Power Extraction Research Thrust Using a Full Fusion Nuclear Environment

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Mission Scope and Summary

The demonstration of efficient and reliable power extraction from the Demo fusion power plant will be a key requirement to prove the economic viability of commercial fusion power and will be necessary to convince prospective commercial vendors that fusion energy will be a profitable investment. As noted in the 2007 report to the Fusion Energy Sciences Advisory Committee, 'Priorities, Gaps and Opportunities: Towards a Long-Range Strategic Plan for Magnetic Fusion Energy', "The scientific issues encountered in fusion power extraction are substantially different than other energy sources including fission." Seven specific issue areas are highlighted:

1) A very high surface heat flux and potentially high peaking factors
2) Complex volumetric heating source involving both plasma products (neutrons, particle and radiation) as well as nuclear reaction in the power extraction components
3) Strong impact of electromagnetic field (both static and dynamic) on heat transfer
4) Large temperature and stress gradients which can derive a multitude of complex physical phenomena
5) Compatibility with the fuel cycle (tritium production and extraction)
6) Complex geometry
7) Evolving material properties (due to radiation effects)

Additionally, the report notes that this is "uncharted scientific territory with extreme conditions."

The power extraction system has two major objectives: 1) maintain components at safe thermal limits, and 2) use the heat generated by the plasma to efficiently produce electricity or process heat. In the Demo, the power extraction system will also be required to support the fuel cycle process by acting as a transport medium for tritium, and will also contain other transmutation by-products. A significant effort will be needed to understand and characterize power extraction system phenomena and component behavior before a Demo facility can be constructed. It is expected that the knowledge base and understanding of pertinent phenomena and component behavior will be greatly extended by construction and operation of ITER, particularly if the Test Blanket Modules (TBMs) are operated. However, there will remain significant gaps in our knowledge of the power extraction process under prototypical fusion conditions even after ITER is operational. For instance, because ITER is being designed as a plasma test facility, it will achieve fluence levels two orders of magnitude less than those expected in a Demo facility, and operate with short plasma times. Only the TBMs in ITER will resemble those that could be used in Demo, while a variety of other non-prototypic features of ITER will require extension to a Demo facility.

To bridge the knowledge gap between ITER and Demo that will exist in the power extraction area, both analytical and experimental efforts will be required. Experimentally, some issues can be addressed in ex-reactor testing. These might include cooling tests under high and peaked heat flux conditions using heating sources other than the fusion plasma, evaluation of flow in complex geometries and high magnetic fields, development of power conversion cycles, etc. However, the conditions that will be required to test and establish the technical knowledge for, and to prove the feasibility and operability of the Demo power conversion system, cannot be duplicated outside of a full fusion environment.

Closing the Research Gap between ITER and Demo

Volumetric heating within the first wall components, including the coolant, will be a complex three dimensional field in the fusion environment. Capturing this behavior in an ex-fusion environment will not be possible. The heating distribution ultimately dictates material temperatures, the design of the cooling system, and the stress levels imposed on the components and sub-components. Additionally, transient plasma behavior will have a significant impact on both surface and volumetric heating and therefore material temperatures which in turn impact tritium release behavior and long term material lifetimes.

Tritium retention, transport, and release from structural materials and coolant comprising the power extraction system will be dependent on the thermal and neutronic history and instantaneous temperatures and neutronic environment of the structural components. In order to appropriately understand and design the power extraction system to accommodate tritium behavior expected in Demo, a prototypic fusion environment will be needed to provide a substantial database and operational knowledge of tritium behavior in the fusion environment.

A full fusion environment is also required to study the long term interaction of multiple physics processes impacting power extraction. This is not possible to simulate in a non-fusion environment, and many of these effects are unknown. These include the combination of the above factors and the influence of issues such as material irradiation behavior, component alignment, transient behavior, magnetic field effects, etc. Further, only a full fusion environment will provide quantitative information on reactor component failure rates, failure modes, and the effects of failures on operation which will be required before a reliable Demo design can be developed.

The power extraction systems generally have a direct safety function. Operation of these systems in a nuclear environment will also therefore significantly enhance the safety arguments that will be required by the regulators of a Demo facility. Long term testing in a fully instrumented, experimental facility, providing a full fusion environment can be used to develop the data that will be required to build a strong regulatory case.

Ex-reactor experimentation and improved analysis techniques will also be necessary to develop design details and operational strategies for power extraction components and systems. This will include detailed thermal and fluid performance characterization as well as materials performance characterization and fuel cycle development. Fusion compatible power conversion components such as heat exchangers, turbines, etc. will also need design and development efforts. Instrumentation required to monitor and control power extraction components and that can survive in the appropriate fusion environment will to be identified and developed. Data from these activities will be needed to benchmark design and safety codes and provide confidence in predictive capabilities. Additionally, thorough systems analysis will be needed to optimize operating parameters and establish component configurations. Experimentation in a full fusion environment extends predictive ability by allowing multi-physics codes to be validated and provides confidence in the design process necessary to configure Demo.

Enabled R&D

Performance, reliability, and safety characterization of power extraction components can be quantified in an integrated and prototypic environment. Expected diverter, blanket, and first wall designs use multiple coolant types, differing heating rates, multiple tritium inventories, etc. A full fusion nuclear environment will allow these various design and operating features to be evaluated in an integrated environment, while providing more instrumentation, and component flexibility than will be possible in Demo. Data taken in a experimental full fusion nuclear facility that is necessary to support power extraction system development (along with development of all other fusion systems) will include detailed thermal performance characterization, tritium transport, materials performance, and fluid loop characterization, as well as a variety of others necessary for the success of Demo.