RAMI Research Thrust Using a Full Fusion Nuclear Environment

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1. Motivation and Purpose of white paper

The Fusion Energy Sciences Advisory Committee 2007 report, "Priorities, Gaps and Opportunities: Towards a Long-Range Strategic Plan for Magnetic Fusion Energy" [1], identifies "Reliability, Availability, Maintainability" (and Inspectability, or RAMI) as one of the 15 knowledge gaps between ITER and Demo that must be closed in order to provide the technology base to design and construct Demo. More specifically, RAMI is cited as critical to Demo success in order to "demonstrate the productive capacity of fusion power and validate economic assumptions about plant operations by rivaling other electrical energy production technologies". In addition, RAMI research is necessary to build "the knowledge base for efficient maintainability of in-vessel components to guarantee the availability goals of Demo are achievable".

The purpose of this white paper is to identify critical remote maintenance research thrusts in Fusion Nuclear Science (FNS), an important element of the RAMI knowledge gap. A separate white paper, "Fusion Nuclear Science Research Thrust and the Required Full Fusion Nuclear Environment" [2], more broadly addresses fusion research thrusts and knowledge gaps that are fulfilled through a FNS Facility (FNSF) based on a Spherical Tokamak (ST) Component Test Facility (CTF) [3]. This paper specifically addresses the remote maintainability knowledge gap that a FNSF like the ST CTF is required to fulfill as a *fully enabled fusion nuclear environment*.

2. Closing the Research Gap during the ITER era

The expected availability goal of Demo (> 50%) is extremely challenging and unprecedented given the very limited operation and power production of fusion experiments to date, and the inherent complexity of all envisioned fusion reactors. No fusion experiment ever built and operated is representative of a nuclear fusion power source, and only one has applied remote handling technology to an appreciable extent (JET).

ITER is expected to operate only a small percentage of the total time in a year (plasma duty factor ~ 1 to 2 %), and remote maintenance will be performed in a very time inefficient manner with outage durations that range from several months to multiple years to remotely exchange in-vessel components. A major change in fusion remote maintenance design and techniques must be developed to achieve the specified availability goals of Demo, or even to achieve a plasma duty factor an order of magnitude greater than ITER (>10%). An order of magnitude increase in duty factor is representative of a ST CTF fusion machine and its design concept has shown that major changes in remote maintenance techniques must be employed [3]. A FNSF combining all the aspects of a nuclear environment is necessary to investigate and close the RAMI gap to Demo.

The fusion nuclear environment is viewed by many as the most challenging of the remote handling applications. It is characterized by extreme radiation levels, space-constrained in-vessel access openings, complex and relatively heavy in-vessel components with complex mounting and service connections that require precision positioning and complex handling kinematics by robotic mechanisms that are well beyond today's state-of-the-art technology. The limited in-vessel access typified by tokamak fusion designs is in direct conflict with simple, expedient maintainability. Moreover, fusion energy concepts include robotic handling and transport of large activated components through the plant facilities, and refurbishment in hot cell laboratories; operations that are challenging and unprecedented in themselves.

If acceptable mean-time-to-repair (MTTR) time for all activated fusion components is not developed and demonstrated in conjunction with high component reliability, or high mean-time-before-failure (MTBF), an acceptable fusion power source availability cannot be achieved. A FNSF would provide a major step towards fusion nuclear energy representative remote maintenance techniques, in addition to providing the knowledge base needed in many other important FESAC Report technology gap areas as addressed by Ref.s 1 and 2. In each of the proposed operating phases of Ref. 2, from "Scientific Exploration" through "Component Engineering Development and Reliability Growth", all aspects of RAMI would be investigated and advanced in the fully enabled fusion nuclear environment.

The most agreed and foreseen solution to acceptable component MTTR time is large integrated in-vessel component modules that are time efficient for remote exchange between the reactor and hot cell, with off-line refurbishment performed in the hot cell. Concepts of FNSF and Demo developed to date by multiple organizations include this common design feature, yet no representative fusion device is planned, including ITER. Hence, it is not surprising that RAMI is identified as an important knowledge gap to Demo.

The related cross-cutting remote maintenance technology R&D gap thrust areas include: 1) large scale, radiation-hard robotic devices that can provide dexterous manipulation and precise positioning of highly activated in-vessel components; preferably with simple linear and time efficient motions, 2) a multitude of specialty remote tooling and end-effectors, including precision remote metrology systems to measure PFC alignment and erosion in the extreme fusion environment (high radiation, bakeout temps, vacuum), 3) credible, low MTTR in-vessel component design solutions (time efficient and reliable remote mounting and service connections) that are also highly reliable (high MTBF), and 4) supporting hot cell facility remote handling systems and tooling necessary to refurbish and/or waste process the activated in-vessel components.

3. Enabled R&D

The first step in the R&D process is the development of the conceptual designs of the high plasma duty factor / high availability device, whether a ST CTF or other tokamak, including the remote maintenance features of the components, the supporting remote handling systems, facility and hot cell laboratories. This must be done working in close collaboration with the various component designers in order to develop reliable, fully functional, and efficiently maintainable component solutions. Many remote handling elements of these designs will be new and unique, and must be prototyped, tested and demonstrated in mock-ups ranging from relatively small to large in scale.

The final and most important step of the development process is the construction and operation of a FNSF from the break-in through the final advanced stages of science and technology demonstration. A FNSF during the ITER era, and beyond, should address all elements of the remote maintenance knowledge gap to Demo, and provide the required step towards developing the experience and knowledge base for credible Demo design solutions.

References

[1] http://www.ofes.fusion.doe.gov/FESAC/Oct-2007/FESAC_Planning_Report.pdf

[2] Y. K. M. Peng et al., white paper on “Fusion Nuclear Science Research Thrust and the Required Full Fusion Nuclear Environment,” submitted to ReNeW (February 2009).

[3] Y. K. M. Peng et al., "Extensive Remote Handling and Conservative Plasma Conditions to Enable Fusion Nuclear Science R&D using a Component Testing Facility", FT/P3–14.