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ABSTRACT

Vanadium alloys and SiC/SiC composites offer significant advantages in their low activation characteristics and high thermal performance capability. However, a design based entirely on these advanced structures would be expensive. Therefore, it is essential to limit the use of such advanced materials to highly irradiated components such as plasma facing components and blanket. The cost savings for replacing the V and SiC structures of the massive shield with steel are significant. This will degrade the thermal conversion efficiency of the system somewhat since steel cannot operate at temperatures as high as V or SiC. The dividing boundary between the high temperature and low temperature zones will therefore depend on how much power could be dumped as low grade heat without significantly reducing the useful thermal power. This novel approach for designing the shield of V- and SiC-based fusion power plants, along with other innovative ideas that improved the shield performance, reduced the overall cost of electricity by 10%, which is significant.

I. INTRODUCTION

The ARIES series of fusion plant studies is a multi-institutional research effort to identify the technical feasibility and R&D issues for U.S. power plants and to determine the economic and safety features of fusion systems employing low activation advanced materials. The project demonstrates the interactions between the design and assessment to improve the economics and safety of fusion power plants. The ARIES study has indicated that vanadium alloy, SiC/SiC composites, and low-activation ferritic steel are the most promising candidates for the in-vessel components. V and SiC offer significant advantages in their low activation characteristics and their high thermal performance capability. On the other hand, low-activation steels are relatively inexpensive, have a higher shielding performance than V or SiC, and have the largest database and industrial support, and hence the smallest uncertainty in performance.

Advanced materials will certainly offer the benefits of operating at higher wall loadings (making the design more compact and less expensive), operating at higher temperatures (meaning higher thermal conversion efficiency), and having lower radioactive inventory and afterheat. Nevertheless, the ARIES studies have indicated that the economic advantage of the advanced materials is limited. A power plant made entirely out of V or SiC structures will be expensive. Thus, some design tradeoffs are necessary in order to improve the economics and minimize the impact on the safety and environmental features of the design.

Over the past several years, six different detailed tokamak designs have been produced. ARIES-I[1] is a helium cooled SiC/SiC composite structure with Li_2ZrO_3 solid breeder and beryllium multiplier. ARIES-II[2] is a self-cooled lithium design with a vanadium alloy structure. ARIES-IV[2] is a helium cooled SiC/SiC composite structure with Li_2O solid breeder and beryllium multiplier. PULSAR-I and -II[3] are inductively-driven, pulsed machines based on ARIES-IV and -II in-vessel components, respectively, whereas the ARIES designs are steady-state machines that use RF current drive. ARIES-RS[4] is an on-going study which explores the benefits of both advances in tokamak physics, such as reversed shear (RS), and engineering improvements to in-vessel components of Li/V systems. All these designs are conceptual, D-T burning, 1000 MWe power plants. They have a moderately high plasma aspect ratio of ~ 4, a low plasma current of ≤ 10 MA, a peak field at the coils of ≤ 16 T, and a lifetime of 40 years with 76% availability.

The ARIES team has recently established a set of challenging goals and requirements for U.S. fusion power plants.[5] The safety requirements severely limit the material choices for all in-vessel components while high performance requirements provide strong incentives to operate at high coolant temperature and thermal efficiency. The economic requirements constrain many aspects of the design and urge designers to optimize the performance of all in-vessel components, employ low cost materials, and extend the useful life of all components as much as practically possible. Hence, an assessment of the shield design options has been performed for the three candidate structural materials along with the economic impact of the various options on the overall cost of the machines. This assessment was carried out within the Starlite project leading up to the analysis and design of the ARIES-RS power plant. The Starlite project has evaluated the engineering systems of the ARIES-II and IV designs as candidates for the ARIES-RS design. Thus, several in-vessel components of ARIES-II/IV were modified to improve the economics. The work reported here highlights the improvements made to the shield design in particular, the rationale for making the changes, and the design optimization activities that enhanced the performance and reduced the cost of the shield and overall machine.

II. PREVIOUS DESIGNS

In ARIES-II/IV, the first wall and blanket are followed by the reflector and then the shield. An elevation view of the ARIES-IV design is shown in Fig. 1. The energy deposited in all the in-vessel components is recovered as high grade heat. Because V (300$/kg) and SiC (400$/kg) structures are expensive, power plants made entirely out of V or SiC structures will not be competitive as evidenced by the fact that the cost of electricity of ARIES-II and -IV would be 114 and 92 mills/kWeh, respectively (all costs reported herein are in 1992$). Therefore, some tradeoffs were made to improve the economics. For instance, the space between the coolant channels of the shield was filled with cheap filler materials, instead of being made out of solid structures. There is no structural role envisioned for the filler materials. Another improvement that helped reduce the cost of the ARIES-II shield in particular is the use of steel fillers, instead of V filler. Besides having a lower unit cost, steel has better shielding performance than V and thus results in thinner radial builds and a smaller machine. The economic analysis provided

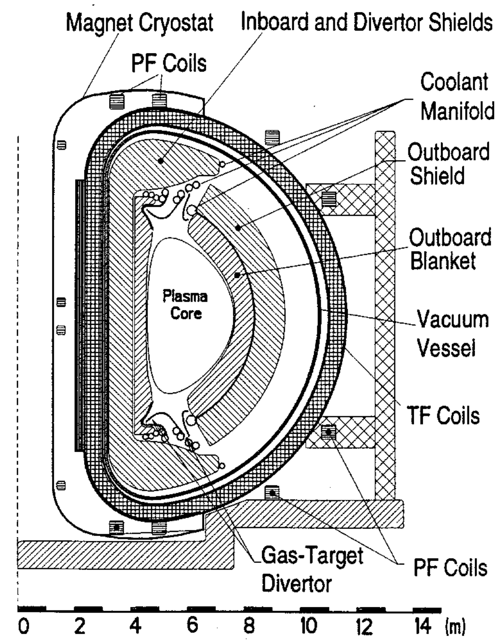

Fig. 1. Vertical cut through ARIES-IV design.

by the ARIES systems code (ASC) has indicated that these improvements to the shield design have lowered the ARIES-II and -IV costs of electricity to 74 and 68 mills/kWeh, respectively. However, the shield, which is well optimized for high neutronics performance, still represents a major cost item.

Further breakdown of the cost revealed that the outboard shield constitutes more than 50% of the shield cost and, more importantly, the V (or SiC) structures comprise ∼ 60% of the overall shield cost, even though these advanced materials occupy only 15% of the shielding space. The cost breakdown of the ARIES-II shield is illustrated in Fig. 2. These findings have prompted the need to minimize the use of V and SiC structures in the shield (and external systems) and instead utilize less expensive steel structure to reduce cost. It is essential, therefore, to limit the use of V and SiC to components where high temperature performance is most needed, i.e., in the plasma facing components and blanket. It should be mentioned that this problem of expensive shield is quite unique to advanced designs. Previous designs traditionally employed water-cooled steel shields to protect the magnets. For safety and technical reasons, the water-cooled steel shield cannot be used in the ARIES designs. Firstly, the use of lithium breeder in ARIES-II and SiC/Be in ARIES-IV will probably make the use of water in the shield impossible for safety reasons. No coolant other than Li and He is known to be compatible with V and SiC, respectively. Secondly, since steel cannot operate at temperatures

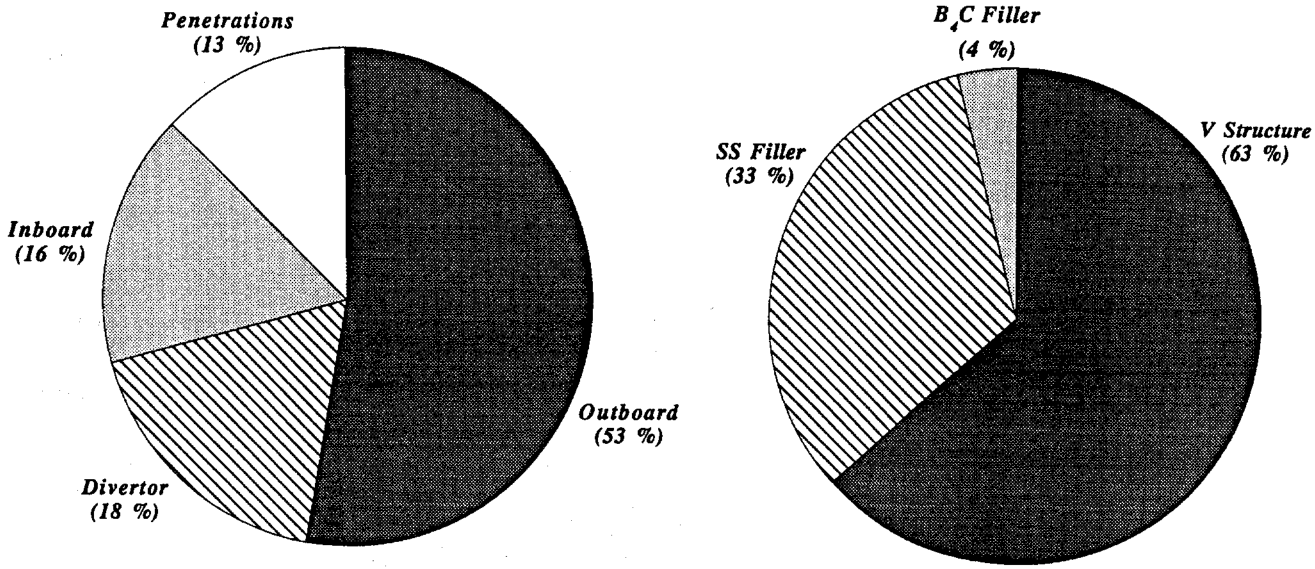

Fig. 2. Breakdown of ARIES-II shield showing V alloy is dominating the cost.

as high as V or SiC, the use of steel structure in the entire shield will certainly degrade the overall thermal conversion efficiency of the system. In addition, the option of running the entire shield at lower temperature is not viable because the nuclear heating generated in the shield is significant ($\sim$ 20% of the total) and cannot be dumped as low grade heat without negatively impacting the power balance of the machine. For these reasons, V and SiC structures should be used in all or part of the shield to increase the ability to extract the heat with Li and He coolants at high efficiency for the purpose of generating electricity.

III. INNOVATIVE SHIELD DESIGN

We anticipated that the following three main modifications would offer potential improvements to the ARIES-II/IV shield design:

1. The unit cost of steel should be revisited and compared with estimates from other designs for components with similar level of complexity.
2. Further enhancement to the shielding performance is needed by optimizing the composition and employing highly efficient, inexpensive (particularly for the outboard) shielding materials.
3. The use of advanced V and SiC materials must be limited to those regions where it is absolutely necessary for high temperature operation.

We assessed the impact of the improvements to the ARIES-II/IV shields on the overall size and cost using the ASC. Several runs were made to quantify the cost saving of each change made to the shield design. We made the changes one at a time sequentially and determined the incremental cost reduction for each sequential change. We first investigated the impact of changing the unit costs of fabricated steel structure and filler. The ARIES-II/IV design is based on unit costs for steel structure of 68 \$/kg and steel filler of 25 \$/kg. It should be mentioned that any type of steel could be used in the shield and vacuum vessel (V.V.). These components are well protected and not subjected to as high a radiation level as the FW/blanket. There are several low activation steels (MHT-9, Tenelon, Fe1422, 316SS, F82H-M, MANET, etc.) that are readily available for use in fusion power plants. As shown later, steel will be employed in the outer part of the shield, V.V., and all ex-vessel components. The steel shield and V.V. will run at low temperatures relative to the FW/blanket; will not suffer as much radiation damage (meaning simpler welds or less inspection); will have much simpler configuration, fewer attachments, and less plumbing; and will thus have the ability to be quickly maintained. These features should translate into lower costs for such moderate-complexity components. Other designs[6,7] have quoted lower cost estimates such as $\sim$ 35 \$/kg for steel structures and $\sim$ 10 \$/kg for steel fillers. These values are based upon industrial experience with large steel structures and cost estimates for similar shielding and V.V. components. Using these lower unit costs, the ARIES-II shield and V.V. cost has been reduced substantially by $\sim$ 100 M\$ and the overall cost of electricity (COE) has dropped by 3 mills/kWeh.

TABLE I
Cost Impact of Changes Made to the ARIES-II Design in 1992$

	Shield Cost (M$)	COE (mills/kWeh)	Incremental Reduction in COE (mills/kWeh)
ARIES-II Design	366	73.8	
Modified ARIES-II Design:			
Reduced steel unit cost	295	70.9	2.9
More efficient shield	248	69.0	1.9
HT/LT shield	164	66.8	2.2

The second change made to the ARIES-II/IV designs is that the performance of the shield was enhanced by employing more efficient shielding materials such as tungsten carbide and borated-steel. Specifically, boron carbide was replaced by tungsten carbide (65 $/kg) in the inboard side and the steel and SiC fillers were replaced by borated-steel filler (10 $/kg) in the outboard and divertor regions. These modifications have reduced the radial build of ARIES-II and -IV by 8-22 cm, the major radii by 8-16 cm, and the COE by 2-3 mills/kWeh.

The third change examined the potential of using the less costly steel structure in the shield while maintaining the safety features of the design. An attractive solution is to divide the shield into two parts: the inner part follows the blanket and operates at a high temperature, while the outer part operates at a relatively lower temperature ($< 500°$C). Hence, the high temperature (HT) shield along with the FW and blanket employs V or SiC structure whereas the low temperature (LT) shield utilizes stainless steel as the main structural material. The heat extracted from the LT shield will not be recovered. The tradeoffs between stainless steel and advanced materials will thus depend on the dividing boundary between the two layers of the shield and on how much power could be dumped as low grade heat without overly affecting the power balance. We anticipated that the allowable reduction in the useful thermal power to be on the order of 1–5%. The savings in ARIES-II/IV cost due to dividing the shield into two zones is 2-3 mills/kWeh. It should be stressed that this modification should not impact the safety characteristics of the design as the shield is subjected to low radiation flux, generating low levels of radioactivity and afterheat. In fact, separating the shield into two zones helps the design in case of an accident. It is true that the gap between the two zones will slow down the conduction of decay heat from the HT shield to the LT shield, but more importantly, the LOCA analysis[8] has shown that the Li (or He) cooled LT shield which operates at a temperature below 300°C (as compared to 600°C in ARIES-II), acts as a heat sink and helps the FW temperature to drop faster after the first day following any accident.

By making the three main changes mentioned above, the COE has been reduced substantially as compared with original designs. Table I details the impact of the sequential changes made on the cost of the shield and COE for the ARIES-II design. Note that the reduced unit cost of steel results in the largest saving in the cost of ARIES-II. Tables II and III compare the original and modified ARIES-II/IV design emphasizing the impact of the changes made on the machine sizes, shield dimensions, and total (direct and indirect) costs. These results pertain to the case where the LT shield is sized to contain 1% ($\sim$ 20 MW) of the total nuclear heating generated in the in-vessel components. For this particular case, the modified shield contains $\sim 5\%$ advanced structure (V or SiC) and $\sim$ 10% steel structure.

TABLE II

Selected Parameters for the Original
and Modified ARIES-II Designs
(1 GWe net power with 46% thermal efficiency)

Design	ARIES-II	Modified ARIES-II
HT/LT shield thickness (cm):		
Inboard	70/0	30/32
Outboard	100/0	30/50
Divertor	105/0	60/36
Major radius (m)	5.6	5.52
Minor radius (m)	1.4	1.38
Neutron energy multiplication	1.38	1.366
Masses (tonnes):		
Shield	6,020	5,090
FPC	10,800	9,730
Shield Cost (M$)	366	164
V.V. Cost (M$)	50	27
Total Cost (M$)	4,170	3,700
COE (mills/kWeh)	74	67

TABLE III

Selected Parameters for the Original and Modified ARIES-IV Designs (1 GWe net power with 46% thermal efficiency)

Design	ARIES-IV	Modified ARIES-IV
HT/LT shield thickness (cm):		
Inboard	95/0	57/26
Outboard	112/0	40/50
Divertor	125/0	80/28
Major radius (m)	6.04	5.88
Minor radius (m)	1.51	1.47
Neutron energy multiplication	1.23	1.22
Masses (tonnes):		
Shield	3,620	4,700
FPC	9,010	9,830
Shield Cost (M$)	407	230
V.V. Cost (M$)	52	28
Total Cost (M$)	3,670	3,250
COE (mills/kWeh)	68	62

To quantify the impact of dumping more heat (e.g., 5%) in the LT shield, the ARIES-II design is used for this comparison and the results are given in Table IV for 1 GWe power plants with 46% net thermal efficiency. Note that as more heat is dumped, the LT shield gets thicker allowing more V structure to be replaced with steel, thus resulting in a lower cost. Interestingly, the thicker inboard LT WC shield provides better protection for the magnets resulting in a thinner radial build and a smaller machine. This tradeoff indicates that throwing away more heat to make a less expensive shield may in fact pay off.

IV. CONCLUSIONS

Neutronics and economics considerations were used iteratively within the Starlite project to guide the shield toward an optimal design. A successful attempt was made to lower the cost of the shield designed previously for V- and SiC based power plants while keeping the attractive safety features of the designs. Enhancing the shielding performance, limiting the use of advanced materials to highly irradiated components, and employing low-cost steels for non-plasma facing components have reduced the shield cost, which represented a major cost item in ARIES-II/IV, by a factor of $\sim$ 2 and consequently resulted in $\sim$ 10% decrease in the cost of electricity. This is a significant reduction. The improved shield design was judged to be attractive because of the enhanced neutronics and economics performance. Hence, the ARIES-RS power plant will employ the improved ARIES-II shield to protect the magnets.

TABLE IV

Cost Impact of Allowing Higher Fraction of the Nuclear Heating in the LT Shield

Heating in LT Shield	1%	5%
Neutron Energy Multiplication	1.366	1.31
HT/LT Shield Thickness (cm):		
Inboard	30/32	15/42
Outboard	30/50	15/63
Divertor	60/36	36/57
R (m)	5.52	5.48
a (m)	1.38	1.37
Shield Cost (M$)	164	134
COE (mills/kWeh)	67	66

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