The path toward next-step fusion development demands increased emphasis on the boundary plasma-material interface. A critical issue facing the design and operation of next-step high-power steady-state fusion devices is the development of suitable plasma-containment system (PCS) solutions for divertor and main chamber walls. The PCS includes the plasma facing material (PFM) including any replenishment system, especially for liquid walls, the structure supporting the PFM, the coolant system, and maintenance/replacement approach to the PCS components. Viable PCS solutions are a universal challenge to fusion energy, regardless of confinement concept. These solutions must provide adequate power and particle handling, and be compatible with the required core plasma performance. Candidate solutions should eliminate or minimize core contamination and/or dust production due to erosion; have reasonable lifetimes under high heat, particle and neutron bombardment with or without replenishment/refurbishment; minimize tritium retention; provide high operating temperatures; and minimize total life-cycle costs of the near plasma components. The materials systems for the first wall and divertor are arguably the largest challenges facing fusion energy development.

Addressing this challenge of the plasma-materials interface system in fusion nuclear devices requires a new, more integrated approach. The current strategy of searching for a single, simple material solution has exhausted the periodic table. In order to prepare for next-step nuclear devices and beyond, we propose a new, more focused strategy that places the long-term objective of a successful fusion power plant at the heart of the search.

This new focused program should bring together several elements of the fusion research community, including the fusion materials community, the core physics community, the boundary physics community, and fusion energy device system studies. It should assess all options systematically in order to identify an optimum design that addresses not only plasma confinement characteristics, but also long-term sustainability and nuclear component behavior in a burning plasma device. The resulting integrated solution may not fulfill all of the desires for peak performance in every area, but will better identify trade-offs and provide a more coherent and coordinated path forward to future research and development (R&D) in confinement physics, plasma-material interactions, and nuclear systems performance needed for next-step nuclear devices. This program will bring together many parts of the fusion community in an integrated fashion needed to optimize the R&D efforts in this area going forward.

Plasma-facing materials (PFMs) already benefit from a long history of research in worldwide fusion programs, with material choices driven largely by efforts to improve plasma confinement. Low-Z materials such as carbon and beryllium dominated the field for decades. More recently, in
the ITER era, concerns over tritium inventory and dust generation led research programs to reject carbon in favor of beryllium on the first wall, and tungsten in the divertor. Presently, tungsten dominates the conversation on ITER and next-step fusion devices. However, there are serious concerns regarding the susceptibility of tungsten to melting and cracking under high heat flux and the production of surface nano-tube “fuzz” leading to surface arcing and dust production. These issues become more serious for “advanced tokamak” modes of operation where the combination of steady state, relatively smaller size, higher confinement, higher power density, and lower plasma density to facilitate non-inductive current drive, lead to even greater sensitivity to core high-Z contamination and consequent radiative collapse. Additionally, future high duty cycle devices may experience significant material migration leading to local buildup. Managing such buildups appears more tractable using low-Z materials than high-Z metals.

In fusion power plant and nuclear test facility studies, alternative solutions have been considered, including bare steel or bare SiC first walls, W-coated steel or SiC, W-alloy components with W armor, and a variety of liquid PFMs. The absence of a clear winner combined with the large uncertainties extrapolating to a power plant PCS environment has made these choices, and that part of the integrated plant design, largely ad-hoc in most cases.

It is clear that for any real progress to be made toward large, long-pulse burning plasmas generating copious amounts of neutrons, innovation in materials and designs will be required. These innovations will require consideration not only of the consequences on core plasma performance, but also the edge plasma configuration and conditions, material surface evolution, and PFM behavior in a reactor-relevant high-temperature nuclear environment. Bridging the gap between plasma-facing materials for present-day devices and the PCS for future nuclear devices is a timely and essential program need.

A coordinated R&D plan is needed to facilitate progress. Within magnetic fusion energy research, a clear development path should be adopted to bring novel materials and component configurations from concept to near end-use readiness. Ideas for developing advanced PFMs in toroidal devices include, but are not limited to, thin-film coatings of low-Z materials on high-Z bulk or SiC substrates, cutting-edge advanced manufacturing techniques for thin layer and/or nanostructured alloys, and liquid PFMs. A well-focused, comprehensive research program targeting such advanced solutions will not only focus current experiments on more reactor-relevant PFM regimes, but will also lead to unique world-wide leadership for the US fusion effort. Key scientific topics that must be understood in the development of materials solutions include (1) the impact of PFM selection on the core plasma; (2) erosion, redeposition, and material migration under both steady and transient plasma conditions; (3) the effects of high bulk temperature PCSs; and (4) refurbishment, replenishment or replacement of the PCS components. These topics and details are discussed extensively in the 2009 Fusion Energy Sciences Advisory Committee (FESAC) ReNew report [1] and the 2012 FESAC materials science report [2]. Figure 1 highlights the main elements of a PCS development path.
Step 1. Building consensus: The first step in this activity is to develop community consensus on a coordinated research plan, drawing from both the plasma and material science arenas. This planning phase will likely require multidisciplinary community workshops. A key attribute and objective of this thrust area is tighter collaboration and communication between material researchers and plasma researchers. Experimentalists, theoreticians, designers, and technologists should be involved in the planning phase. A cohesive roadmap is needed to evaluate, assess, explore, and improve new concepts for the PCS.

Step 2. PFM testing and component R&D: The fusion materials program is critical to the success of any PCS program. Materials science effort is needed not only to develop materials and components to test, but also for modeling the effects of both incident plasma and neutron fluxes on these materials. This fundamental understanding is crucial to the ultimate development of predictive models for PFM. In parallel, testing of targeted materials is needed and is efficiently carried out on linear devices such as PISCES, the proposed Material Plasma Exposure eXperiment (MPEX), and Magnum-PSI in the Netherlands. These devices offer easy access to materials samples for detailed measurement and modeling and provide a simulated long-pulse environment and will remain the bulk of the materials development effort.

Step 3. Integrated testing: Ultimately, samples will need to be tested on toroidal devices, both long- and short-pulsed. While long-pulse devices will provide the most comprehensive PCS test before a Fusion Nuclear Science Facility (FNSF) or demonstration power plant (DEMO), short-pulse devices such as DIII-D are a critical element since they provide a mitigated risk path for testing regarding cost, accessibility, and turn-around time, in conjunction with a comprehensive set of diagnostics and a realistic plasma environment. Coupling this measurement capability with linear devices and model validation constitutes a virtually ideal component test environment. Toroidal plasma devices provide not only an essential platform for integrated testing, but also can serve a role to focus and guide research throughout the entire program. We envision toroidal
confinement devices as the final proving ground in a competition of ideas for next-step nuclear facility and DEMO PCSs.

Integrated tests in a plasma confinement device can provide focus to the program: In a typical technology development program, such a grand challenge is addressed by developing an R&D program that is focused on the next step, or next prototype, in the maturing of the technology. This is used to focus the work of the different technical communities into the trade-offs needed to select the best approach(es) that should be funded in the near term. To obtain convergence by the plasma confinement and fusion materials communities on a program centered on the large confinement device(s) is being suggested. If a program such as the FNSF was currently being pursued, this would tend to naturally happen in defining the design of the machine. To some extent this happened for ITER, but did not cover all the aspects of a fusion energy device.

The US is not currently pursuing the near-term implementation of a next-step device, which means there is less of a driving function to push the technical communities toward an integrated development effort. A PCS program could be built in the near term around testing in a toroidal confinement device such as DIII-D. There is a limited number of components that could be tested over time; therefore, competition will be generated to be included in the test program. Also, the confinement physicist working with the machine will be intimately involved in all aspects of the development of the experiments. This is where those two communities come together in the near term. To be in the program, the approach proposed must show strength in all aspects of PCS for a fusion energy device. In order to properly assess progress and establish R&D needs, a systems-level assessment will be needed in the context of specific device parameters and design choices. This systems-level activity could be carried out in the context of the US national concept studies team, or a separate activity carried out in a similarly integrated way.

There are limited resources to develop fusion materials and PCSs. The large number of options available makes progress on any given technical approach too slow if the research is not focused on a select number(s) of approaches. It is suggested that a program be established to help direct the R&D effort on PCSs to help the US prepare for future efforts for the next-step device, to integrate the activities of different technical communities within the fusion research community, and to generate a leadership position in PCS development in the US.

REFERENCES