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ARIES-AT maintenance system definition and analysis

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Abstract

A fusion power plant must have a high availability to be competitive in the electrical generation market. Attaining high plant availability is difficult because the fusion power core has a limited service lifetime. Moreover, the core components are radioactive and very large. To assess these issues, the maintainability of the ARIES fusion power core is analyzed and integrated into the early power core design process, which results in a maintainability approach capable of attaining a relatively short refurbishment time. The developed timelines are presented for the scheduled maintenance of the power core. The short core refurbishment time coupled, with evolutionary improvements in the maintainability of the reactor plant equipment and the balance-of-plant equipment, infer an attractive plant availability in the range of 90%.

Keywords: ARIES; Fusion; Tokamak; Maintenance; Availability; Power core; Vacuum vessel

1. Introduction

The ARIES studies, sponsored by DOE and led by UCSD, has explored, developed, and examined numerous magnetic and inertially confined conceptual commercial electric power plants. The latest in this series is the ARIES-AT power plant [1], which represents an advanced tokamak power core that incorporates the most current physics and engineering data. The maintenance system discussed in this paper was developed for the ARIES-AT power plant study.

To help understand the nomenclature and the plant power core elements, a brief introduction of the power core is discussed along with explanatory figures. The configuration shown is the final product of many trade studies. This paper discusses the maintenance trade studies that lead to the final design. Had the trade studies resulted in different conclusions, the power core configuration would be different.

The power core is defined to be the innermost subsystem that produce and contain the plasma and convert the fusion power into thermal power. The power core consists of the first wall, blanket, shield, divertor, in-vessel shielding, internal structure, TF and PF coils, vacuum vessel, cryostat, in-vessel heating, and current drive elements. The power core systems are a part of the reactor plant equipment that is uniquely configured to the particular magnetic or inertial fusion confinement concept.

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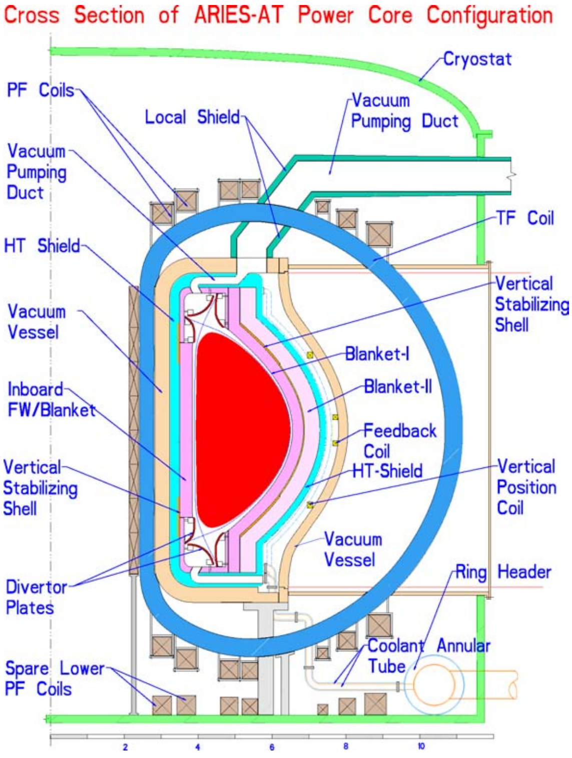

Fig. 1. ARIES-AT power core.

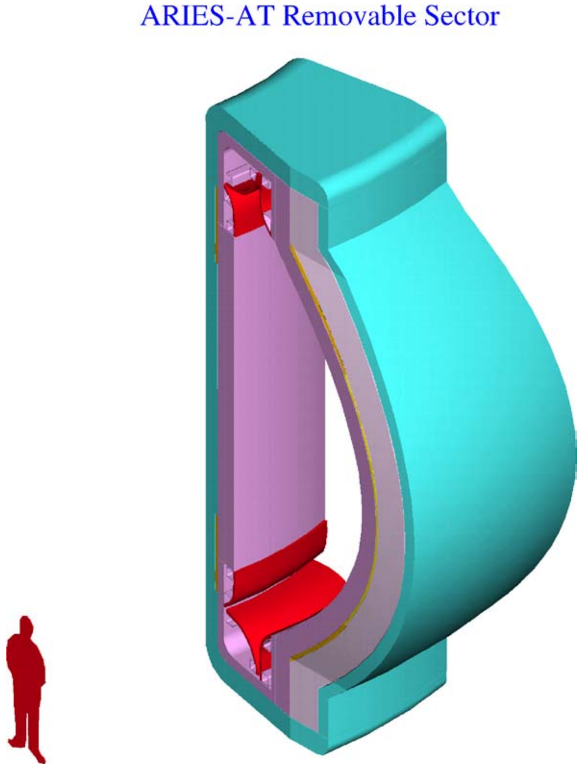

Fig. 2. Removable sector containing first wall, blankets, divertor, and supporting structure.

Fig. 1 illustrates the ARIES-AT power core. The plasma is a double-null configuration with divertor regions at the top and bottom of the plasma. The 16 TF magnets are wider than a constant tension "D" magnet to allow withdrawal of complete sectors between these magnetic coils. The PF coils on the outside of the TF magnets are placed higher and lower than normal to allow the withdrawal of the replaceable sector. The first wall, blankets (Inboard Blanket and Outboard Blanket-I), and divertors are life-limited components due to erosion and neutron damage. They are designed to have comparable lifetimes to ease maintenance. There is a second blanket zone, Blanket-II, in the outboard region that is a life-of-plant component. To structurally connect all of these elements and provide for coolant connections, a structural shield is used just outside the blankets and divertor that will allow the entire unit to be withdrawn as an integral component or sector as shown in Fig. 2. The vacuum vessel is designed as a cylinder with horizontal flanges to support the sectors and allow horizontal removal of the sectors. There is a removable vacuum vessel door that forms the remainder of the vacuum enclosure. There are ports that extend from the basic vacuum vessel to the cryostat wall that allow removal of the vacuum vessel door and the sector while maintaining the vacuum for the TF and PF coils.

2. Power core maintenance philosophy

Two of the primary guiding principles, or goals, for the overall fusion power plant continue to significantly influence the design and operation of its maintenance system—the plant must be safe and economical.

The plant must be safe both to the general population and to the plant workers, including the maintenance workers. A fusion power plant is a nuclear device that emits high-energy neutrons during operation. During shutdown periods, secondary reactions from the highly irradiated power core materials continue to produce beta and gamma radiation inside the power core at a much lower rate as compared to the dose rate during operation. The power core materials are chosen to minimize these secondary radiation levels and long-lived radioactive waste products. After a 24 h cooling off period, the radiation level within the power core will decrease by two orders of magnitude to a level suitable for remote access with radiation-hardened maintenance equipment, as for ARIES-RS see Ref. [2]. It is anticipated that the regulations for allowable radiation levels for nuclear plant workers will continue to be upgraded to assure no hazardous exposure. This assumption would effectively mandate that all maintenance and refurbishment of power core replaceable components would be accomplished entirely by robotic equipment. No hands-on maintenance of the power core components is assumed.

To be economical, the maintenance actions must be efficient and expedient to keep the maintenance downtimes as short as possible. It is assumed that aggressive maintenance research and development programs will be implemented to accomplish a robotic maintenance system that can quickly and 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 control. 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.

3. Evaluation of the scheduled power core maintenance frequency

Most of the outer portion of the ARIES-AT power core is designed to last the lifetime of the plant with no scheduled replacement of components. The inner portion of the ARIES power core has a finite lifetime that requires the entire power core be replaced approximately every four full-power years (specifically, four calendar years/plant availability) to account for first wall erosion and radiation damage exceeding the allowable dpa limit. The ARIES-AT design is configured so that all power core components would roughly have the same operational lifetime. The entire power core could be changed out either all at once or a fraction of it at a time to better correspond to other major scheduled maintenance activities by the reactor plant equipment (RPE), turbine plant equipment, electric plant equipment, electric plant equipment, and miscellaneous plant equipment.

The power core forms the basis of the reactor plant equipment, but there are other subsystems accounted within the RPE, but are not considered as part of the power core, such as: exo-vessel heating and current drive elements, primary supporting structure, vacuum pumps, main heat transfer and transport, cryogenic cooling, radioactive waste treatment, fuel handling, maintenance equipment, and instrumentation and control. For convenience, all other plant equipment can be lumped into a miscellaneous category of balance of plant equipment.

Table 1 compares some of the attributes of various maintenance frequency options.

Removal of one-fourth of the power core are required the least amount of high temperature shield spares. These spare shield structures are populated in the hot cell with new core components for use in the next maintenance period. When sectors are removed, the position where they vacated is immediately filled with the refurbished sector from the hot cell. The refurbishment of the removed sector is accomplished in the hot cell during plant operation. The time needed to shutdown and to startup the power core is fixed regardless of the number of sectors replaced. With frequent maintenance, these fixed actions represent a sizable portion of the entire downtime, especially when the smaller fraction of the power core is replaced. As the frequency of maintenance is reduced, these fixed actions become less important and the availability increases. Plant availability increases as the number of sectors replaced during a maintenance session increases.

As mentioned previously, the larger number of sectors replaced at a single time, the larger number of spare high temperature supporting structures required.

Table 1
Comparison of power core maintenance actions (4 FPY)

Fraction of core replaced	Frequency	Assessment	Recommendation
One-fourth of core (4 sectors)	12 months/availability	Yearly maintenance is feasible. Cool down and start up durations is detrimental to availability goals. Requires minimal number of hot maintenance spares.	Too frequent.
One-third of core (5 or 6 sectors)	16 months/availability	Very similar to annual. Fixed tasks continue to be a major factor of outage time. Requires small number of high temperature structure spares. Maintain BOP every other cycle	#2 choice
One-half of core (8 sectors)	24 months/availability	Probably matches up with BOP major repair. Requires eight sets of spare hot structures	#1 choice
Entire core (16 sectors)	48 months/availability	This 4-year frequency also might be well matched with the BOP major repairs. Requires a large number of spare hot structures and maintenance equipment. Probably would yield highest availability	#3 choice

These high temperature structures serve many functions: shielding, conversion of the kinetic energy of the neutrons to thermal energy for the power cycle, restraint of the first wall, blanket I (the inner blanket modules), and the divertor components. These components are designed to be life-of-plant, but if they are removed, to be repopulated with the inner core components and replaced at the next maintenance cycle (they will not serve their full lifetime in the reactor). Additional structural components must be provided as the initial partial set of spares, which adds to the volume of irradiated waste.

Certain key issues, such as power plant availability; cost of maintenance systems, spares, and facilities; waste volume; and contamination, govern the choice of frequency of power core maintenance. Perhaps the most important criterion is the ability to properly time-phase power core maintenance actions with those for the BOP and RPE elements. If the power core replacement schedule is short (and frequent) as compared to the BOP and RPE major refurbishment cycles, this would be detrimental to the overall plant availability. Likewise, choosing a much longer maintenance cycle can produce a lower availability. For this analysis, it is assumed the likely BOP and RPE major maintenance cycles is close to a 24-month period, so maintaining eight sectors at a time (24 months/availability) is the preferred choice. The next best choice would favor a maintenance approach with fewer spares as the availability gains are minimal for cycles exceeding 24 months.

4. Definition of maintenance options for ARIES-AT

There are three general approaches identified to accomplish maintenance on a commercial tokamak fusion power plant. These are:

- in situ replacement inside the power core,
- replacement of life-limited components immediately outside power core,
- replacement of life-limited components with a refurbished sector from remote hot cell.

Each of these different options has distinct advantages and disadvantages. They are discussed below to help understand and quantify their advantages and disadvantages, along with possible design variations.

4.1. In situ replacement

This is the maintenance approach employed by many magnetically confined fusion (MCF) experimental devices. When the radiation levels inside experimental devices became prohibitive for manned access, machines are designed and built for remote maintenance. TFTR [3] has a remote manipulator arm that entered one port and extended 180° around the interior torus region for inspection and maintenance of all interior first wall and divertor components. This is a typical design for many experimental reactors.

Another approach is the rail system with a mobile maintenance machine with shorter articulated arms.

ITER chose during the engineering design activity (EDA) to employ a temporarily installed rail-mounted vehicle maintenance system [4] deployed from two diametric maintenance ports. One of ITER's maintenance approaches is to internally (in situ) remove and replace the 720 individual shielding blanket modules [5]. These shielding blanket modules are from 1.4 to 2 m in length, 0.8 m wide, and 0.32 m deep, with a weight of approximately 4 t. Blanket shield modules are removed through two additional maintenance ports located 90° to the rail ports. The rail is supported from all four maintenance ports. Manipulator arms and end-effectors held the shield blanket modules while other manipulators released the securing mechanical fasteners. The ITER-specified replacement time for one blanket module is less than 8 weeks, a toroidal array of modules in 3 months, and all modules in 2 years. A second ITER maintenance approach is used for the ITER divertors. In this approach, 60 divertor cassettes [6] are maintained with a separate and distinct maintenance system from the blanket shield modules. Each divertor module is about 5 m × 2 m × 1 m and weighed more than 20 t each. A permanently mounted rail system moves divertor modules toroidally to four divertor access ports. Removal of one module should not take longer than 2 months and all modules in fewer than 6 months.

The approach adopted for in situ maintenance described above for ITER and TFTR is quite appropriate for experimental devices, but the maintainability requirements for commercial operation are much more demanding. From a previous ARIES-RS analysis [7], it is assumed the allowable *scheduled* power core maintenance plan is approximately 10 days per year to achieve competitive plant availability (90%), including the time from plant power down to power up. The cool down time and time for the torus radiation levels to decline to acceptable levels is assumed to be approximately 24 h. A similar time is necessary for the startup sequence. So the allowable *scheduled* maintenance period is on the order of 8 days, assuming one scheduled maintenance period per year to replace one-fourth of the blanket and divertor modules. Other replacement combinations are possible.

To achieve such a demanding maintenance timeline, a much more efficient and streamlined approach must be demonstrated and validated. The underlying assumption is that the power plant being described is the tenth-of-a-kind plant; hence all development difficulties will have been solved before this plant comes on line. Therefore, the approach assumed can be somewhat more aggressive than one for a plant to be built in the immediate future (assuming some technical progress can be made in the interim).

4.1.1. Choice of in situ maintenance equipment

The first choice to be made is the type of in situ maintenance approach to be adopted. The choices seem to be the installed rail system (ITER) or the cantilevered arm approach (TFTR).

The *rail system* tends to favor systems with heavier blanket modules as the rail is more rigid and supports more weight. Additional time is required to install and remove the rail with the help of an articulated arm(s). One or more rail vehicles are required and rail support points must be provided (ports or permanent attach points). ITER chose to use two ports to deploy the rail and two other ports to receive and dispense modules. It is possible that as maintenance equipment and techniques are improved only two ports would be required. Two ports are probably the minimum number as some redundancy for failure is required.

The *cantilever system* could be deployed from one port, but arm deflection under load becomes very difficult. Two port locations would probably be recommended and would provide coverage around the torus of ±90°. Additionally, emergency coverage to 180° would offer a redundancy capability. Modules could be received and dispensed from a separate port or two. It might be possible to use the arm dispensing port as a module receiving and dispensing port if the arm can be withdrawn and extended quickly.

To the first order, the cost of both systems is roughly similar. There is probably more hardware associated with the rail system. On the other hand, the articulated, cantilevered arms would be more complex, longer, and stiffer. The time to accomplish the removal, transport, and reinstallation probably would not significantly differ for the two approaches as the time would be dominated by module disconnection, removal, and reattachment as opposed to module transport. It was assumed that the cost and effectiveness of both approaches are similar, to the first order; thus the choice of the approach is not a significant impact to the maintenance costs or times.

4.1.2. Module size and port opening

The size of the blanket and divertor modules must be small enough to pass through a port opening. The present ARIES-AT inboard (IB) blanket and first wall is divided into 16 segments, each 4.74 m long, 1.5 m wide, and 0.35 m thick, weighing around 1.4 t when drained of the LiPb coolant. Due to the core geometry, this inboard module should be removed first. The port opening would have to be quite tall (7–8 m) to accommodate the removal and rotation of the first IB blanket module. Removal of other IB blanket modules could pass through this port opening. Weight is probably not a severe constraint as the ARIES-AT SiC/SiC blankets are rather lightweight in the smaller envelope dictated by the port constraints.

The divertor modules are the heaviest components; the divertor replaceable shields contain 75% ferritic steel (FS). The divertor modules are roughly 1.3 m × 1.4 m × 1.9 m and weigh around 8 t. If the horizontal port dimension is determined to be the size of a single sector (22.5°), the divertor modules would easily pass through the opening. This approach allows removal of any inboard blanket or divertor module at random, providing the matching inboard blanket is removed first.

The outboard Blanket I modules are crescent-shaped with vertical upper and lower ends. Each 22.5° sector is comprised of two identical first wall and blanket segments for a total of 32 segments, each covering 11.25°. The segments are around 7.75 m tall, 1.34 m wide, and with a cross-section of 0.3 m, weighing about 1.6 t without coolant. From geometry constraints, it seems the only possible means of removing an integral one-half of sector segment would be to make the port the full height of the blanket (∼8 m) and a full sector width of 22.5°. [An alternative removal approach is to split the blanket segment—see paragraph below for assessment.] Then the two segments immediately in front of the port would be removed. With the full height and width port, the inboard blanket sectors could be removed, followed by the divertor modules. If the top of the upper divertor is slightly taller than the top of the OB Blanket I, then the difference in height creates a clearance space above and below the OB Blanket I when they are moved radially inboard. This clearance space allows the OB Blanket I to be transported toroidally around the torus, in the space vacated by the divertors, to the ports. Without this clearance space, it would seem impossible to toroidally translate the OB Blanket I. This approach also requires that all sectors within a quadrant be removed to replace the most distant module. Note that this full height, full sector, width port has the same port enclosure geometry restrictions on the TF and PF coils as does the full sector maintenance approach. Thus this approach cannot claim a benefit of a smaller reactor with reduced capital cost.

Some space will be required outside the power core to locate and store the in-core maintenance arms or rails, rail vehicles, local storage for spare or used components, and transport equipment to take modules back to the hot cell.

A smaller port size (1.5 m × 2 m) is only possible if the OB Blanket I segments can be disconnected at the midplane. This approach allows a smaller TF and PF coil geometry to be used, but it requires an in situ field splice of the outboard first wall and blanket modules at the midplane of the power core. These modules are intricate cooling structures consisting of many passages containing counter-flowing coolants. It does not seem feasible to postulate achieving a reliable field joint of these modules while inside the power core.

Thus the recommended port size is one that is sufficient to remove a full size outboard blanket module in the upright position. These ports probably would be slightly larger than the current sector removal option. However, only two ports would be required.

4.1.3. Mechanical attachment

A method of mechanically attaching the blanket and divertor segment to the high temperature shield/structure for in situ maintenance is a significant technical challenge. The ITER team evaluated several detailed design approaches to remotely attach the blanket shield modules to their structural backplate. The radial space between the replaceable blankets and the HT shield is nominally 1 cm for ARIES-AT, which is insufficient for mounting unless local clearance pockets are provided. Toroidal and poloidal gaps between blanket modules are deliberately minimized to reduce neutron streaming. The final design will probably have steps between modules to further minimize neutron streaming. Thus access between adjacent modules is improbable. In-place, remote-controlled actuators would be difficult to operate and not reliable in the severe neutron and thermal environment between blankets and high temperature shields. The most plausible approach would be to have multiple holes on the front face or sidewalls of the blanket modules to access attachment devices. These holes could be plugged for operation, with an attendant thermal performance penalty.

The number of modules to be removed from inside the torus for a full replacement is:

Inboard FW/blanket segments	16
Outboard FW/blanket I segments	32
Divertor plate/replaceable HT shield modules	32
Total number of components	80

Assuming there is a minimum of three fasteners for each module/segment, this would suggest that a minimum number of fasteners might be 240.

4.1.4. Mechanical and plumbing considerations

Determining the required plumbing connections for the smaller, replaceable modules/segments inside the torus is very nebulous without a detailed plumbing schematic and a definitive design for this particular maintenance approach. The present ARIES-AT design is based upon a three-circuit/sector design of the divertors and blankets plus two-circuit/sector designs for the high temperature shield to equally balance thermal power and mass flow rate between the five circuits. It is assumed all field connections will be a welded or fused connection, as opposed to a mechanical joint that might be subject to minor leakage. It is also assumed that all joints will be rigorously inspected to assure a highly reliable joint. A set of connections is defined herein for a baseline comparison. Only the three circuits for the first wall and blankets are evaluated, as the shield is a lifetime component and will not be replaced on a regular basis.

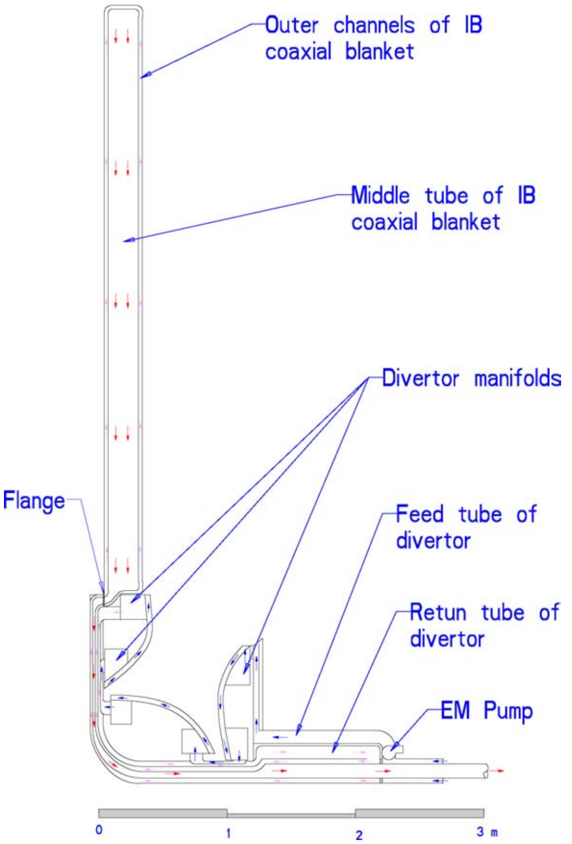

Fig. 3. Circuit 1—lower divertor + IB Blanket.

Circuit 1. In the baseline ARIES-AT configuration for sector removal, the lower divertor and inboard blanket are connected in series as shown in Fig. 3. This assumption would still be valid in this in situ replacement approach. A coaxial connection can be made between these two components because the outlet temperature of the blanket will be above the allowable structural temperature of the outlet pipe, which must be cooled with the incoming coolant. The divertor receives the low-temperature coolant from the main distribution header outside the torus. However, a booster pump and distribution system is located beneath the outboard blanket system. This location traps the divertor plumbing and not allow extraction of the divertor upwards. Therefore, a connection must be made between the divertor and the pump/distribution header. This entails a coaxial connection and two regular connections. The pump/distribution system will now be a part of the outboard blanket assembly. Total: two simple connections and two coaxial connections.

Circuit 2a. This circuit is thermally and mass flow balanced by combining the upper divertor with one of the outboard Blanket I segments as shown in Fig. 4. It is assumed that the entire outboard Blanket I can be removed through the maintenance port in this approach. Two pipes behind the HT shield route the lower temperature coolants between the top and

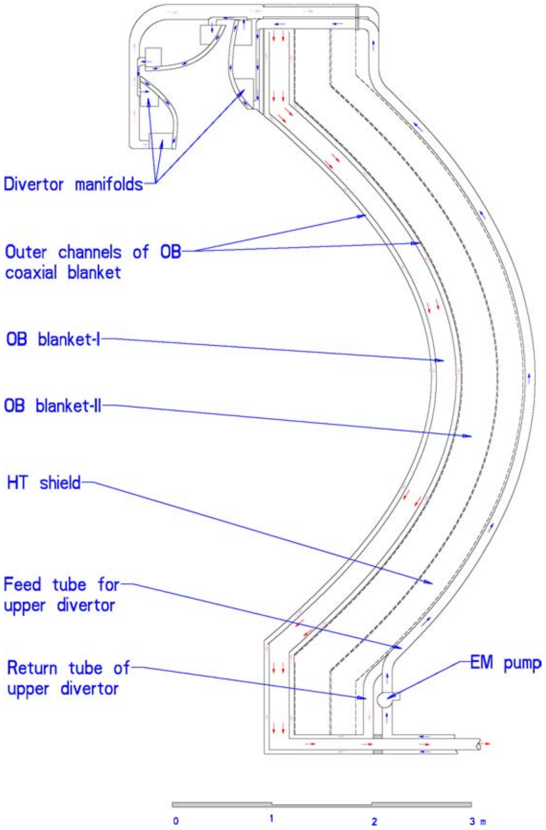

Fig. 4. Circuit 2a—upper divertor + one-half of OB Blanket.

bottom of the segment. Therefore two simple pipe connections will be employed between the divertor and the OB Blanket I. It is presumed there are no coolant connections with the OB Blanket I at the top of the module. There will be one coaxial connection required at the bottom between the OB Blanket I and the piping located within or beneath the OB Blanket II. Total: two simple connections and one coaxial connection.

Circuit 2b. This circuit only consists of half of the outboard Blanket I. Fig. 5 shows this plumbing arrangement. Since no divertor module is associated with this module, only a single coaxial connector will be required. This coaxial connection will be at the bottom of the power core just at the exit from the outboard Blanket I as the coolant pipes go under the Blanket II module. Total: one coaxial connection.

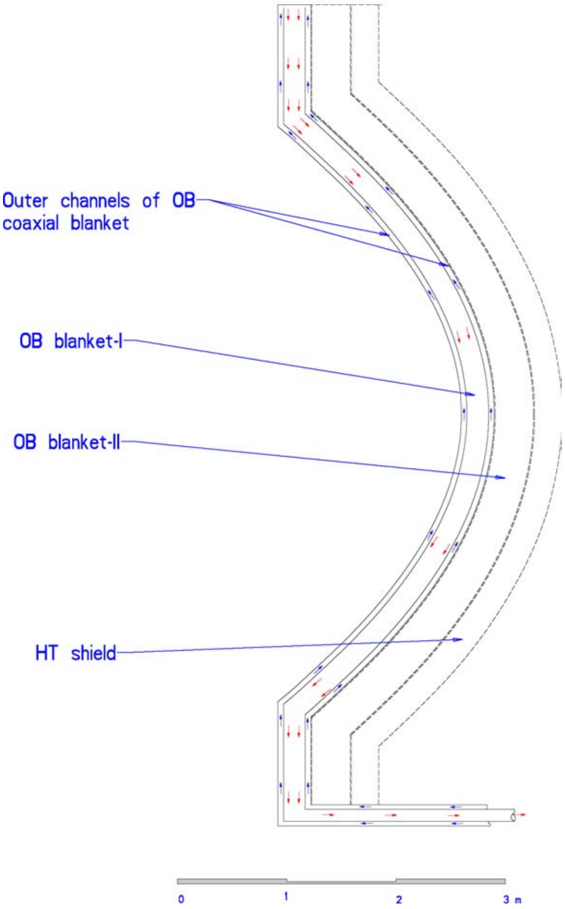

Fig. 5. Circuit 2b—one-half of OB Blanket.

Table 2 summarizes the plumbing connections for the in situ maintenance approach. Although there are only four simple connections and four coaxial connections for each of the 16 sectors, all these connections are located in very inaccessible locations, such as between core components with little or no gaps as required for

Table 2
In situ maintenance plumbing connections

Circuit nomenclature	Simple plumbing connections	Co-axial connections
1. Lower divertor + IB Blanket	2	2
2a. Upper divertor + one-half of OB Blanket	2	1
2b. One-half of OB Blanket	0	1
Total	4	4

minimal neutron streaming. It is doubtful that there would be any access to any of the coolant connections from the interior of the torus. Therefore, the only access will be from the interior of the coolant passages.

Severing the connections from inside the coolant passages is a conceivable, but difficult, process. All cutting debris must be contained and removed. The simple plumbing connection could be disconnected by cutting the single pipe connecting the two plumbing elements. On the coaxial connection, the inner tube would have to be dismantled and removed to gain access to the outer tube. Additional time must be allowed to provide access to the interior of the coolant passageway and ingress of the inspection and cutting tool to the connection location. The real difficulty appears to be the ability to join the new module connections to the existing module within the power core. The examination of the condition of the existing plumbing connection is possible from the interior of the core after the blanket modules are removed. As the new modules are being installed, alignment tools will be necessary from the outside of the module and, perhaps, within the tube being joined. First the exterior pipe (or the single pipe) will be joined and inspected to assure a highly reliable joint free of inclusions and cracks. The surfaces of the joint must also be smooth to provide necessary flow conditions. Then the inner pipe elements must be assembled and welded (fused) to form the interior flow channel. Since multiple elements will be required to construct the inner channel, this will be a very time consuming and difficult process.

4.1.5. Replacement of life-of-plant components

In the event a life-of-plant component fails and cannot be repaired in place, an entire sector of the high temperature blanket and shielding structure must be replaced. Two approaches are possible to accomplish this replacement. This could be accomplished by adopting the sector removal approach. The other approach is to internally remove as much of the first wall and blanket modules necessary to gain access to the high temperature shielding structure. This might be as much as a quadrant of the core. Then the mechanical and plumbing connections of these elements will have to be disassembled sufficiently to allow removal. These elements will have to be designed, to be removed and reassembled in situ. This process is even more difficult as the structural capability of the high temperature sectors will have to be completely reverified.

4.1.6. Summary

The in situ maintenance approach has the inherent advantage of a minimal amount of spare parts being employed, hence a minimal amount of contaminated waste from the high temperature shielding structure is being generated and disposed of. On the other hand, removing and replacing the entire first wall, blanket, and high temperature shield components in a timely and reliably manner every 4 years does not seem likely. At least two maintenance ports will be required. These ports will have to be at least as large as the horizontal sector replacement approach, so the size of the power core cannot be decreased. Installation of a maintenance rail or two long-reach manipulator arms will be required. The number and kind of plumbing connections are reasonable, but access for cutting, joining, and inspection seems to be limited to internal access to the coolant tubes. This would be more than difficult for simple tubes, but rejoining a coaxial connection seems to be beyond postulated technologies. Replacement of individual, random components is possible on the inboard blankets and divertor modules, but sequential removal of other components are required to remove the outboard blanket modules. Therefore a replacement of a single, failed, life-limited module might entail a major teardown of the power core. Premature failure of a life-of-plant high temperature blanket or shield would require removal of some of the replaceable elements and might involve a major teardown of the power core.

4.2. Corridor replacement

The corridor maintenance approach is designed to improve the access to the mechanical and plumbing connections of the replaceable components while minimizing the life-of-plant spares and the volume of waste produced. The sector components would be quickly replaced onto the same high temperature blankets and shielding structure, and immediately placed back into the power core. For this design approach each of the 16 power core sectors is capable of being removed horizontally through 16 large dedicated port doors and enclosures. After removal of the power core sector, it is extracted to the corridor region immediately outside the power core. This approach uses the baseline power core design for ARIES-AT, as well as its predecessor, ARIES-RS. However, the refurbishment of the sector is accomplished in this local corridor region.

4.2.1. Maintenance equipment

A transporter must be able to move the cryostat door, vacuum vessel door, and power core sector. The cryostat door is relatively thin and lightweight. They will be removed and relocated in the maintenance corridor. The vacuum vessel doors weigh 13.2 t when drained of cooling water. The transporter must be able to cut the sealing welds and disconnect the water coolant connections. After removing the doors, they will be relocated in the maintenance corridor. The transporters must be able to disconnect the 121 t power core sector and remove and replace it. Supplemental cooling for the power core sector must be supplied during the removal, refurbishment, and replacement process. At the corridor maintenance location, portable maintenance and inspection tools will effect removal, inspection, and replacement of all worn-out or failed first wall and blanket components, as well as disconnecting and reconnecting all plumbing and structural connections.

4.2.2. Port opening and maintenance location size

The size requirement for the power core, including the coil systems, is similar to that required for the sector removal approach. Individual vacuum vessel doors and enclosures are required at each sector. Also, there has to be storage space for the new and used power core components as well as access space for maintenance equipment. The required space on either side of the extracted sector might not allow simultaneous maintenance operations on adjacent sectors.

4.2.3. Mechanical and plumbing connections

The method of disconnecting and reconnecting the mechanical and plumbing connections is very similar to that of the in situ approach. Mechanical supports may be accessible from the sides or the back of the module, which would be easier. Plumbing connections will probably still be accomplished internally. This approach has five additional coaxial plumbing connections because the sector also must be disconnected from the main coolant headers at a location just inside the vacuum chamber door. Table 3 shows the coolant connections to be disconnected and reconnected in this replacement approach.

Table 3
Summary of corridor maintenance plumbing connections

Connections	Simple connections	Co-axial connections
Blanket to shield (from Table 1)	4	4
Sector to header	–	5
Total	4	9

4.2.4. Replacement of life-of-plant components

In the event a life-of-plant component prematurely fails and cannot be repaired in place, an individual sector can be withdrawn. This is probably easier and less time consuming than in situ replacement.

4.2.5. Summary

The corridor maintenance approach also has the inherent advantage of a minimal amount of spare parts being employed, hence a minimal amount of contaminated waste is being generated and disposed of. On the other hand, removing and replacing the first wall, blanket, and high temperature shield components is extremely difficult because of the lack of access space between modules and the high temperature shielding structure. All sectors require a vacuum port and a port enclosure. A detailed layout is required to determine the corridor space to effect the removal and reinstallation of the first wall and blanket components. Access to mechanical attachments may be somewhat better. The access to the plumbing connections remains equally difficult to that of the in situ maintenance approach. This limited access may be the dominant factor in determining the maintenance times for this approach. This corridor replacement approach has the highest number of plumbing connections to be accommodated real-time. However, this approach has the advantage that a random failure only requires removal of a single sector. This approach does present significant difficulty in controlling the contamination and debris arising from removal and replacement of components outside the power core in the large corridor space. It is likely this space will be subdivided; but all the spaces will likely be contaminated.

4.3. Hot cell replacement

The hot cell maintenance approach utilizes the basic sector removal core design approach. The sectors are transferred from the power core to the hot cell for refurbishment. A previously refurbished sector is immediately reinstalled back into 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 hot cell can refurbish the removed segments 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 variation to this approach involves taking the sectors back to the hot cell, but the sectors are refurbished real time while the reactor core is being dismantled and rebuilt. The viability of this approach depends upon the speed and efficiency of the hot cell maintenance to meet the maintainability goals.

4.3.1. Maintenance equipment

Transporters will also be used in this approach exactly as in the previous approach, to disconnect/connect and remove/install cryostat door, vacuum vessel doors, and power core sectors. The added requirement is to transport the sectors back to the hot cell and return them to the power core. Options would involve transporting a bare sector that has a high potential for contamination and spreading of debris, a wrapped sector that lessens the degree of contamination, and an enclosed transporter cask that would minimize the contamination hazard in the corridor and pathways to the hot cell.

The same functions must be accomplished in the hot cell as in situ or in the corridor, but with stationary equipment rather than mobile equipment. This is true of inspection, viewing, and testing equipment. Depending on the available time and the maintenance times, the number of sets of equipment and operators/supervisors might be reduced.

4.3.2. Port opening and maintenance location size

The port opening is exactly the same as the corridor approach. The maintenance location is in the hot cell and the maintenance location size might be smaller if more work can be accomplished in series during plant operation while in the hot cell.

4.3.3. Mechanical and plumbing connections

The total number of mechanical and plumbing connections are identical to the corridor approach. However, the number that must be accomplished real-time and accounted for in the operational timeline will be reduced only to the five coaxial connections to the main coolant header, as shown in Table 4. These connections have a greater amount of access due to their location in the main port enclosure.

Table 4
Summary of hot cell maintenance plumbing connections

Connections	Simple connections	Co-axial connections
Blanket to shield	Four in hot cell	Four in hot cell
Sector to header	–	5
Total		5

4.3.4. Replacement of life-of-plant components

This approach is identical to the corridor replacement approach since any sector can be removed in a random sequence. This approach requires extra spare blanket and high temperature shield components as ready replacements for the failed component (not required for the other two approaches).

4.3.5. Summary

For both scheduled and unscheduled major maintenance actions, removing sector enclosure and vacuum door accesses an individual power core sector. Plumbing and structural connections are removed. The sector is removed from the power core and transported to a hot cell to be refurbished and verified ready for replacement. The refurbishment is conducted off line to reduce the power core down time and enhance the reliability of the refurbished power core segment. Multiple refurbishment lines in the hot cell could be employed, depending on the capital investment and the time required for refurbishment.

5. Comparison of power core maintenance approaches

The previous section described the three identified power core maintenance approaches being considered. To compare these three options, eight criteria are identified that characterize the attractiveness of the approaches. Table 5 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 waste volume is important since the volume of waste must be disposed of. Contamination is important as it is a safety concern and the amount

Table 5
Qualitative comparison of maintenance approaches

Criteria (importance)	Maintenance approach		
	In situ maintenance (score)	Corridor maintenance (score)	Hot cell maintenance (score)
Maintenance time (4)	Slowest time as all operations have limited access. Arm or rail operations will be relatively slow and number of parallel operations will be limited (1)	Moderately slow time, not only must the sector be removed, but also access to remove/replace blanket modules is limited. Has the highest number of connections to be accomplished (2)	Fastest maintenance as number of on-line mechanical and coolant connections will be minimal and accessible. All refurbishment will be accomplished off-line (4)
Replacement sector reliability (4)	Lowest reliability as all refurbishment and inspection must be in situ with limited access. Limited time to complete. But it has lowest number of connections (1)	Moderately low reliability, as access is limited. High number of connections. Limited time to complete (2)	Highest reliability because of long time to complete and inspect refurbishment. High number of connections (same as corridor maintenance) (4)
Building cost (2)	Probably the smallest building size, even considering the volume for arm and rails (4)	Might be the largest building size to provide space for refurbishment equipment in corridor (2)	Slightly less building size than corridor maintenance to just accommodate removal and transport sectors (3)
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 transporters are needed (4)	Higher cost than hot cell approach as several portable refurbishment carts are needed to speed on-line maintenance. Also requires several transporters (2)	Moderate cost for four to eight transporters, but transporters are moderate cost compared to mobile refurbishment carts (3)
Spare equipment cost (1)	Lowest spare equipment cost as all high temperature shielding structure modules are used to the fullest (4)	Lowest spare equipment cost as all high temperature shielding structure modules are used to the fullest (4)	Highest spare equipment as high temperature shielding structure modules are extracted for refurbishment. Effect can be mitigated with fractional replacement (2)
Waste volume (3)	Lowest waste volume as all high temperature shielding structures are used to the fullest (4)	Lowest waste volume as all high temperature shielding structures are used to the fullest (4)	Highest waste volume as high temperature shielding structures are extracted for refurbishment. Effect can be mitigated with fractional replacement (2)
Contamination control (2)	Little contamination control as all cutting, disassembly, reconnecting, and reassembly is done within the torus (0)	Better because all cutting, disassembly, reconnecting, and reassembly are done outside the torus. However the corridor can be contaminated during disassembly and reassembly (1)	Minimal cutting and reassembly in torus or corridor. Contamination from segment probably controlled (4)
Applicability to scheduled and unscheduled maintenance (3)	Lots of disassembly to reach most distant modules (1)	Same approach on both. Some disassembly required to reach most distant modules (2)	Same approach on both. Random access to all modules (4)
Total (max. score) (80)	39	46	69

Scoring—0: lowest, 4: highest.

determines how it can clean up. Any approach must be largely applicable to both scheduled and unscheduled maintenance.

Table 5 discusses how each of the three maintenance approaches addresses each of the criteria and assigns a numerical score 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. It 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 corridor approach is moderate in the maintenance times and reliability, but these are important criteria. It scored well in the spare equipment cost and waste volume, but these have low importance ratings.

The hot cell approach scored well because it is perceived to have high availability and reliability. Also, contamination control is good, as well as being applicable to both scheduled and unscheduled maintenance. As a result of these scores, the hot cell maintenance approach is the recommended maintenance scheme.

6. Evaluation of sector transport to hot cell

In the selected hot cell maintenance approach, there are three options of how to transport the removed sector back to the hot cell. They are:

- bare sector,
- shrink-wrapped sector,
- mobile cask enclosure.

The bare sector approach is the cheapest and fastest, with the minimum-maneuvering envelope in the corridor (thus the smallest building). But it would present the greatest threat in dispersing the largest amount of debris and gamma rays throughout all of the power core and the core corridor area (safety hazard). Once the sector is removed, the remainder of the core and corridor is exposed. A door could be added to the end of the port enclosure to limit the exposure to short periods.

A shrink-wrapped sector could limit the spread of debris while being transported to the hot cell. If a gamma-absorbing film were available, that would help reduce the gamma exposure. The shrink-wrap could be adapted to keep the port opening semi-protected at all times. A concern would be finding a material that would tolerate the high exposure to radioactive particles and gammas. The film must be highly flexible to wrap around the sector. This would be a difficult material and packaging system to design and develop. It would be an inexpensive solution if proven feasible.

The transporter cask system is recommended for use in ITER EDA Phase [3] for both the divertor modules and the test blankets. It offers more protection than the shrink-wrap approach. Solid cask walls offer more shielding and debris containment. Double doors will be used to completely isolate the interior volumes of the power core and the cask. However, it requires more room to maneuver, is more costly, and will be somewhat slower to accomplish core replacement. Since the large, curved vacuum vessel door cannot be placed inside the cask and still have room for the transporter to access and remove the power core sector, two separate operations must be conducted to remove the vacuum vessel door and then the core sector. Thus the transit time would be roughly twice that of the bare sector.

To assess the relative merits of these three approaches, a trade study is conducted with the same set of criteria mentioned in the previous trade study. The sector reliability is not applicable to this trade study. Applicability of maintenance equipment to both scheduled and unscheduled maintenance actions seems to be similar, so it is not included. The importance of the waste criterion is downgraded, as the generated waste would not be of the magnitude of the power core. The importance of the contamination control is upgraded, as this maintenance step is likely to be a major source of contamination.

Table 6 shows the rationale for each transport approach as it pertains to each criterion.

The time to remove the port enclosure door, the vacuum vessel door, and the power core sector is very important. The bare sector approach would accomplish these operations very quickly, but all the operations to handle three components (cryostat door, vacuum door, and core sector) are serial. The first three components are removed and repositioned within the maintenance corridor, but the core sector will be moved to the hot cell. Multiple transporters and casks could be simultaneously used on multiple ports to reduce the overall time, but this is true of all transport approaches and is not a discriminator. The shrink-wrapped

Table 6
Qualitative comparison of sector transport approaches

Criteria (importance)	Sector transport approach		
	Bare sector (score)	Shrink-wrapped sector (score)	Cask enclosed sector (score)
Time to remove cryoshield door, enclosure port door, and vacuum vessel door plus transit to hot cell (4)	Transporter removes cryoshield door, enclosure port door, and vacuum vessel door. Bare sector is a fast transit with transporter. All serial operations (4)	Removal of components and transit time should be as fast as bare sector. However time to accomplish shrink-wrap will increase the overall time. All serial operations (3)	Cask must make a trip for vacuum door and also sector. Transit time should be twice the time as bare sector (2)
Building cost (2)	Probably the smallest building size, with just enough corridor width to rotate transporter and sector (4)	Same as bare sector (4)	Slightly larger corridor width to accommodate cask length and width (3)
Maintenance equipment cost (1)	Transporter multi-purpose—removal of cryostat and vacuum vessel doors plus removal and transport of core sectors (4)	Same transporter as bare approach. Requires shrink-wrap equipment to seal opening and cover sector, which is an added cost (3)	Requires transporter to remove sector. Requires mobile cask to contain sector and transporter (2)
Spare equipment cost (1)	Lowest spare equipment cost as only one type of maintenance equipment is required (4)	Transporter spares plus the shrink-wrap equipment spares (3)	Transporter spares + cask spares (2)
Waste volume (lowered impact as the volume is minor compared to core volume) (1)	Lowest waste volume, as only one type of maintenance equipment is required (4)	Slightly higher waste than bare approach (3.5)	Waste would include the transporter plus the cask (2)
Contamination control (importance increased) (4)	Little to no contamination control as there is no containment barrier after the sector is removed. Likely debris contamination and gamma irradiation during transit (0)	Some control as there is a possible containment barrier after the sector is removed. Debris contamination should be controlled and gamma irradiation reduced during transit (1)	Best containment barrier to core. Best debris and gamma irradiation protection (4)
Totals (max. score) (52)	36	33.5	36

Scoring—0: lowest, 4: highest.

sector approach would have the same transport time, but additional time is required to accomplish the wrapping and opening isolation process. Some additional time is assumed for the cask docking process. The cryostat doors in this approach are automated and would not require special handling or significant time to open or close. The mobile cask containing the transporter must go from the air lock to the power core port and back to the airlock twice (once for the vacuum vessel door and once for the power core sector). It is assumed the cask transport requires more time for the overall sector removal than the bare or wrapped sector approaches.

Building and maintenance/spare equipment costs are not high importance items and are not large discriminators. Neither is the generated waste volume associated with the transport system.

The contamination control is thought to be an important criterion. There are significant differences in the three approaches. The bare approach offers little or no contamination control. The shrink-wrap approach is an attempt to mitigate the deficiencies of the bare approach, perhaps with limited success. The mobile cask approach to enclose the transporter and sector for transit is the most effective (and costly) contamination control approach.

The results of the weighted matrix shown in Table 6 indicate that there is a minimal difference between the three approaches. The current definition of the hardware or operation of the hardware is limited and a more detailed definition could significantly alter the outcome. Likewise, a modification in the weighting of the criteria or introduction of different criteria could result in a new preferred approach. The recommendation is that all approaches should be retained as possible transport systems. It really comes down to a "quick and dirty" approach as compared to a more expensive, slower, contained approach. The wrapped approach might be better if it is proven feasible and is cheaper and/or quicker. In further analysis of this maintenance system, the cask approach will be adopted as the baseline approach since it has the best defined contamination barrier and, therefore, is judged to be the safest approach.

7. Definition of power core change out actions and duration

As shown earlier in Table 5, the favored maintenance option is to remove a power core sector (1/16 of the power core) and replace it with a refurbished module from the hot cell. This allows the power core and power plant to return to service in the fastest possible time for the highest availability. This section defines the actions required for this planned maintenance change out and estimate the time for this action.

It is also recommended that one half of the power core sectors be replaced every 2 years, see Table 1. This replacement approach offers the better match to the planned maintenance of the other plant systems with a reasonable compromise of low spares cost, low waste generation, and a good mix of fixed and repetitive maintenance times.

The comparison of possible transporter options is not conclusive. The transport of the power core sector within a mobile cask is selected since it is perceived as having safety and contamination advantages, although it is the more expensive and slower option.

The change out maintenance action is defined from the time the plasma in the power core is extinguished until the plasma is back to full power condition; see Fig. 6 for a schematic representation. Detailed timelines are developed for the shutdown and startup timelines plus the removal and replacement timelines for a single sector that can be repeated for multiple sectors.

At the beginning of the maintenance action, there are shutdown procedures and preparations for maintenance actions that will be required before the actual disassembly of the core commences. After the core reassembly is complete, there are other actions to be completed prior to bringing the plasma back to full power conditions. These fixed actions will be defined and added to the repetitive removal and replacement times to complete the trade study of the number of sectors to be replaced per maintenance period and the number of transporter casks to be used. After the cool down and maintenance preparations are completed, the disassembly and reassembly of the power core can start. For this analysis, the disassembly and reassembly times are defined for the removal and replacement of a single sector. The trade study then evaluates the total maintenance action duration for various replacement options with varying numbers of transporters and casks.

The definitions of maintenance actions contained herein are only rough approximations of the actual maintenance actions and the time to accomplish these actions. Moreover, it cannot be predicted how these actions will be accomplished and the stage of maturity of the remote, autonomous, computer-controlled maintenance equipment in the time period when this technology would be employed. It is assumed these maintenance actions apply to the tenth-of-a-kind power plant and all development problems are solved and learning effects are matured. But identifying each action to be accomplished and estimating its duration will help understand and scope the maintenance action and the importance of design and operational choices. For the maintenance actions, serial operations are the most important. Some, but not all, parallel actions are identified, with the longest or longest set being the defining action for the serial operations.

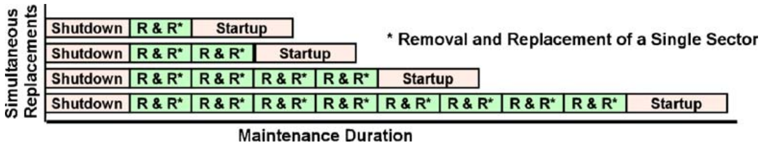

Fig. 6. Total removal and replacement timelines for a range of sectors.

Table 7
Shutdown timeline

Maintenance action	Duration of serial operations (h)	Duration of parallel operations (h)
Shutdown and preparation for maintenance		
Cool down of systems, afterheat decay	24	
De-energize coils, keep cryogenic		2.0
Pressurize power core with inert gas		2.0
Drain coolants, fill with inert gas	6	
Subtotal for shutdown and preparation	30	

Table 7 identifies the actions to be accomplished and the related duration of the action to shutdown the plasma and power core along with preparations for the maintenance action. The action could be related to either a scheduled or unscheduled outage. After the ramp down of the plasma, a period of 24 h is provided to allow for the cool down of the systems and a significant reduction in the radioactivity level inside the power core. Since the maintenance action is planned to be for an extended time, in parallel to the cool down the TF and PF coils can be de-energized, but are kept in a cryogenic state to avoid thermal cycling effects. The power core will be filled with an inert gas to ambient pressure. After the 24 h cool down period, the high-temperature portion of the power core will be drained of the lithium lead coolant and replaced with an inert gas, probably helium. The inert gas will continue to be circulated until the sector is to be replaced. Later, when the sector is to be removed, the sector coolant connections to the primary header are disconnected and reconnected to the onboard cooling system of the transporter.

The time required for startup is also a fixed time, not related to the repetitive actions to remove and replace a portion of the power core. Table 8 shows the necessary startup tasks. Any transporters and casks would be returned to the hot cell. The power core chamber would be evacuated to initial conditions. The trace heaters and/or helium would be used to heat the primary coolant piping and core elements. After reaching temperatures above the melting point of lithium lead, this coolant can be added to the primary coolant loop and fill the power core. After the coolant fills the primary loop, the temperature of the loop can be raised to accomplish the core bake out (12 h). The final step is to check and power up the systems, which can be done in some degree with prior operations.

After the shutdown actions are accomplished, the actual removal of the power core can commence. The transporter casks are loaded with transporters and are poised at the airlock to gain entry to the maintenance corridor.

Table 9 lists the repetitive tasks to be accomplished and an estimate of the duration of the maintenance actions. The table includes the serial operations to be accomplished along with some tasks that may be accomplished in parallel.

The determination of the fixed maintenance times and the repetitive times provides data to estimate the duration of the power core scheduled maintenance outages for different fractions of the power core being

Table 8
Startup timeline

Maintenance action	Duration of serial operations (h)	Duration of parallel operations (h)
Startup tasks		
Move transporters and casks to hot cell		0.8
Evacuate core interior	10.0	
Initiate trace or helium heating		10.0
Fill power core coolants	8.0	
Bake out (clean) power core chamber	12.0	
Checkout and power up systems	4.0	12.0
Subtotal for startup	34.0	

Table 9
Removal and replacement task timeline, common for each transporter and cask

Maintenance Action	Duration of serial operations (h)	Duration of parallel operations (h)
Removal and replacement maintenance tasks		
Move cask to port and dock to port	1.0	
Open cask door and raise port isolation door	0.2	
Disengage vacuum vessel door	3.6	
Move transporter forward to engage vacuum door		0.2
Remove weld around vacuum door		2.0
Disconnect VS coil electrical and I&C connections		0.2
Disconnect vacuum door water coolant connections		1.0
Disengage door to prepare for removal		0.2
Remove vacuum vessel door into cask	1.0	
Lower isolation and transporter doors and undock cask	0.2	
Move to hot cell, unload vacuum door, return, and dock	2.5	
Open cask door and raise port isolation door	0.2	
Disengage power core sector	3.2	
Move transporter forward to engage power core sector		0.2
Disconnect I&C connections		0.2
Disconnect five coax LiPb coolant connections		2.0
Disengage mechanical supports		0.6
Disengage sector to prepare for removal		0.2
Remove power core sector into cask	1.0	
Lower isolation and transporter doors and undock cask	0.2	
Move to hot cell, unload sector, load new sector, return, and dock	3.0	
Open cask door and raise port isolation door	0.2	
Move power core sector from cask into near-final core position	1.0	
Install power core sector	7.7	
Align sector and finalize position		1.0
Engage mechanical supports		1.0
Connect five coax LiPb coolant connections		5.0
Connect I&C connections		0.5
Disengage transporter and move back inside cask		0.2
Lower isolation and transporter doors and undock cask	0.2	
Move to hot cell, load vacuum door, return, and dock	2.5	
Open cask door and raise port isolation door	0.2	
Move vacuum door from cask into near-final position	1.0	
Install vacuum door	5.7	
Align vacuum door and finalize position		1.0
Prep, weld, and inspect door perimeter		3.0
Connect door water coolant connections		1.0
Connect VS coil and I&C connections		0.5
Disengage transporter and move back inside cask		0.2
Lower isolation and transporter doors and undock cask	0.2	
Subtotal for repetitive tasks	34.8	

replaced. Table 1 previously compared the merits of replacing different core fractions (1/4, 1/3, 1/2, and 1/1) at different scheduled maintenance period frequencies. A trade study is conducted for this range of core fraction replacement scenarios with the results shown in Table 10. Note that replacing one-third of the power core requires two replacements of five sectors and one replacement of six sectors.

The inherent availability of the scheduled replacement scenarios shown in Table 10 are slightly different, amounting to a difference of two equivalent days per year (8.47–6.47 days per year) for the two extreme

Table 10
Comparison of several scheduled maintenance scenarios (one cask and one transporter)

Fraction of core replaced	Number of sectors replaced	Shutdown and startup time (h)	Time to replace sectors (h) (No. × 34.8 h)	Maintenance action duration (h)	Maintenance actions over four FPYs (h)	Availability for scheduled core outages	Equivalent days per year
1/4	4	64	139.2	203.2	812.8	0.977	8.47
1/3	5	64	174	238	748.8	0.979	7.80
	6	64	208.8	272.8			
1/2	8	64	278.4	342.4	684.8	0.981	7.13
1	16	64	556.8	620.8	620.8	0.983	6.47

cases (one-fourth and the entire power core). This availability difference equates to a loss of revenue of US$ 2.4 million each year for a 1000 MWe power plant with a COE of US$ 0.05 kWh^{-1}. The recommended maintenance approach of eight sectors replaced at a time (from Table 1) is shown in the shaded row. This results in a planned maintenance time of 7.13 days per year and the availability of 0.981 for the scheduled maintenance actions (not the total plant availability). Replacing the entire power core at one time has a slightly higher availability, but as stated in Table 1, that approach might not match well with the BOP and RPE and it has double the number of spare hot structures with more radioactive waste. Thus, it is deemed prudent to retain the option to replace one-half of the sectors at a time as the recommended approach.

Even shorter maintenance times can be accomplished by using multiple sets of transporters and casks. Table 11 presents the equivalent scheduled maintenance days per year with multiple sets of transporters and casks. For the likely power core removal scenario, based on eight sectors replaced ever 2 years, the equivalent annual scheduled maintenance time drops from 7.13 to 4.23 days per year for two sets and on up to 1.70 days per year for 16 sets. The use of two sets would represent a conservative approach, perhaps with an additional set designated as a spare. In the event that the estimated times prove not to be accurate, improvement factors of 3.5–4 can be obtained with multiple sets of scheduled maintenance equipment. For the availability assessment in the following section, the equivalent annual scheduled maintenance allotment of 4.23 days per year is adopted.

8. Derivation of plant availability

The fusion community has not developed a detailed and substantiated availability value for a commercial fusion power plant to date. Such availability data cannot be determined because the underlying detailed database has not been developed. All the fusion hardware remains experimental or yet to be developed, thus no credible reliability database has been developed. The basic power core and maintenance hardware has not been tested to determine life expectancies based upon operational experience. Even the maintenance approaches and maintenance procedures have not been developed. However, this study is attempting to postulate what might be a reasonable projection for refurbishment downtimes for the plant systems, culminating in an anticipated plant availability.

Table 11
Equivalent days per year scheduled maintenance using multiple maintenance sets

Fraction of core replaced	Number of maintenance casks and transporters					
	No. of sectors replaced	1	2	4	8	16
1/4	4	8.47	5.57	4.12	3.39	3.03
1/3	5 and 6	7.80	4.90	3.45	2.73	2.36
1/2	8	7.13	4.23[a]	2.78	2.06	1.70
1	16	6.47	3.57	2.12	1.39	1.03

[a] Selected as baseline for further analysis.

Starfire [8] discusses the anticipated maintenance approach, but finally adopted a nominal 75% plant availability as a reasonable goal. In the previous ARIES series [9,10] of reactors, a nominal value of 76% is adopted with no detailed analysis. ARIES-RS [11] is designed to be a quick refurbished fusion power plant. Detailed procedures and maintenance approaches [12] for ARIES-RS are developed, which predict higher values of availability than previous studies. However, the baseline availability for ARIES-RS remains at 76% as a conservative goal.

There is strong economic incentive to improve the performance systems. A fusion plant with an investment of US$ 3 billion in direct capital costs can afford an additional US$ 550 million of direct capital cost to improve the plant availability from 76% to 90%. Research and development money should be used to develop improved maintenance systems, equipment, procedures, and knowledge databases. With the tenth-of-a-kind plant, this level of availability should be commonplace and necessary for a capital-intensive power plant to be competitive. So with that assumption, the ARIES-AT power plant will be examined to determine the feasibility of attaining availability goal of 90%.

The requisite availabilities for the major power plant systems are examined. To simplify the analysis, only three elements are considered: the balance of plant (BOP), other reactor plant equipment (RPE) (cryogenic plant, fuel processing plant, main heat transfer and transport, and others), and the fusion power core. The availability of the BOP for large power plants has steadily been improving and will likely be in the range of 97.5%. The availability of the RPE does not have a substantial database upon which to draw. But these systems are remote from the core and can have redundant subsystems and components to bring the availability as high as necessary. It is judged that the RPE would also need to have a combined availability of 97.5%. This requires the power core to achieve around 95% availability to meet the 90% overall goal ($0.975 \times 0.975 \times 0.947 = 0.90$). For the power core, an availability of 0.947 equates to 20.56 days of maintenance per full power year.

The overall 95% availability goal for the power core contains all the maintenance actions for the power core. These actions are both scheduled, as discussed in the previous paragraphs, and unscheduled (unplanned outages to repair or replace failed or non-operating critical components). The unplanned outages are dependent upon the reliability of the components and systems, which may or may not have redundant capabilities. On the other hand, the planned outages are dependent upon the wear out and damage characteristics of the components. The historical trend is that both the life and the reliability of the components continue to improve in similar amounts and that both contribute equally to the overall unavailability of the power plants. It is thought that this trend and the relative balance will continue. This would suggest that equal times of approximately 10 days per year should be allotted to these two maintenance time elements. The prior analysis develops a rationale for the scheduled maintenance. However, the unscheduled power core maintenance cannot be estimated at this point in time. In the interest of developing a conservative estimate, it is recommended that the nominal 10 days per year for unscheduled maintenance be increased to 20 days per year. This increase in allowable unscheduled maintenance will reduce the plant availability below the desired availability goal of 90%.

As shown in Table 1, the optimal regular power core maintenance period is to remove and replace one-half the power core every 2 FPY. As shown in Table 10, the replacement of eight sectors every 2 years takes 342.4 h or 7.13 days per year using one cask and one transporter. This time can be reduced to 4.23 days per year by using two sets of casks and transporters as shown in Table 11. Further availability gains can be obtained with the use of more casks and transporters, but the benefit/cost ratio declines rapidly. For further availability analysis, the annual equivalent time to replace the power core is assumed to be 4.23 days per year as compared to the prior estimate of 10 days per year.

Thus the simplified bottoms-up estimate only accounts for about 40% of the time allocated to a nominal 95% availability (scheduled) for the power core, 4.23 days out of the 10.28 days of annual scheduled maintenance. Table 12 shows the breakdown of the annual maintenance days to achieve the overall plant availability. Since the allotted time is not completely assigned, the remaining unused time of 6.05 days is allocated to the scheduled maintenance of the *minor* power core equipment. As mentioned above, the allotted time for annual unscheduled maintenance is chosen to be double the scheduled maintenance for a total of 20.56 days per year. If the RPE and the BOP can achieve both their scheduled and unscheduled maintenance for

Table 12
Annual maintenance times allocated by systems group

System group maintenance	Maintenance (days/FPY)	System availability
Power core, major, scheduled	4.23	0.989
Power core, minor, scheduled	6.05	0.984
Power core, unscheduled	20.56	0.947
RPE, scheduled and unscheduled	9.37	0.975
BOP, scheduled and unscheduled	9.37	0.975
Total		0.876

9.37 days/FPY, an overall plant goal of an availability of 87.6% could be attained.

9. Summary

The scheduled frequency of power core maintenance is analyzed and a replacement frequency of changing one-half of the ARIES power core every 24 months is found to be optimal. The maintenance options of refurbishing the core elements in situ, in the maintenance corridor, and in a remote hot cell are assessed and the hot cell option is adopted. An evaluation of the method to transport the sectors and minimize contamination is conducted. The three options of a bare sector, shrink-wrapped sector, and a sector contained in a mobile cask are all equally attractive. The rationale is to adopt the more conventional and conservative approach of the mobile cask approach, although it is the most expensive approach.

To obtain an estimate of the expected ARIES fusion power plant availability, an assessment of the power core maintenance shutdown times, startup times, and the repetitive times are conducted. These data are integrated with a range of sectors being replaced for both a single cask and transporter and multiple casks and transporters. The result is 4.23 days per year (equivalent) to replace eight sectors every 24 months. This time represents scheduled power core maintenance. In addition, time is provided for other scheduled maintenance for minor equipment, power unscheduled maintenance, and maintenance times for the reactor plant equipment and balance of plant equipment. This results in an overall plant availability of 87.6% for the tenth-of-a-kind fusion power plant. This result is a reasonable comparison with the trend in other large-scale electric power plants.

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