor and structure. Moreover, tungsten-based refractory composites potentially enable the extensive use of tungsten in fusion reactors for both structural and PFC armor applications. Similarly, newly-designed RAFM steels containing ultrahigh density of nanoscale precipitates (manufactured by conventional or AM approaches) could potentially provide the radiation resistance needed for the economic viability of fusion energy. Fusion should leverage the massive AM R&D activities in industry and non-fusion funding agencies to explore how we can broadly apply the potential of AM to fusion as a transformative enabling capability [8,9].

The materials-design interface and fusion design integration should be reinvigorated to serve as a valuable cross-cutting integrator. Active engagement in design-in-depth activities, e.g., finding limits and iterating to develop solutions and limits, provides valuable experience in the design-materials interface. This requires involvement in comprehensive systems-level engineering designs, as opposed to casual part-time collaboration and reading papers, and in turn depends on other robust activities such as materials development, creative solutions for power handling, and the development of an appropriate cadre of scientists and engineers committed to innovative solutions for fusion. In the near term the US still has an opportunity to regain leadership in this area but this window of opportunity is closing due to anticipated retirements of the few remaining fusion design experts and lack of detailed fusion engineering design initiatives that would attract the next generation of design leaders.

Possible 15-year US Research Agenda: Establish viable PFC and structural material solutions

Adopt innovative approaches to mainline structural and PFC materials – 1) Use advanced computational design approaches to design next generation RAFM steels and refractory alloys; 2) Advance science, design, and manufacture of refractory metallic and ceramic composites; 3) Fully explore W's potential as PFM using advanced tools; 4) Conduct research focused on most critical, fusion-relevant aspects such as radiation damage and plasma compatibility; 5) Obtain access to advanced test capabilities such as fusion neutron sources and plasma exposure devices.

Explore innovative materials and manufacturing technologies to meet materials needs for fusion energy – 1) Evaluate suitability of emerging engineering materials (with modifications) as new classes of attractive materials for fusion reactors; 2) Launch AM initiatives (guided by fusion powerplant design studies): engage in development for specific applications (e.g., PFC and solid breeding components), and industrial/international collaborations.

Start a near-term activity to enhance the materials-design interface. 1) Initiate a comprehensive design study that includes integration of new solutions for power handling as well as advances in magnet technology and tritium breeding and handling. 2) Develop mentoring partnerships regarding the materials-design interface and design integration. 3) Use established contacts worldwide to engage in collaborations where U.S. expertise is insufficient.

Research Directions Beyond the 15-year Horizon: Identify viable integrated blanket concept(s)

For fusion to become a viable energy source, the area of Fusion Nuclear Materials has to grow to involve all aspects from materials development to evaluation in realistic fusion environment and qualification/licensing build upon a sound science base, in a similar way to the historical nuclear materials R&D in fission energy development. Computationally assisted tailor-design of novel/improved materials, utilization of advanced manufacturing, advanced characterizations, and fusion-specific materials test facilities, and enhanced interactions with reactor physics/designs and international activities will be among essential elements of the long-range research directions. Potentially game-changing innovations such as AM will be investigated as appropriate. These capabilities will be used to make an informed decision whether a fusion nuclear technology device is needed prior to the construction of a DEMO commercial fusion power plant, and to enable the DEMO engineering design. Specific milestones would include: downselection between solid and liquid PFC approaches, and downselection of the structural material and blanket concept for DEMO.

Critics' objections (O) and advocates' responses (R).

(O) Focus on front runner concepts and materials. Endlessly expanding materials of interest is not cost-effective.

(R) Fusion is a long-term effort. Our design concepts get outdated if we do not adopt latest developments emerging from the broader scientific research field. The US is uniquely positioned to explore high risk options. Long-lasting, broad discipline value will be generated through a science-based approach.

(O) AM is rife with mega-hype and overblown promises. Many would-be users view AM as a silver bullet to fix all. AM will evolve on its own schedule outside fusion and we can simply benefit as fusion projects arise and the designers survey industry capability. Also, the number of process variables and materials architectures possible implies many options for development.

(R) AM experts can easily determine where AM is useful. While AM would come into fusion via projects (happening already in small ways), early attention to understanding and applying AM will change how we would design a fusion reactor. Winnowing the choices and qualifying AM materials will be a challenge. However, this must be measured against the potential benefits of success as well as the current lack of recognition of the large likely costs of developing and qualifying materials for fusion.

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