COMPARING MAINTENANCE APPROACHES FOR TOKAMAK FUSION POWER PLANTS*

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ABSTRACT

Two generic approaches for maintaining commercial fusion power plants are compared to determine the most desirable maintenance scheme and reactor design approach to consider for the next generation, advanced tokamak power plant, the ARIES-AT[1]. The scheduled and unscheduled maintenance times for the power core of fusion plants are extremely important as they directly determine the plant availability and, ultimately, the cost of electricity. The plant down time is determined by the time to access the failed or worn out part(s), the time to accomplish the replacement, and the time to verify the replacement.

The ARIES-AT power core[2] is the design basis for this comparison. One possible maintenance approach is the in-situ removal of moderate-sized modules of individual first wall, blanket, and divertor elements from inside the tokamak power core. This approach potentially allows smaller and lower cost toroidal and poloidal field coils that tightly fit around the outer surface of the power core shield or vacuum vessel. A second approach uses larger toroidal and poloidal field coils that will allow much larger ports to extract a complete, intact sector module of the first wall, blanket, shield, and divertor elements.

The time to access and egress the power core components is largely determined by operations independent of the maintenance approach, such as reactor cool down, draining/filling fluids, unfastening/fastening doors, vacuum leak checks, etc. Replacement time of the core elements was found to significantly favor the modular sector approach because there are fewer and more accessible coolant and structural joints to unfasten and fasten. For the in-situ maintenance approach for ARIES-AT, there are more, but smaller, modules to handle than with the modular sector approach. Verification of the successful refurbishment is a distinct advantage for the modular sector approach because it can be operationally tested in a remote assembly area before being installed. Only a few main coolant connections will be verified within the power core region. For these reasons, the modular sector maintenance approach was adopted for the ARIES-AT conceptual design.

I. INTRODUCTION

The main and guiding goal for the fusion power plant is to have an attractive cost of electricity that is equal or lower than other competitive energy sources. The cost of electricity is directly proportional to the capital cost of the plant and the operations and maintenance costs and indirectly proportional to the net electrical power produced and the amount of time the plant is available to produce electricity. This paper will address the latter factor, the plant availability, and how it can be maximized.

In addition, the plant must be safe both to the workers and the general population. A fusion plant will generate high-energy neutrons during operation, but the power core is properly shielded to prevent any deleterious effects to the plant worker or the general public. When the power core is not operational, no plasma will exist to emit high-energy neutrons, but the highly irradiated power core elements will continue to produce beta and gamma radiation at a much lower rate compared to the operational dose rate. Core materials are selected to minimize secondary radiation levels and long-lived radioactive waste products. After a 24-hour cooling off period, the radiation level within the core decreases to a level suitable for access with radiation-hardened maintenance equipment.

To be economical, the maintenance periods must be efficient and as short as possible. Before the 10th of a kind commercial plant is possible, aggressive maintenance research and development programs must produce a robotic maintenance system that can quickly and

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efficiently inspect, diagnose, repair, remove, replace, and inspect all components of the power core. This includes both the life-limited and the life-of-plant components. Fully automated, autonomous maintenance machines will efficiently accomplish the remote operations. The use of expert systems will be expanded to help develop experience databases for maintenance systems. Fuzzy logic will be applied to help analyze new variations on maintenance situations. Vision, position, and feedback control will be enhanced to provide precise position and motion. Optimization programs will refine the maintenance procedures to speed the overall process. The ability to predict wear-out and incipient failures will continue to be improved.

II. IN-SITU MAINTENANCE

The in-situ maintenance approach may use either a manipulator arm or a maintenance rail to gain access to and replace the power core life-limited elements.

The manipulator arm is an articulated boom that enters through a port to disconnect, remove, replace, and reattach the core elements to be repaired or replaced. TFTR[3] had such a remote manipulator arm to service its core elements. In a commercial plant, two arms would likely be used in parallel to speed the maintenance procedure and to provide system redundancy. In normal operation, a single arm would reach core elements within a span of plus or minus 90°. If one arm became inoperative, the other arm would be capable of extending plus or minus 180° to reach the inoperative arm for repair or removal. On the end of the arms there would be several end effectors to disconnect, remove, replace, and reattach the core elements. Testing and inspection of the core element must also be accomplished by an end effector. The core elements would likely be removed from the power core through two additional ports, roughly 90° from the arm ports. This would be more efficient than totally withdrawing the articulated arms to remove and bring in new modules.

The maintenance rail approach would employ a supported rail inside the core. It could be permanently located inside the core and deployed when necessary. But the severe environment during plasma operation could make this prohibitive. Rather, the rail would likely be brought into the core and assembled for each maintenance action. The ITER concept employed a temporarily installed, rail-mounted vehicle maintenance system[4] deployed from two diametric maintenance ports. The rail would be mounted on multiple support points within the core. A maintenance machine containing shorter manipulator arms and end effectors would traverse the rail to remove and replace the core elements. Two of these machines would be required for redundancy. The rail system would accommodate the heavier module sizes since the rail is more rigid, would support more weight, and would have a higher positional accuracy. Additional time would be required to install and remove the rail system with the help on an articulated arm.

To the first order, the cost of both systems is roughly similar. There is probably more hardware associated with the rail system but the articulated, cantilevered arms would be more complex and longer. Making the arm sufficiently stiff at maximum extension would be difficult. The time to accomplish the removal, transport, and reinstallation probably would not significantly differ for the two approaches, as the maintenance time would be dominated by the module disconnection, removal, and reattachment as opposed to module transport. Thus, the cost and effectiveness of rail and arm approaches are similar.

Both of these approaches would require the power core elements to be smaller and capable of being transported around the torus and through the maintenance ports. The ARIES-AT design uses SiC structure cooled with LiPb, which will be drained prior to any major maintenance. Each of the 16 inboard first wall and blanket SiC modules spans 22.5° and weighs approximately 1.4 tonnes. The outboard sector is comprised of 32 first wall and blanket modules, each weighing 1.6 tonnes. The weight of these components is compatible with either in-situ approach. However, the inboard and outboard modules must be full height. Subdividing the blanket modules is deemed to be too great a risk to achieve reliable in-situ plumbing and structural connections. Handling the full height module requires a full height maintenance port. Hence the in-situ maintenance approach (for a power core concept that does not lend itself to smaller modules) cannot lead to a smaller reactor size.

The number of modules for an ARIES-AT power core will be 16 inboard, 32 outboard, and 32 divertor modules. Assuming the minimum number of structural attach points would be 3 per module, this amounts to 240 mechanical fasteners to be disconnected and connected for each complete core replacement. The ARIES-AT coolant design approach[5] employed three separate circuits serving a combination of first wall, innermost blanket, and divertor elements. For an in-situ maintenance approach, four simple plumbing connections and four coaxial connections will be required for each sector. Coaxial connections are required to maintain thermal control of piping temperatures with high bulk temperature flow. Hence, there will have to be at least 64 simple and 64 coaxial coolant connections for the maintenance of the core. All of these connections must be accomplished and verified inside the power core.

III. HOT CELL MAINTENANCE

The hot cell maintenance approach assumes the removal of a complete power core sector through a full-sized port. This includes all the first walls, innermost blankets, divertors, life-of-plant blankets, and high temperature shielding structure. The sectors are removed from the power core to the hot cell for refurbishment. A previously refurbished sector is immediately reinstalled back in the reactor to speed the maintenance of the power core and lessen the plant down time. After the power core is refurbished according to the maintenance schedule, the sectors can be refurbished in the hot cell while the plant is operating. More extensive quality and life prediction tests on the refurbished sectors can be conducted off line during the operational period.

A transporter will be used to radially remove and replace the core elements. Several options have been considered, but the most feasible one is the transporter and cask approach that contains the dust and debris during maintenance. The ITER[6] concept had such an approach for the divertor modules and the horizontal port modules, including the test blanket modules. In the ARIES-AT case, the transporter will remove one of the 16 vacuum vessel doors and one sector of the power core (1/16th of the core). The cryostat door will be withdrawn upward when the cask is docked. The cask door will be opened upon docking, allowing the transporter access to the vacuum vessel door.

The vacuum vessel doors weigh 13 tonnes when drained of cooling water. Locking hydraulic arms that restrain the vacuum door will be disengaged and moved out of the way. The transporter will cut the sealing welds and disconnect the water coolant connections to the door. The transporter will withdraw the door into the cask for transport to the hot cell for temporary storage. The transporter will then return and disconnect the 120-tonne power core sector coolant and structural connections and move it into the cask for transport to the hot cell for refurbishment. There are five coaxial coolant connections for the entire sector that must be disconnected. The extra two coaxial connections are for the outermost, life-of-plant blanket and the high temperature shield and structure. Supplemental cooling for the power core sector must be supplied during the removal and transport procedure.

In the event a life-of-plant component prematurely fails and cannot be repaired in place, an individual sector can be withdrawn. This will be easier and less time consuming than in-situ replacement, which would require removal of several blanket and shield components to gain access to the failed component.

IV. COMPARISON OF MAINTENANCE APPROACHES

The previous section described the two power core maintenance approaches being considered. To compare these options, eight criteria are identified that characterize the attractiveness of maintenance approaches. Table 1 lists those eight criteria in the first column. Numbers in the first column indicate the perceived relative importance of each factor from 0 to 4. Maintenance time is an important factor as this time determines the outage time and the power core availability. The reliability of the core sector relates to the mean time between failures, which also directly influences power core availability. The building cost, replacement sector cost, and spare equipment cost are important factors as they all contribute to the overall plant cost. The volume of waste is very important due to the concern of storage and disposal of radioactive waste. Contamination is important, as it is a safety concern. Any approach must be largely applicable to both scheduled and unscheduled maintenance.

Table 1 discusses how each of the maintenance approaches addresses the criteria and a numerical score is assigned to each criteria/approach cell. The score of each approach is determined by the sum of the criteria for each approach. The in-situ approach scored well in all cost categories and had the lowest waste generation. This in-situ approach did poorly in time to accomplish the maintenance cycle, contamination impact (as it is difficult to control and cleanup), and applicability to both types of maintenance. The hot cell approach scored well because it was thought to have high availability due to the ease of removal and increased reliability because of the increased time to replace and inspect the refurbished modules. Also, contamination control was good. The sector replacement module approach is well suited to both scheduled and unscheduled maintenance.

As a result of these scores, the hot cell maintenance approach is the recommended maintenance scheme for the ARIES-AT commercial fusion power plant.

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Table 1. Qualitative Comparison of Maintenance Approaches

Scoring: 0 = Lowest, 4 = Highest

	Maintenance Approach	
Criteria (Importance)	**In-Situ Maintenance (Score)**	**Hot Cell Maintenance (Score)**
Maintenance Time 4	Slowest time as all operations have limited access. Arm or rail operations will be relatively s[illegible] and number of parallel operations [illegible] be limited. 14	Fastest maintenance as number of on-line mechanical and coolant connections will be minimal and accessible. All refurbishment will be accomplished off-line.
Replacement Sector Reliability 4	Lowest reliability as all refurbishment and inspection must be in-situ with limited access. Lim[illegible]d time to complete. But it has lowest [illegible]umber of connections. 14	Highest reliability because of long time to complete and inspect refurbishment. High number of connections (same as Corridor Maintenance).
Building Cost 2	Probably the smallest building size, even consideri[illegible]e volume for arm and rail. 43	Slightly less building size than Corridor Maintenance to just accommodate removal and transport sectors.
Maintenance Equipment Cost 1	Not clear, but this approach probably has the lowest maintenance cost even with maintenance arm or rail. One or two simpler tra[illegible]orters are needed. 43	Moderate cost for 4-8 transporters, but transporters are moderate cost compared to mobile refurbishment carts.
Spare Equipment Cost 1	Lowest spare equipment cost as all high temperature shielding structure modules are used t[illegible]e fullest. 42	Highest spare equipment as high temperature shielding structure modules are extracted for refurbishment. Effect can be mitigated with fractional replacement.
Waste Volume 3	Lowest waste volume as all high temperature shielding structures are used to the fulle[illegible]. 42	Highest waste volume as high temperature shielding structures are extracted for refurbishment. Effect can be mitigated with fractional replacement.
Contamination Control 2	Little contamination control as all cutting, disassemb[illegible]reconnecting, and reassembly [illegible] done within the torus. 04	Minimal cutting and reassembly in torus or corridor. Contamination from segment probably controlled.
Applicability to Scheduled and Unscheduled Maintenance 3	Lots of disassembly to reach most distant modules. 14	Same approach on scheduled and unscheduled maintenance. Random access is available to all modules.
Totals MAX. SCOR 80	39	69

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