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Overview of the fusion nuclear science facility, a credible break-in step on the path to fusion energy

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ABSTRACT

The Fusion Nuclear Science Facility (FNSF) is examined here as part of a two step program from ITER to commercial power plants. This first step is considered mandatory to establish the materials and component database in the real fusion in-service environment before proceeding to larger electricity producing facilities. The FNSF can be shown to make tremendous advances beyond ITER, toward a power plant, particularly in plasma duration and fusion nuclear environment. A moderate FNSF is studied in detail, which does not generate net electricity, but does reach the power plant blanket operating temperatures. The full poloidal Dual Coolant Lead Lithium (DCLL) blanket is chosen, with alternates being the Helium Cooled Lead Lithium (HCLL) and Helium Cooled Ceramic Breeder/Pebble Bed (HCCB/PB). Several power plant relevant choices are made in order to follow the philosophy of targeted technologies. Any fusion core component must be qualified by fusion relevant neutron testing and highly integrated non-nuclear testing before it can be installed on the FNSF in order to avoid the high probability of constant failures in a plasma-vacuum system. A range of missions for the FNSF, or any fusion nuclear facility on the path toward fusion power plants, are established and characterized by several metrics. A conservative physics strategy is pursued to accommodate the transition to ultra-long plasma pulses, and parameters are chosen to represent the power plant regime to the extent possible. An operating space is identified, and from this, one point is chosen for further detailed analysis, with R = 4.8 m, a = 1.2 m, I_P = 7.9 MA, B_T = 7.5 T, β_N < 2.7, n/n_{Gr} = 0.9, f_{BS} = 0.52, q_{95} = 6.0, H_{98} ~1.0, and Q = 4.0. The operating space is shown to be robust to parameter variations. A program is established for the FNSF to show how the missions for the facility are met, with a He/H, a DD and 5 DT phases. The facility requires ~25 years to complete its DT operation, including 7.8 years of neutron production, and the remaining spent on inspections and maintenance. The DD phase is critical to establish the ultra-long plasma pulse lengths. The blanket testing strategy is examined, and shows that many sectors have penetrations for heating and current drive (H/CD), diagnostics, or Test Blanket Modules (TBMs). The hot cell is a critical facility element in order for the FNSF to perform its function of developing the in-service material and component database. The pre-FNSF R&D is laid out in terms of priority topics, with the FNSF phases driving the time-lines for R&D completion. A series of detailed technical assessments of the FNSF operating point are reported in this issue, showing the credibility of such a step, and more detailed emphasis on R&D items to pursue. These include nuclear analysis, thermo-mechanics

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and thermal-hydraulics, liquid metal thermal hydraulics, transient thermo-mechanics, tritium analysis, maintenance assessment, magnet specification and analysis, materials assessments, core and scrape-off layer (SOL)/divertor plasma examinations.

1. Introduction

For fusion research to take the step beyond ITER it will have to embrace the fusion nuclear science along with fusion plasma science. The hardware that surrounds and supports the plasma will become part of the challenge for research and development since fusion power plants will rely on these structures to recover the power emitted, breed the tritium fuel, provide neutron and gamma shielding, and provide the magnetic fields and the vacuum environment the plasma requires. The Fusion Nuclear Science Facility (FNSF) is a fusion nuclear device that is considered as the first step in a two-step pathway from ITER to commercial power plants in the U.S [1]. The project reported here is exploring this facility to better understand its characteristics and how it moves the demonstration of sustained fusion energy production toward our present vision of power plants.

In order to address this facility several technical strategies and choices had to be established, including the need for a fusion break-in step, the importance of power plant relevance, the practicality of a single primary blanket approach, the need for a fusion core component qualifications, the need for a plasma strategy, and a series of technical decisions that stem from these. A set of missions that must be accomplished to reach an electricity producing power plant are described, and several metrics are proposed for measuring their progress. A program is postulated for the FNSF to expose the steps required to advance these missions, and force the consideration of allocating time to plasma operations, inspections, and maintenance. Although these steps are dominated by the neutron fluence they reach, and blanket operating temperatures, they can also include other incremental technical steps. The blanket testing part of the program is developed by considering plasma support systems (e.g. heating and current drive, fueling, diagnostics), inspection needs, maintenance, and the hot cell. Similar testing would be performed for the divertor, and possibly the other special plasma facing components (e.g. RF launchers and diagnostics).

Systems analysis is used to identify a conventional aspect ratio operating point and its surrounding operating space, with focus on the plasma and engineering constraints, and the need for robustness to account for the considerable uncertainty in reaching the desired parameters. The operating point (its geometry) is used in detailed analysis of the plasma core, scrape-off layer and divertor, nuclear analysis, steady and transient thermo-mechanics, thermal hydraulics, liquid metal MHD breeder analysis, magnets, maintenance, radio-frequency structures and apparatus, tritium behavior and inventory, and materials considerations. These calculations are being used to establish the credibility of such a facility at its smaller size, identify the benefits/penalties of specific technical decisions, uncover vulnerabilities and approaches to provide margin, and help in establishing targeted R&D for the FNSF. The accompanying papers in this issue provide the detailed assessments [2–13], and will only be summarized here. The cost of the fusion core, or the facility, was not determined since it was considered outside of the scope of this activity. In particular, the range of costs to consider is complex (e.g. R&D) and the typical cost algorithms used in 10th of a kind power plant studies, generally unit costs (e.g. $/kg), does not appear appropriate for the first of a kind and one of kind facility like the FNSF. The level of effort required to construct bottoms-up costing for a wide range of systems is not credible at this pre-conceptual level.

This paper is organized as follows. In Section 2 the background for the FNSF is outlined by briefly describing the present fusion landscape, and how the FNSF appears in and impacts the fusion development pathway. Its importance is motivated by the need for a fusion nuclear step that provides an actual fusion environment for the first time, and technical strategies are described. Section 3 describes the facility mission, and metrics for measuring progress. Section 4 describes the physics assumptions and supporting experimental observations. Section 5 describes the systems analysis and results in deriving the operating space for the device. A program is described in Section 6. Summaries of the detailed technical analysis are given in Section 7, and pre-FNSF R&D is described in Section 8. A summary and conclusions are presented in Section 9.

2. Background

The FNSF is examined as part of the development path toward commercial fusion energy-based electricity production in the U.S. The FNSF can take on many possible missions, and this is demonstrated by several different forms previously reported [14–18] ranging from a volumetric fusion neutron source to an electricity producing pilot plant. The present comprehensive study is focused on an FNSF that will contribute to the development path in a definable way. The landscape in which fusion energy research finds itself now has evolved over the last 40 years, and plays an important role in what is conceivable as a development path. Early roadmaps [19] (1976) for the U.S. fusion program often identified multiple engineering steps before a commercial fusion power plant. These included TFTR (which was built and operated), an engineering research facility or engineering test reactor, a prototype experimental power reactor or ignition test reactor, an experimental power reactor, and finally a demonstration reactor. The list also includes several plasma physics facilities. By the mid 1980's [20] this view had changed significantly, with discussion of a burning plasma facility, international cooperation on an engineering test reactor (referred to as ETR or ITER), and several plasma physics experiments and non-confinement facility engineering test stands (including a materials test facility). International collaboration took a much stronger position at this point due to significant budget reductions in the 1980's. Finally in the mid 1990's [21] a restructuring of the U.S. Fusion Energy Sciences Program took place, moving the emphasis of the program to advancing the plasma science, fusion science and fusion technology, with ITER as the only new fusion facility, directly associated with fusion energy, on the landscape. A much richer description of the history of the U.S. fusion program, and many program studies produced, can be accessed on the FIRE website [22]. In the U.S., and globally, the appetite for several fusion engineering facilities to advance toward a power plant has diminished and there exists now increased pressure to advance any fusion nuclear facilities in as few steps as possible. By 2010 and later, with the international commitments to the ITER project and construction in place, several countries turned to examining what might follow, or proceed in staggered-parallel with, ITER to move toward fusion energy-based electricity production [23–26]. As part of this, this project is targeting a better understanding of 1) what

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