Design approach of the ARIES-AT power core and vacuum vessel cost assessment

Lester M. Waganer a,*, Farrokh Najmabadi b, Mark Tillack b, Xueren Wang b, Laila El-Guebaly c, and The ARIES Team

a The Boeing Company, Mail Code S111-1300, PO Box 516, St. Louis, MO 63166, USA
b University of California at San Diego, San Diego, CA, USA
c University of Wisconsin, Madison, WI, USA

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Abstract

The complexity of fusion power plants require the integration of many diverse and important system requirements to achieve a design approach that is viewed as a commercially viable electric plant. The ARIES-AT power core design builds upon a history of fusion power core designs that evolve along with physics and engineering advances. The baseline design point is optimized for maximum performance and minimum capital cost based upon the ARIES systems code results, along with physics and engineering analyses. The ARIES-AT power core is designed to be quick and easily maintainable to achieve high plant availability. A key element to achieve the high availability is the integration of the core elements with the design of the vacuum vessel. The vacuum vessel design is developed in more detail to assure the key assembly and maintenance features could be realized at an affordable cost.

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

1. Power core design philosophy

The improved physics understanding of advanced plasma confinement modes, which have been advanced in recent years, have lead to more efficient tokamak plasma and power core configurations for power plant designs. The prior ARIES-RS [1] power core design reflects many of the new reverse shear plasma confinement improvements. The ARIES-AT [2] design improves upon these plasma confinements to incorporate several new plasma and engineering advancements. The goal of the engineering design of ARIES-AT is to increase the credibility of the
power core engineering by achieving a high degree of systems integration while obtaining a maintainable design with high availability for a reasonable capital and operational cost.

The starting point is to understand how the maintenance approach affects the power core design. Waganer conducts an analysis concluding that the ARIES-AT power core maintenance approach [3] permits a complete power core sector to be extracted and replaced with a refurbished unit from the plant hot cell. This is determined to be the most reliable and expedient core maintenance approach for a tokamak power core. This approach was previously used in the ARIES-RS power core design [4].

Extracting a complete power core sector requires positioning the poloidal field (PF) coils in regions above and below the removable power core sector components. All other systems, such as the vacuum pumping ports and RF, or neutral beam systems, are located away from this central, outboard region. The toroidal field (TF) coils are sufficiently large to provide adequate clearance between the coils to extract a complete power core sector. The traditional constant tension coil shape is changed to a wider “D” shape to improve the maintenance access. These D-shaped coils require additional coil structural reinforcement. Fig. 1 illustrates the wider toroidal coils and the relocation of the poloidal field coils to enable the 1/16 sector to be withdrawn out between them. The plasma major radius, minor radius, and elongation are drawn to scale along with representative thickness of the power core elements.

All life-limited (non life-of-plant) elements have nearly identical power core lifetimes to improve the plant availability. Removal and replacement of the power core sectors containing all these life-limited
elements significantly improve the change out of life-limited components. Otherwise, the plant availability decreases due to many plant shutdowns to replace smaller components on non-optimized maintenance schedules. El-Guebaly [5] addresses this issue in the design of ARIES-AT by tailoring the materials, placement of the materials, and the component thicknesses with compatible lifetimes for the inner and outer blankets and divertor modules. On the outboard region, an additional second blanket component is employed to enhance the tritium breeding and energy extraction. This second blanket is a life-of-plant component, which greatly helps the plant availability. Just outside the blankets and divertors, a life-of-plant shield region provides adequate shielding for the superconducting TF and PF magnets.

These blanket and shield components are designed to operate at high temperatures ($\geq 1000$ °C) to extract the maximum useful thermal energy from the fusion neutrons. Careful routing of the lithium lead (LiPb) coolant lines provides maximum cooling to the highest heat flux regions, principally in the divertors and the first walls. Since the shields encompass or encircle all the life-limited core components, they are designed as structural elements for attachment of the life-limited components. This approach enables a complete self-supporting power core sector that is withdrawn and reinserted into the power core as a self-contained sector. This integral unit is the entirety of the high-temperature portion of the power core. This approach simplifies the sector plumbing.

The vacuum vessel completely surrounds the high temperature, removable sector as shown in Fig. 1. This vessel provides a vacuum boundary for the plasma core and supports the core elements. The vacuum vessel locally extends between the TF coils to allow removal of the individual power core sectors. The integration of the vacuum vessel with the other power core elements is critical to the ability to quickly and efficiently remove, and replace the core sectors.

Maintenance of the power core is accomplished remotely to not endanger the power plant workers. The level of neutron-induced radioactivity inside the power core, even during non-operational periods, greatly exceeds the levels allowable for hands-on maintenance. As described in Ref. [3], fully automated, remote maintenance equipment disconnects and removes power core sectors to be replaced with refurbished units from the plant hot cell. The design approach stresses the use of a minimal number of coolant and electrical connections to be disconnected and reconnected with the power core sectors. The removed power core sectors are extracted into sealed casks connected with the vacuum vessel port enclosures. These casks contain and transport the sectors to and from the hot cell to minimize the spread of irradiated dust and debris.

2. Power core design approach

The ARIES-AT power core design builds upon many features of the ARIES-RS design [4]. Horizontal removal and replacement of a power core sector (i.e., 1/16 of the torus) is a key feature of ARIES-RS, and is an important design goal for ARIES-AT. The ARIES-RS design affirms the value of horizontal removal of the large sectors containing all life-limited components attached to a removable life-of-plant structure. A review of the ARIES-RS design indicates vacuum vessel is more complicated than necessary and the design of other power core elements could be improved.

The design of the ARIES-AT tokamak power core is a refinement based on many prior tokamak power plant designs. Choosing the number of TF coils as 16 is a compromise between acceptable toroidal field ripple and adequate maintenance access. The selection of the double null plasma is attractive because the heating and particle exhaust load is shared on two divertor sections and the plasma is balanced and symmetrical. The ability to maintain the upper divertor region is eased by removing an entire power core sector. Control of the plasma location and tendency to disrupt should be well understood and accomplished when this plant is operational. Superconducting coils (either low or high temperature) are attractive for their low power consumption. The first wall and blanket should closely conform to the plasma shape. Plasma control for the reverse shear is accomplished by embedding passive and active control coils within the power core sector. An efficient vacuum vessel is an enabling element to achieve high maintainability and availability.

The primary function of the vacuum vessel is to provide the high-level vacuum environment necessary to achieve and maintain high-quality fusion plasma. The vessel must be a leak-tight structure with large ports in each of the 16 core sectors between TF coils.
These ports allow maintenance access for removal and replacement of complete sectors of the power core. The vacuum vessel contains and supports the power core thermal elements of the blanket, shield, and divertor. The vacuum vessel is located between the high-temperature core and the superconducting coils. This location of the vacuum vessel provides the additional neutron shielding for the coils. The interior shielding is designed such that the vacuum vessel is a lifetime core element. Low temperature water circulating between the vacuum vessel structural walls removes any waste heat not contained and extracted by the high-temperature power core.

The preliminary thickness of the power core elements and the coil system surrounding the initial plasma equilibrium field line plots initiated the definition of the power core elements. Nominal thicknesses and material allocations are assigned based upon previous similar design solutions. Design assumptions and CAD models are refined as neutronic models and are constructed and analyzed. Preliminary inboard, outboard, and vertical material builds [5] are defined and refined to yield a suitable, balanced solution for surface and volume heating fluxes, burnup fractions, tritium breeding ratio, and estimated component operational lifetimes. These radial and vertical build definitions are used to generally define the possible envelope of the vacuum vessel.

The component adjacent to the plasma inboard and outboard regions is the first wall and inner blanket (Blanket-I), both of which are limited-lifetime components. Likewise, the divertor is a limited-lifetime component. Since the neutron flux is at a maximum on the outboard region, a second blanket [5] (Blanket-II) is provided in this outboard region to obtain the required level of tritium breeding. Due to the significant neutron attenuation by the first blanket region, the second blanket is designed as a life-of-plant component. The next layer, away from the plasma, shields the neutrons and extracts most of the remaining thermal energy not recovered by the blanket components. The level of thermal energy recovered in this shield region is sufficient to justify operating the shield at the same high temperature as the blankets to recover high-quality heat from the shield. Thus all core elements inside the vacuum vessel operate at a high temperature.

The simultaneous replacement of all life-limited components is highly desirable for the inboard first wall/blanket, outboard first wall/blanket, and the divertor to significantly improve the maintainability and availability associated with the power core. Since the plasma is a double-null plasma and the divertors are slot divertors, there is no credible means to provide a structural element bridging the inner and outer blanket regions to form an integral structure. An integral structure is necessary to allow the simultaneous removal of all the life-limited structure as a single integral piece. Therefore, the shield is designed to function as the primary structural member for the sector. This structural concept allows the removal of a complete sector of the power core. However, this approach requires removal of the life-of-plant components, such as the second outboard blanket (Blanket-II) and the high-temperature shield, as schematically shown in Fig. 1. Different maintenance scenarios relating to replacement schemes and refurbishment approaches are assessed [3] in an ARIES-AT maintenance task. The recommended maintenance approach is to remove 8 of the 16 sectors every 2 years. These sectors are immediately replaced with sectors previously removed and refurbished, off-line, during normal operation.

To meet both the neutronic and thermal coil protection requirements, the combination of the first wall, blanket, shield, and vacuum vessel must be sufficiently neutronically dense to protect the TF coil superconductor to the level of $10^{19}$ n/cm$^2$ ($E_n > 0.1$ MeV) over the lifetime of the plant. The evolving design of the first wall, blanket, and shield, to maximize the conversion of the high-energy neutrons into tritium and thermal energy production, yielded a highly efficient design that enabled a simple and cost-effective vacuum vessel design. The design uses a double-walled, low-activation, ferritic steel (such as F82H or ORNL 9Cr-2WVTa) vessel. The space between the walls is filled with water and tungsten carbide (WC) spheres as additional shielding material. This design approach is cost-effective from the manufacturing point of view.

The outboard PF coils near the midplane are designed to be located above or below the horizontal maintenance ports to enable extraction of the full size core sectors. Extensive equilibrium analyses are conducted to obtain flux surfaces with the correct plasma configuration.

After interaction between physics and engineering groups, the final power core design incorporated most of the desired physics and engineering features. Fig. 2
is a cross-sectional elevation view of the ARIES-AT power core. The highly elongated, double-null plasma with high triangularity is surrounded by a close fitting, high-temperature SiC structural first wall and blanket modules. Divertor regions are located at the top and bottom of the plasma. A vertical stabilizing shell is located between the Blankets-I and -II. The high-temperature shield is located immediately outside the blanket regions. This shield also serves as the high-temperature structural frame supporting the first wall, blanket, and divertor modules. Located on the inner surface of the vacuum vessel door are vertical position coils that run toroidally. These coils have joints that can be broken for door removal. On the door, there are also resistive wall mode feedback coils that are window or saddle coils. These coils would be removed with the door.

Fig. 3 shows the high-temperature elements of a removable power core sector. These elements are the life-limited first wall, blanket, and divertor systems along with the life-of-plant high-temperature shield that also functions as a structure supporting and...
aligning the first wall, blanket, and divertors. The first wall, blankets, and divertor elements are attached to the high-temperature shield that completely encircles these life-limited elements. This figure shows how the 22.5° sector (one of 16) is self-supporting, and capable of being removed into a sealed cask for transport to the hot cell for refurbishment.

The plan view of the power core at the midplane, Fig. 4, presents the detailed layout and the radial build of the high-temperature core, vacuum vessel, and coils. This view shows the inner first wall and blanket closest to the plasma on the inboard region. These first wall and blanket elements have a design lifetime of four full power years (FPY). Further inboard are the high-temperature shield (that serves as the high-temperature core structural support), vacuum vessel, and TF coil inner legs. This is a typical arrangement for a tokamak power core.

Outboard, the blanket region is subdivided into an inner zone (FW/Blanket-I) having an operational lifetime of four FPY and the next zone (Blanket-II) with an operational life equal to the plant lifetime, see Ref. [5]. The next outboard element is the structural high-temperature shield. Outside the shield, space is provided for plumbing and plasma stabilization coils. As described previously, the intent is to

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![Cross-sectional and isometric views of ARIES-AT blanket/divertor/shield.](image)
remove all of the high-temperature core elements as a single integral unit through the maintenance port. Parting lines between adjacent sectors extend from the junction between Blankets-I and -II. The port is designed to accommodate this width. The sector width is at a maximum condition on the power core midplane and less at other elevations. The vacuum vessel door is curved to match the outer curved surface of the shield plus plumbing space. The vacuum vessel doors are secured with large pneumatic, locking screw jacks. These jacks are shown in both an open and closed position in Fig. 4. After the vessel is evacuated, these devices are redundant. During maintenance, they swing out of the way into pockets in the vacuum vessel port to facilitate sector removal. The vacuum doors are sealed for vacuum by a reweldable bellows.

3. Conceptual design of the vacuum vessel

The preliminary vacuum vessel definition described in the previous section established the parameter and option design space for the power core necessary to meet the overall system requirements. The next step is to refine the vacuum vessel geometry within the bounds and constraints of the plasma shape and the other power core elements. Computer aided design (CAD) models are constructed to accurately define components, assess design options, and examine geometry constraints consistent with horizontal sector removal.

The vacuum vessel is designed as a double-walled, spool-shaped structure supporting the removable blankets and shield elements. Fig. 5 is an isometric of the inner spool assembly that is a permanent structure to support the power core elements and form the...
inner vacuum vessel boundary. This simple shape is easy to fabricate and should be relatively inexpensive.

The fabrication process for the innermost wall is to weld together bump-formed, 2-cm-thick plates into a leak-tight vessel wall. Vertical ribs will be welded to the wall to support the second outer wall. If the shielding material is in a block form, it could be added before the outer closure plates are added. If the shielding material is a bulk form, such as spheres, it can be added after the assembly is formed.

The spool would probably be assembled in quadrants with field welds at the construction site. These welds are recessed or protected from neutrons to allow future rewelding, if necessary. After each quadrant is installed, the TF coils for that quadrant are brought radially into the correct position and translated circumferentially into final position. The final quadrant requires a tailored assembly procedure with an internal construction joint. Fig. 6 shows the overall dimensions of the inner spool assembly in an elevation view.

Fig. 7 shows 32 ribs extending vertically in the cylindrical section to connect the inner and outer walls. These ribs vertically direct the flow of the water coolant. Additional ribs continue in the circular curved transition area and into the radial flange areas. Water coolant connections for each flow passage, not shown, supply water coolant ingress and egress.

Outboard of the spool assembly, removable doors, and frame assemblies complete the vacuum vessel assembly. The size of the core sector being removed defines the door opening over the height of the sector. The door is contoured to closely fit the outer surface of the shield, but allows sufficient space for vacuum conductance from top to bottom of the vessel. There is also a requirement to provide space for plasma control coils on the inner surface of the vacuum vessel. The power core cross-section, Fig. 2, shows the curvature of the door and the provision for the feedback coils.
Fig. 5. Vacuum vessel spool assembly.

Fig. 6. Vacuum vessel spool dimensions.

Fig. 7. Spool structural details.
The elevation cross-section, Fig. 8, defines the door curvature.

The two cross-sections through the door at midplane and near the top of the door are shown in Fig. 9. The door is subdivided into several compartments to channel the cooling water flow from bottom to top. The door thickness of 25 cm gives a reasonable shielding thickness and door stiffness. The thickness and materials are refined during detailed design and analysis [5]. There is a step completely around the door to provide a positive door engagement and alignment and to help reduce the neutron streaming around the door.

While the general curvature and height is defined from the side view cross-section, the width of the door is determined from the plan view cross-section at various elevations through the door region. The midplane of the power core is shown previously in
Fig. 4. Fig. 4 shows the parting line between core sectors extending radially from the inner radii of the inboard high-temperature shield out to the inner radii of the outboard high-temperature shield. From that point outward, the parting line deviates from a radial line to a line parallel to the centerline of the power core sector and the vacuum vessel port. The two parallel parting lines, plus a clearance allowance, establishes the door, doorframe, and port enclosure geometries.

The preliminary vacuum vessel doorframe details are shown in Fig. 10. This figure shows one of the 16 subassemblies of the doorframe. When assembled, the subassemblies form complete rings for the upper and lower door flanges. The curved center sections form adjacent vertical doorframes. Joining the frames in the middle of the opening allows greater strength edge doorframes. Cooling water is introduced at two locations on the bottom frame and flows up to the upper frame and coolant outlets.

The geometry definition of the removable sectors is discussed earlier. The parting line for the sectors deviates from a radial direction to a direction parallel to the centerline of the sector at the intersection point between the outboard Blankets-I and -II. This location allows all Blanket-I elements to be completely removed during planned maintenance actions.

Most of the Blanket-II and the high-temperature shield elements are also removed. However, there is a small wedge of Blanket-II and the high-temperature shield that permanently remains in the core for the life of the plant as shown in Fig. 11. The vacuum vessel doorframe supports the high-temperature wedge. The wedge is constructed of materials similar to those in the second blanket and shield. The high-temperature coolant for these elements is routed through the water-cooled frame.

Port enclosures are designed to help protect and isolate the volumes outside the vacuum vessel from radioactive contamination during the maintenance actions. These enclosures are sufficient to accommodate the mobile containers housing the removed components and maintenance/transport equipment. These enclosures are double-walled, water-cooled, ferritic steel structures. The thermal heating by neutrons in the enclosure is low enough to suggest that the next iteration level of design might consider a strengthened single-walled structure. One enclosure is provided for each of the 16 ports. The ports extend out to just beyond the cryostat. In the midplane view, shown in Fig. 4, the port enclosures are only slightly larger than the width and height of the vacuum vessel doors and the power core sector to minimize the size of the enclosures and to allow the TF coils to be as close to the plasma as possible. A trinomial view of the port enclosures is shown in a final vacuum vessel assembly figure discussed in a subsequent paragraph.

The enclosures provide a feature to help secure and hold the vacuum vessel door in place. During operation, an interior vacuum provides a positive pressure differential on the door to hold the vacuum vessel door in place against the circumferential door flange. To provide a positive means of securing the door, under all possible operational and accident conditions, 10 or more locking screw jacks around the perimeter of each door will swing out from the mounted pockets into the port enclosure to engage and secure the doors during operation as shown in Fig. 12. The pockets allow quick repositioning of the jack into the port enclosure wall for removal of the door and sector during maintenance.

Fig. 13 shows the same power core midplane view as shown in Fig. 4. However, in this view, the sector is being withdrawn into the vacuum maintenance port. The view also shows the vacuum port door in the maintenance port enclosure. These elements are withdrawn in separate operations. This view is used to construct the necessary clearances on the midplane. This view also shows the door-securing jacks rotated into their stowed position.

The companion elevation view of the sector withdrawal is shown in Fig. 14. The vacuum vessel door is disconnected and is located in the port enclosure. The core sector is moved and is just starting to enter the port enclosure. The maintenance transporter or containment casks are not shown in this view.

Fig. 15 shows a 270° isometric view of the vacuum vessel with the inner spool, doorframes, doors, and port enclosures installed. The inner spool assembly forms the inner, upper, and lower boundaries of the plasma chamber vacuum region. Cryogenic vacuum pumping ducts are connected to the top of the spool assembly. In the current design, they are defined as quite lengthy, but the cryogenic pumps should be closely located to the vacuum vessel to be effective.
Fig. 10. Door frame details.
Closure of the outer perimeter of the vacuum vessel is accomplished with removable curved vacuum vessel doors that allow access to the interior of the core. These doors are withdrawn through the port enclosures for access to the power core sectors (doors are not shown in Fig. 15). The large port enclosures attach to the doorframes. They isolate the port passageway from the interior of cryostat enclosing the TF and PF coils. Doors on the end of the enclosures are required, but not shown or discussed. The port enclosures are large enough to allow withdrawal of complete power core sectors (1/16 of entire power core). Gravity supports, shown below the vessel, support the static and seismic loads of the entire power core.

4. Maintenance system design approach

The prior section discussed the basic core configuration and design development to enable a complete sector removal and replacement approach. This section
The maintenance approach must be capable of:
- quickly extracting and replacing the core sectors;
- adequately contain the dust and debris from the core and the maintenance operations;
- apply to both scheduled and unscheduled maintenance actions;
- have low capital cost for the buildings, maintenance equipment, and spares;
- have minimal radioactive waste; and
- have a high level of system reliability.

Several maintenance options are evaluated [3] for the above maintenance criteria. The most attractive option is the mobile cask system. A mobile cask system [6] is also selected for the ITER divertor and horizontal port modules. Mobile casks are designed to house ARIES-AT vacuum vessel door or a power core sector plus a transporter, move from the hot cell through an air lock and maintenance corridor, and dock to the extremity of the port enclosure. A generic transporter is shown in Fig. 16. Upon cask docking, double doors on the mobile cask and the port enclosure open to allow the onboard transporter access to the vacuum vessel door. After disconnecting the door mechanical, hydraulic, and electrical connections, the vacuum vessel door is moved into the cask and transported to the hot cell. Then the cask and transporter return to disconnect and remove the power core sector. The complete sequence of operations is illustrated in Fig. 17. Sufficient radial clearance space is provided in the maintenance corridor to allow full access of casks to all port regions. As described in Ref. [3], removal of one half of the power core sectors at one maintenance period matches well with the balance of plant maintenance periods, has a reasonable set of maintenance spares and equipment, and produces an attractive inherent availability. Multiple casks and transporters are used to speed maintenance actions to achieve a competitive plant availability factor.
5. Vacuum vessel cost assessment

5.1. Assessment approach

The ARIES systems code parametrically computes most of the power plant engineering and cost data. The code results give a good indication how to scale and optimize the plant, in general. However, more detailed cost data for individual systems is determined before undertaking a final design. Since the ARIES-AT vacuum vessel subsystem design is more detailed than in prior ARIES studies, it is decided to assess the cost of the vacuum vessel components in more detail. This also helps anchor and validate the systems code modeling for future power plant studies and designs.

The basic assumption for the conceptual design is that it is representative of a 10th-of-a-kind power plant.
Thus, no development or tooling charges is assessed against the capital cost. Also, the learning curve is applied to the 10th unit. Costs are expressed in US$ 2000.

The entire vacuum vessel assembly is constructed of welded ferritic steel. The construction technique is a double-walled vessel with water-cooling between the faceplates. To enhance the neutronic effectiveness, spheres of tungsten carbide are added in the interspaces. Techniques to fabricate the components are evaluated. Material quantities are estimated with appropriate wastage for the fabrication process used. The nominal material thicknesses of 2 cm are used on the spool assembly and the port enclosures. Material thicknesses of 3 cm are assumed to reduce the stresses in the doors and doorframes. No detailed design and stress analysis is done at this stage. The masses of the major vacuum vessel components are shown in Table 1.

Table 1

<table>
<thead>
<tr>
<th>Component</th>
<th>Each mass a (kg)</th>
<th>Quantity</th>
<th>Total mass a (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spool assembly</td>
<td>136,043</td>
<td>1</td>
<td>136,043</td>
</tr>
<tr>
<td>Removable doors</td>
<td>13,208</td>
<td>16</td>
<td>211,328</td>
</tr>
<tr>
<td>Doorframes</td>
<td>3,522</td>
<td>16</td>
<td>53,632</td>
</tr>
<tr>
<td>Port enclosures</td>
<td>66,132</td>
<td>16</td>
<td>712,448</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>1,113,451</td>
</tr>
</tbody>
</table>

a Structure only. WC shielding materials and cooling water not included.

The large plates for the spool assembly are flat plates, rolled plates, or stampings with cost estimates from vendors. Cost estimates are obtained from vendors for the explosively formed doors. The door and doorframes incorporate extruded Z-section materials to provide an inexpensive means to form the flanges. Cost estimates for these Z-sections are provided by extrusion vendors. Welding and welding inspection estimates are determined by size and length of weld. Labor costs are representative of recent fabrication subcontracts. Allowances are added for vacuum construction and inspection. Nominal fees and a sufficient contingency are applied. The summary costs of the major vacuum vessel components are shown in Table 2.

As shown above, this assembly is fabricated with conventional techniques and the cost estimates are consistent with the cost of large welded vacuum structures. Table 3 summarizes the unit costs for the major components. These unit costs help validate that the estimates are reasonable for the type of material and fabrication process. These are provided as data for the ARIES systems code.

5.2. Discussion of cost results

Examination of Table 2 shows that the fabrication cost of the vacuum vessel dominates the cost of the vacuum vessel assembly as its 87% of the total (US$ 25.9 out of 29.6 million). Application of innovative design or fabrication approaches should help bring this cost element lower. Within the fabrication cost element, the cost of welding represents 69% of the overall cost (not shown in Table 2). Welding is a rather mature process, but there are new innovations, such as friction stir welding, that may help to reduce the cost while achieving a higher quality weld. Also using more preformed parts, such as the Z-section extrusions for the doorframes, would help lower the costs. The interior bulkheads were the single most costly element on spool, doors, and enclosures (52%). Using integrally stiffened structures would help reduce these cost elements. As mentioned earlier, the port enclosures are very costly (55% of the total cost), but they are 64% of the total mass. It might be possible to reduce these costs by using common larger port enclosure or using single-walled, integrally stiffened, uncooled structures.

This vacuum vessel design approach is an innovative approach with a reasonable cost using conventional
Table 2
Summary of vacuum vessel component costs

<table>
<thead>
<tr>
<th>Component</th>
<th>Total mass (kg)</th>
<th>Material cost (US$)</th>
<th>Fabrication cost (US$)</th>
<th>Total cost (US$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spool assembly</td>
<td>136,043</td>
<td>494,30</td>
<td>2,614,897</td>
<td>3,108,327</td>
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<tr>
<td>Removable doors</td>
<td>211,328</td>
<td>859,863</td>
<td>6,241,880</td>
<td>7,101,743</td>
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<tr>
<td>Doorframes</td>
<td>53,632</td>
<td>356,555</td>
<td>2,736,320</td>
<td>3,092,875</td>
</tr>
<tr>
<td>Port enclosures*</td>
<td>712,448</td>
<td>2,020,698</td>
<td>14,309,096</td>
<td>16,329,794</td>
</tr>
<tr>
<td>Total</td>
<td>1,113,451</td>
<td>3,730,546</td>
<td>25,902,193</td>
<td>29,632,739</td>
</tr>
</tbody>
</table>

Contingency (20%) 5,926,739
Prime contractor fee (12%) 3,555,929
Total subsystem cost 39,115,216

Costs are expressed in 2002 dollars.
* Mass of port enclosures includes the outer port door structures.
Fig. 17. Sequence of maintenance operations removing vacuum vessel doors and power core sectors.
Table 3

<table>
<thead>
<tr>
<th>Component</th>
<th>$/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spool assembly</td>
<td>30</td>
</tr>
<tr>
<td>Removable doors</td>
<td>44</td>
</tr>
<tr>
<td>Disconnector</td>
<td>76</td>
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<tr>
<td>Port enclosures*</td>
<td>30</td>
</tr>
<tr>
<td>Composite rate</td>
<td>35</td>
</tr>
</tbody>
</table>

* Mass of port enclosures includes the outer port door structures.

Costs are expressed in 2002 dollars.

fabrication processes. Additional design and analysis effort is needed to optimize the design and validate that it is ready to proceed to fabrication. Design and fabrication improvements may be investigated to significantly improve the cost of this subsystem.

6. Summary

A design approach is defined for the ARIES-AT power core that supports advanced tokamak confinement schemes, high efficiency power conversion, low activation materials, reduced waste products, and high plant safety (no evacuation plan is needed) to yield a highly maintainable and available plant. This design approach features low cost fabrication of components and high availability that results in a fusion plant with an attractive cost of electricity.

The integration of all these elements into a complete power core is shown in Fig. 18. This isometric view shows the cryostat surrounding the vacuum vessel, coils, and core elements. The coils and core elements employs all the most current capabilities of the advanced plasma confinement approaches. The design uses the high-temperature blanket technology to obtain a high efficiency thermal conversion approach. Efficient coil structures enable TF and PF coil systems to enable rapid maintenance of power cores. The entire power core is specifically designed to enable rapid replacement of the power core, obtain a high plant availability, and achieve a low cost of electricity.

References
