Abstract — The configuration and maintenance procedures for a power plant based on a low-aspect ratio (LAR) tokamak are likely to be very different than a "standard tokamak". Power plants with aspect ratios in the range of 1.4–1.6 and plasma elongation of ~3 have been examined to better understand the unique advantages and disadvantages of this concept, and to determine whether they are capable of meeting the top-level goals for availability and maintainability which are so important for the overall attractiveness of a fusion power plant.

I. INTRODUCTION

The availability of the power core has a large impact on the cost of electricity and, thus, on the attractiveness of the entire plant, since utilities can not accept frequent shutdowns or extended replacement periods due to the high cost of replacement power. The availability is set by the reliability of the components (mean time to failure, which sets the frequency of unscheduled maintenance), their lifetime (which sets the frequency of scheduled maintenance), and the time required for replacement. In the ARIES-RS tokamak design, horizontal maintenance through large ports in the vacuum vessel was adopted to help meet availability goals by enabling rapid sector replacement [1,2]. However, the configuration and maintenance procedures for a power plant based on a low aspect ratio (LAR) tokamak are likely to be very different than a “standard tokamak”.

Power plants with aspect ratios in the range of 1.4 to 1.6 and high plasma elongation (up to 3 or more) may have in-vessel components which are very tall and skinny. The geometry inboard is substantially different than outboard, and the inboard TF coil system will most likely have to be replaced frequently. Probably the most important difference is that the possibility for de-mountable copper coils, which are likely to be used with a LAR tokamak, opens up several new possibilities for maintenance.

Three major classes of maintenance have been explored:

1. **Vertical maintenance from the top.** All replaceable items are lifted out of the top of the machine. The lifting and positioning capability of the overhead crane and the supporting structure are major concerns. This concept requires a strong, tall building.

2. **Vertical maintenance from the bottom.** All replaceable items are lowered out the bottom of the machine with hydraulic jacks. The building size could be reduced, but a pit is needed for the hydraulic equipment. The jacking system can provide a better capability to handle loads and position components.

3. **Horizontal maintenance.** One or more (up to half) of the outer parts of the TF coils are removed to gain access to the power core. This requires a large volume surrounding the machine for the upward and downward movement of the superconducting PF coils and horizontal removal of the power core components.

II. MAINTENANCE PHILOSOPHY

Previous ARIES designs [1–4] have shown that power plant availability is maximized by utilizing single-piece maintenance of sectors. Components that are known to require frequent scheduled maintenance, e.g., the first wall, divertor plates, and blanket, are integrated as a single replacement unit. This approach is dramatically different from that of an experimental device such as ITER, due to several factors:

1. Experiments have very low neutron fluence, such that frequent power core replacement is not anticipated,

2. Availability is not a driving motivation behind the design of experiments. Low availability is expected and tolerated.

3. Mature power plants are assumed to achieve relatively high reliability, or the technology will never be adopted. Availability in that case will be dominated by scheduled, as opposed to unscheduled outages.

Some of the components in the fusion power core are not exposed to the intense irradiation environment, and can survive for the entire lifetime of the plant. These may be permanent or moveable, depending on their relationship to the limited lifetime components. For example, movement of some parts of the radiation shield and some of the PF coils may be required in order to remove the power core. Every component must be designed to be maintainable in case of failure.

The most important considerations in defining and choosing a maintenance scheme include:

1. Location of copper coil joints;
2. Vacuum vessel location and vacuum sealing concept;
3. Type of segmentation of fusion power components;
4. Sector and centerpost removal paths;
5. Attachment and support of in-vessel components;
6. Coolant piping and disconnects;
7. Containment of radioactivity during maintenance.

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III. VERTICAL MAINTENANCE FROM ABOVE

Figure 1 shows a side view of a power core adopting vertical maintenance from the top. Sliding joints are possible near the centerline because the constant tension loads on the outboard TF coil legs can be resolved with a reacting ring structure. Therefore, the centerpost (CP) stresses are dramatically reduced and the coil can be removed independently. The vacuum vessel could be located either inside or outside the TF coils. In this case, an inner vessel is chosen to avoid a massive vacuum port above the machine, needed to provide containment during maintenance operations.

The inboard first wall (FW) structure serves as the vacuum boundary. If the centerpost resistive losses could be reduced sufficiently to allow a cylindrical cross section, then the CP could be removed without breaking vacuum. If shaping is needed, then the breaks in the vessel can be located behind the upper and lower shielding to allow vessel rewelding. The lifetime of the CP is expected to be roughly the same as the inboard FW, such that independent replacement is not a high priority.

The weight of the 31.5 m long center-post is estimated to be 600 tones. To replace the center-post vertically from the top, an overhead bridge crane, which has a lift capacity of 600 tones will be employed. The major step for the removal of centerpost requests to decouple the outer TF legs, therefore, the electrical sliding connectors at the top and bottom need to be removed first.

The 22.5° of removable sector unit weights 120 tones. The largest-scale module maintenance scheme will be helpful for saving the maintenance time and reducing the cost. The size of components to be removed as a sector unit is limited by crane capability. The procedures of replacing the sector unit are: (1) the upper PF coils are raised; (2) the electrical sliding connector is decoupled and the TF outer legs are disconnected; (3) the TF upper lid is lifted and removed; (4) the replaceable unit is lifted and transferred to a shielded cask in order to control radioactive contaminants.

Vertical maintenance of the power core raises the same configurational dilemma as with the CP: if the outboard FW/blanket is curved to follow the plasma shape, then the surrounding shield would obstruct movement. A cylindrical outboard shield that partially resolves this problem is shown in Figure 1. During maintenance, the removable sector units will be lifted and removed, however, the remaining outboard shield and divertor shield still stay in the power core as permanent components. If radial blanket segmentation is used, similar to ARIE-RS, then the outer zones would be removed and replaced during a later maintenance interval. The centerpost, TF coils and replacement units are supported separately from the bottom through pillars.

In this design, all replaceable items would be lifted out of the top machine. The major concern is the lifting and positioning capability of the overhead crane. This also requires a very tall building with strong walls to support the crane.

IV. VERTICAL MAINTENANCE FROM BELOW

Vertical maintenance from the bottom can be employed for the replacement of all components to be replaced frequently, i.e. blanket, divertor plates, and the centerpost, provided demountable TF coil are used. Figure 2 shows the elevation view of the configuration. In the design proposed the TF coil system is composed of a centerpost, a outer leg, and a bottom lid. The electrical sliding joints possibly locate at the top between the centerpost and outer TF legs to minimize the centerpost stresses. Electrical bus could be attached to the centerpost and outer TF legs at bottom. During maintenance operation, all the electrical bus can be disconnected from bottom and lowered down to the pit.

Unlike the vertical maintenance power components from above, the vacuum vessel in this case is proposed to locate outside TF coils, therefore, radioactivity is contained during maintenance procedures. The blanket is segmented into two zones, i.e., front zones and outer zones. The front zones including the first wall and breeding blanket have a short lifetime and need to be replaced frequently. The outer zones, for example the shields, have longer lifetime and would be replaced during a later maintenance. As shown in Figure 2, the outboard FW/blanket is curved to follow the plasma shape, but a cylindrical shield is adopted to make the movement of power core more easier over a curved shield design.
For the replacement of the power core, the de-mountable joint locate at the bottom lid. In order to allow for a quick maintenance, the power core is attached to this bottom lid only, and all led through for coolant lines, instrumentation cables and so on are located on the lid. After all access lines have been opened and bottom plate is disconnected from the outer leg by working from the bottom region, the bottom lid with attached power core can be lowered into a large pit providing a closed containment for activated particles as well as radiation shielding.

In view of the extreme weight of this assembly, a system of hydraulic jacks is employed for this operation rather than an overhead crane. In order to save height, either telescopic jacks are used, or a step-wise motion with temporary fix is performed. When the power core is moved completely out, there is free access to all components to be replaced. All hot cell and storage areas required for the handling of the activated components are located surrounding the pit at the same level, resulting in short ways and low maintenance time. Basically the entire power core could be replaced as one piece but a separation into six sectors maybe the better solution. After removing the used components, new sectors are attached to the bottom lid and aligned. The entire assembly is lifted its operating position. If the expected lifetime of the centerpost is shorter than the one of the power core, the design must allow for a separate replacement of this component. In this case the centerpost has to be disconnected from the TF outer leg at the top. At the bottom, the electrical bus connected to the centerpost also needs to be decoupled. It can be lowered with an overhead crane into a transport cask placed temporarily in the pit.

With this design very limited space is required above and at the outer peripheries of the biological shield, minimizing the size of building. The unrestricted access to the power core in the pit facilitates a quick replacement. Confinement and shielding of radioactive components and particles should be easier than the vertical maintenance from the top.

VI. HORIZONTAL MAINTENANCE

This configuration is based on the horizontal removal the fusion power core, including the biological shield, for the replacement of inboard shield, outboard first wall, divertor, outboard blanket and shield. Figure 3 shows the configuration of the horizontal maintenance.
maintenance operation with the extraction of each sector accomplished with a single straight line motion between TF coil; and a second option where the number of segments equals a 1/4 or 1/2 of TF coils. The size of sector depends on removing one or more TF coils outward in a straight line.

Similar to the configurations of the vertical maintenance, the sliding joints are possible at the top between the centerpost and outer TF legs. The vacuum vessel locates immediately at the outboard shield, and the inboard shield will be a part of the vacuum vessel. The advantage for employing the inboard shield as a part vacuum vessel is that the TF centerpost can be replaced without disturbing the vacuum system and the power core components, therefore, the maintenance time would be reduced. The TF coils are supported from bottom through an operating floor. The centerpost is supported by a removable structure. The removable sector unit is supported from bottom through torus support rail systems, which potentially offer a rapid replacement in radial direction.

There are two maintenance approaches to be considered for the replacement of the fusion power core. The approach without moving any TF coils and the replacement through a maintenance port between TF coil similars to ARIES-IV and ARIES-RS, and the maintenance procedures were described in references[3,4]. The difference between the maintenance approaches of ARIES-RS and the LAR fusion power core is that the PF coils of the LAR fusion power core has to be removed in order to clear the radial access for the removal of fusion power components. The centerpost would be replaced vertically from below by using of an overhead crane without disturbing the vacuum. In second approach, the maintenance operations request to move PF coils, and one or more TF outer legs to perform a large-scale modular maintenance procedure. The PF coils can be lifted/lowered and placed in a storage room. To move the TF outer legs out of center-post, the sliding electrical connectors at the top and bottom require to be disconnected. After all the coolant lines disconnected, the entire sector can be transported to radial transporter for extraction to maintenance cell by a vehicle/manipulator. In order to avoid the activated components and dusts exposing to the surrounding system, the replaceable sector should be transferred into an enclosure, such as a transfer cask, for delivery to a hot cell. A new sector is delivered to the maintenance cell with transfer cask and supplied to the vehicle/manipulator using the radial transporter for installation on the position.

Critical issue for replacing the 32 m long center-post is lifting and positioning capability of the overhead crane. This also requests a very strong, and tall building. The major concern for the upward and downward movement of the superconducting PF coils, and horizontal removal of TF coils, fusion power core components require a large volume surrounding the machine.

VII. SUMMARY AND CONCLUSIONS

Configuration and maintenance options of a LAR tokamak power plant strongly depend on the TF coils design. If TF coils were made without joints, the maintenance would be similar to the horizontal removal scheme of ARIES-RS. Three configurations and maintenance options have been explored based on the premise of a de-mountable joint for the TF coils. (1) Vertical maintenance from the top. All replaceable items would be lifted out of the top of the machine. The concern is the lifting and positioning capability of the overhead crane and supporting structure. This also requires a strong, tall building. (2) Vertical maintenance option from the bottom. All the replaceable items would be lowered out the bottom of the machine with hydraulic jacks. The building size could be reduced. The jacking system can provide a better capability to handle loads and position components. The confinement and shielding the radioactive components and particles should be easier than the vertical maintenance from top. (3) Horizontal maintenance. One or more (up to half) of the outer TF legs would be removed to gain access to the power core. This requires a large volume surrounding the machine for the upward and downward movement of superconducting PF coils and horizontal removal of the power core components. All designs offered the option to remove the center-post separately without disturbing the vacuum system and the replaceable power core components. The critical issue for the options of vertical maintenance is that if the TF coils with the de-mountable joint can be designed, and where the joints can be located. The mechanical and electrical connections between the center-post and the outer TF legs and electrical bus are critical design issues for all the three configurations and maintenance options.

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