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SHIELDING DESIGN OPTIONS AND IMPACT ON REACTOR SIZE AND COST FOR THE ADVANCED FUEL REACTOR APOLLO

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Abstract

Apollo is a D-^{3}He fueled tokamak reactor which directly converts synchrotron radiation to electricity using rectenna circuits. The low level of neutron production allows for significant reduction in the shield size, particularly on the inboard side. Special emphasis has been placed on the design of the inboard shield since it directly impacts the size of the machine and thus the cost of electricity (COE). Several shield design options were analyzed and the effect of the shield type and thickness on the overall machine size and cost was assessed. Besides shielding performance, the choice between the different materials was governed by some safety-related issues, such as tritium production, decay heat generation, and waste management. The most attractive shield design option is the water cooled SS shield. The economic analysis shows that although the SS shield results in a thicker inboard shield, the COE is slightly lower than that of a machine employing an inboard W shield. This is because the lower shield cost has offset the slightly larger machine cost.

Introduction

The design parameters of Apollo are constantly being revised and the details of the "most-up-to-date" design are presented in Ref. 1. In general, the major and minor radii of the different designs are in the range of 7-8 and 2-3 m, respectively. Apollo produces 1200 MW of net electric power with an overall efficiency of ~40%. Only the synchrotron radiation (which carries ~60% of the energy) is directly converted by rectennas to electricity (at 80% efficiency) and the present design makes no provision for recovering the bremsstrahlung, divertor, or neutron power. A high machine availability of 85% was chosen for Apollo because the solid-state rectenna system is more reliable than thermal cycles with turbines.

In Apollo, the neutron production level is very low (factor of ~50 lower compared to DT reactors). The plasma operates at a ^{3}He:D fuel ratio of 2:1 and the neutron wall loading is constrained to $\leq$ 0.1 MW/m^2. The reduced neutron production results in low radiation damage and thus allows the first wall and structural components to last the entire 30 full power year (FPY) reactor life. In addition, the radioactive inventory in the shield at the end of operation is quite low and the decay heat level is sufficiently low that the reactor is considered inherently safe [2]. These advantages are translated into economic credits, as discussed later, by employing non-nuclear grade components for Apollo.

The goal of this study is to determine the sensitivity of the machine size, cost, and performance to the inboard (i/b) shield type and thickness. The selection of the i/b shield materials is driven by several factors including the radiation level limitations imposed by the magnet design, and some safety-related concerns which restrict the level of tritium generated in the shield. In this regard, the performance of various candidate materials for protecting the toroidal field (TF) magnets was examined. This was followed by an economic evaluation of the shield and the various reactor components in order to make a comparison between the alternative shield designs based on the cost of the reactor as a whole.

Neutronics Analysis

The neutronics performance of the shielding materials was examined using the one-dimensional code ONEDANT [3] with the XSLIB cross section library based on the ENDF/B-V evaluation in 30 neutron and 12 gamma groups, and the P_3-S_8 approximation. The reactor components were modeled as infinite cylinders around the machine axis, permitting the representation of both i/b and o/b shields. The neutron source was taken to be isotropic with an energy distribution in which ~30% of the neutrons are at 14 MeV and ~70% at 2.45 MeV. For an average neutron wall loading of 0.1 MW/m^2, the peaks in the i/b and o/b regions are 0.12 and 0.15 MW/m^2, respectively.

The radiation effects in the magnet must be below certain limits in order to insure the proper performance of the magnet. For instance, the fast neutron fluence (E_n > 0.1 MeV) is limited to 10^{19} n/cm^2 to avoid degradation of the critical properties of the Nb_3Sn superconductor. The end-of-life dose to the polyimide should not exceed 10^{11} rads to insure the mechanical and electrical integrity of the insulator. A limit of 2 mW/cm^3 is imposed on the peak nuclear heating in the winding pack to avoid a high cryogenic load. Preliminary neutronics calculations based on the D-^{3}He neutron source spectrum indicate that, at a wall loading of ~0.1 MW/m^2, the limiting factor for the shield design is the neutron fluence rather than the flux. This is because the reactor operates for extended periods (30 FPY) at a relatively low neutron wall loading.

Very critical to the overall size of the machine is the space between the plasma boundary and the winding pack of the TF coils at the midplane of the inboard side. This space (δ) and its constituents are shown in Fig. 1. The first wall has 1 cm SS and the gap includes the thermal insulation for the magnet. In general, the i/b shield thickness

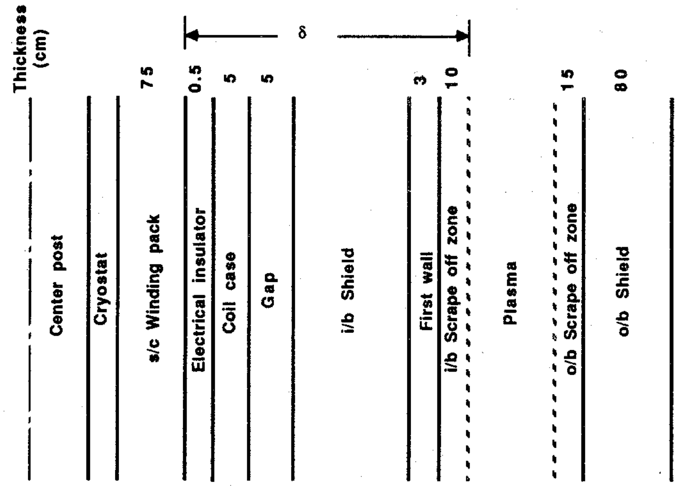

Fig. 1 Schematic of i/b shield and magnet at midplane.

depends on the magnet radiation limits, neutron wall loading, and the effectiveness of the shielding materials. The candidate materials for Apollo are SS, W, boron steel (B-SS), B_4C, and Pb for the shield, and water or borated water (B-H_2O) as a coolant. Our analysis shows that the hydrogen compounds (e.g. H_2O) are superior in slowing down the fast neutrons when combined with SS or W. The boron compounds (like B_4C, B-SS, B-H_2O) significantly improve the performance of the shield. However, the relatively high level of tritium production in the boron raised some safety-related concerns and a decision was made to exclude all borated materials from the shield. The Pb was not found effective in reducing the fluence (which is the shield design driver). Therefore, two shield options remain to be evaluated: the SS/H_2O shield and the W/H_2O shield. Note that at the low neutron level of Apollo, the decay heat problem of W should not cause any concern.

A set of calculations was performed to indicate the optimum content of the water coolant in the W and SS shields. Upon varying the volumetric water content in the shield between 5 and 35%, the fast neutron fluence was found to minimize at 15 v/o and 30 v/o for the W and SS shields, respectively. Replacing the last few centimeters of the shield by a thin layer of H_2O helps reduce the fluence further. The variation of the damage at the magnet with the thickness of the optimized shield is shown in Fig. 2. At least 45 cm of W shield or 56.5 cm of SS shield is needed to satisfy the 10^{19} n/cm^2 fluence limit for the magnet. The corresponding nuclear heating in the winding packs for the two shields are 1.7 and 2.2 kW per meter height of the inner legs of the magnets.

In order to estimate the total nuclear heating deposited in the TF coils, the power rating (in kW/m) has to be integrated over the poloidal length of the coil. It is assumed that enough shielding spaces of at least 60 and 80 cm are provided in the divertor and outboard regions, respectively, in order for the heating to be sufficiently low in the top/bottom parts and outer legs of

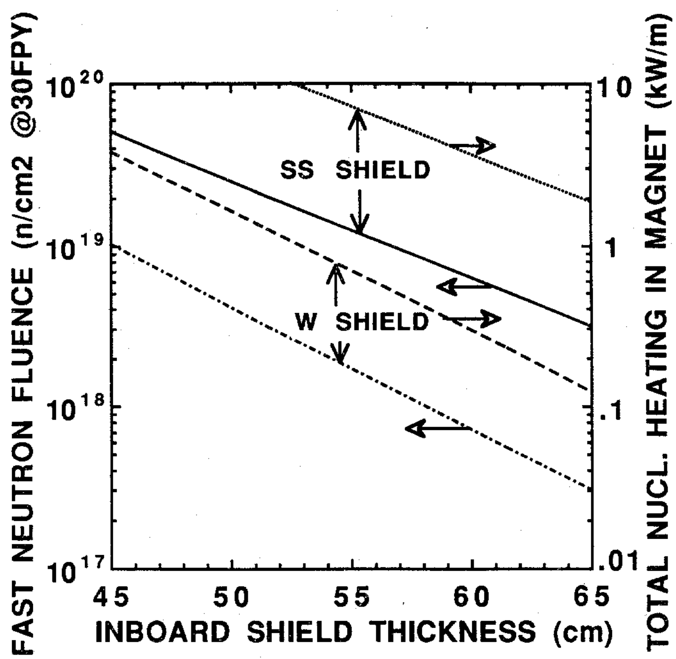

Fig. 2. Variation of radiation effects at the magnet with the inboard shield thickness of two different types of shield.

the magnets. The height of the inner legs is ~10 m and the average wall loading on the inboard side is ~0.08 MW/m^2. It is assumed that the inboard shield follows the plasma boundary and its thickness increases when proceeding from the midplane towards the top and bottom ends. Combining these effects, the total heating in the magnets is estimated to be ~12 and 17 kW for the W and SS shields, respectively. This heat is removed from the magnets by a cryoplant at a power level of 300 W per watt of nuclear heating.

Economic Analysis

The Generomak [4] code was used to perform the costing analysis for Apollo. The details of the code are described in Ref. 4 and we used most of the unit costs contained therein except in specific areas where the code itself and some cost accounting techniques were extensively modified, as discussed later, to reflect the characteristic features of the Apollo design. Because of the safety credits that are attributed to the D-^{3}He system, non-nuclear grade components are partially employed in the design and non-nuclear unit cost estimates were applied to the very low activated components used in Apollo.

The first major modification to the Generomak code was the deletion of the simplified physics module. Instead the required physics parameters which are generated from the physics code DHE3TOK [5] are input to the code. The second major modification regards the issue of energy conversion. The question arises of whether to convert only the synchrotron radiation directly to electricity or to also convert the bremsstrahlung, transport, and neutron energies through a thermal cycle. Therefore, the costing technique of the code

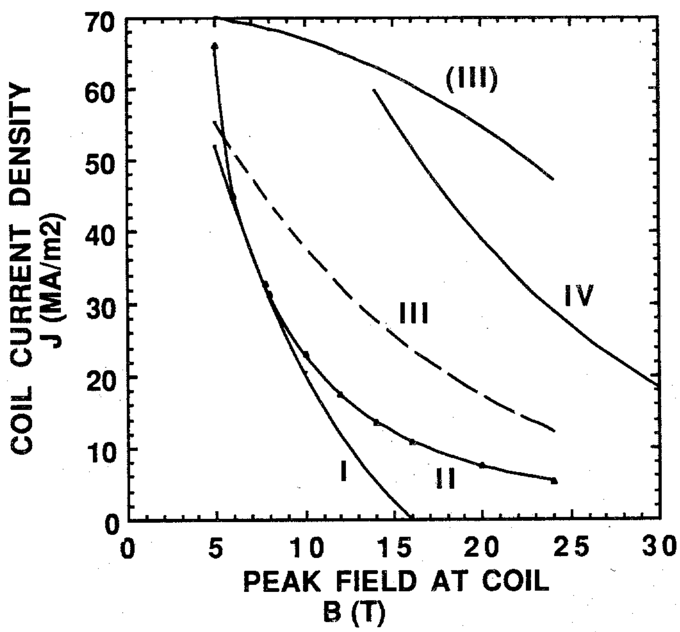

Fig. 3. The winding pack averaged current density as a function of peak field at coil for several scaling laws.

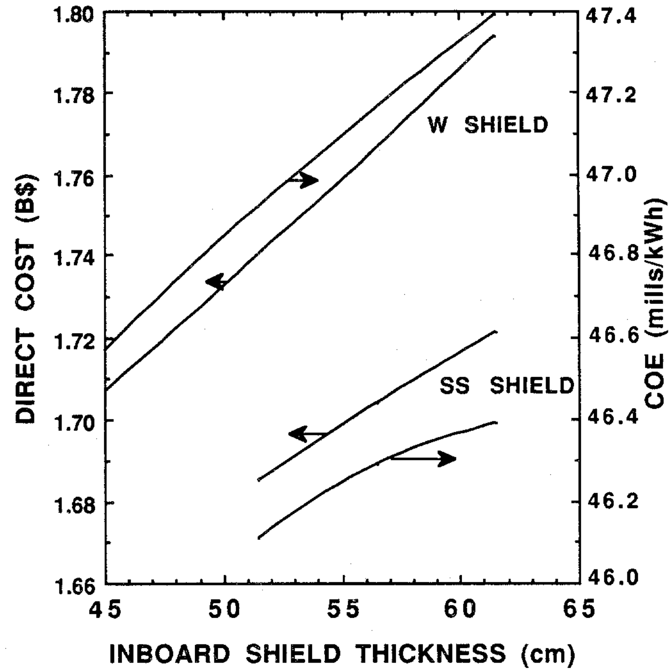

Fig. 4. Comparison of the cost of reactors employing SS and W in the inboard shield.

was modified to allow three energy conversion schemes for the D-^{3}He concept: microwave conversion only at 80% efficiency, full microwave conversion at 80% efficiency and thermal conversion at 40% efficiency, and thermal conversion of all energies at 40% efficiency. Other changes to the code include a new formula for the magnet stored energy and a more realistic expression for the recirculating power in order to include the injected power (which is required to maintain the plasma current) and the cryogenic power (which is proportional to the nuclear heat generated in the magnet). Some of the unit costs were updated. For instance, the auxiliary heating system, ^{3}He fuel, and rectenna circuits are costed at 2.25 \$/W of injected power, 1000 \$/gram of ^{3}He, and 0.27 \$/W of microwave power, respectively.

The Apollo design employs high field (20 T) TF superconductor magnets. In order to keep the magnet cost reasonable, a magnet design with high current density (J) is highly recommended for Apollo. Three magnet design options are available in the Generomak code. The J (averaged over the winding pack) vs. B (peak field) relationship is shown in Fig. 3 for the different options. In option (III), the current density is averaged over the winding pack excluding the SS structure and our estimate would be the dashed curve III if the structure is included. Option III provides the highest current density among the 3 options and we used it in costing the magnet of Apollo presented herein. In more recent studies [1], the latest magnet technology advances [6] known today were used. This is presented as option IV in the figure and this option is now available in the Generomak code. The improvements in J of option IV translate into a significant reduction in the TF magnet cost (factor of ~2) and approximately 5 mills/kWh less in the COE. It should be mentioned that the high beta (~10%) of the Apollo design requires massive secondary coils. In the analysis, the mass ratio of the secondary coils to the primary TF coils is taken as 0.8.

The impact of the i/b shielding material and thickness on the plasma parameters, overall size and cost of Apollo were assessed using the DHE3TOK and Generomak codes. The i/b shield thickness was varied over the range 45-60 cm at an increment of ~ 5 cm. For each shield thickness and type, the nuclear heat load to the TF coils was estimated and the appropriate amount of recirculated cryogenic power was calculated. The key parameters and cost breakdown are given in Table 1 and 2 for the different designs using 1200 MWe net power output, 0.1 MW/m^2 wall loading, 20 T maximum TF coil field, and microwave power conversion only. The unit costs for the SS and W are taken as 20 and 60 \$/kg, respectively. The direct cost and COE of the SS shield design are compared to that of the W shield in Fig. 4. As expected, the decrease in the i/b shield thickness produces a smaller machine and lower cost. As indicated earlier in Fig. 2, 56.5 cm of SS shield and 45 cm of W shield give equivalent attenuation factors and satisfy the 10^{19} n/cm^2 fluence limit for the magnet. Comparing these two cases, the cost difference results primarily from the cost of the shield and magnet. For the W shield machine, the shield is 52 M\$ more expensive because of the higher unit cost of W and the magnet is 36 M\$ less expensive because of the smaller TF magnets. The COE of the SS shield design is slightly lower because the lower shield cost has offset the slightly larger machine cost. On this basis we conclude that there is no clear advantage for using W in the i/b shield of Apollo.

Table 1
Key Parameters and Cost Breakdown for Reactors Employing SS in the Inboard Shield

δ (cm)	75	80	85
Shield Thickness (cm)	51.5	56.5	61.5
R (m)	7.93	8.0	8.06
a (m)	1.98	2.0	2.02
P_F (MW)	2738	2720	2689
P_m (MW)	1651	1648	1641
Cost (M$)			
Shield	52	55	57
Magnet	642	656	668
Other Reactor Components	73	74	75
Reactor Building	206	209	213
Rectenna System	450	448	445
Waveguides	21	21	21
Electric Plant Equipment	74	74	74
Other Reactor Plant Equipment	138	138	139
Miscellaneous	29	29	29
Total Direct Cost	1685	1704	1721
Indirect Cost	505	512	516
Contingency	329	332	336
Overnight Cost	2519	2548	2573
COE (mills/kWh)	46.11	46.29	46.39

Table 2
Key Parameters and Cost Breakdown for Reactors Employing W in the Inboard Shield

δ (cm)	68.5	75	85
Shield Thickness (cm)	45	51.5	61.5
R (m)	7.81	7.91	8.06
a (m)	1.95	1.98	2.02
P_F (MW)	2726	2713	2689
P_m (MW)	1635	1634	1641
Cost (M$)			
Shield	107	113	123
Magnet	620	640	668
Other Reactor Components	76	78	80
Reactor Building	202	207	214
Rectenna System	442	441	445
Waveguides	21	21	21
Electric Plant Equipment	74	74	74
Other Reactor Plant Equipment	136	137	140
Miscellaneous	29	29	29
Total Direct Cost	1707	1740	1794
Indirect Cost	511	522	538
Contingency	333	339	350
Overnight Cost	2551	2601	2682
COE (mills/kWh)	46.57	46.92	47.39

Conclusions

Several shielding materials were examined to assess their ability to protect the magnet of Apollo. The Generomak costing code was used to evaluate the impact of the i/b shield material on the total systems cost. The economic analysis indicates that the SS shield is cost effective and there is no cost benefit for using W in the inboard shield. Because of the safety credits that are attributed to the D-^{3}He concept, Apollo employs non-nuclear grade components and costing method. The highly reliable rectenna systems allow the machine to operate at a relatively high availability of 85%. Based on the Generomak code, the cost of electricity is ~46 mills/kWh which is comparable to that of a similar sized DT reactor.

Acknowledgements

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References

[1] G. L. Kulcinski, et al., "Apollo - An Advanced Fuel Tokamak Reactor Utilizing Direct Conversion," these proceedings.

[2] H. Y. Khater et al., "Activation and Safety Analyses for the D^{3}He Fueled Tokamak Reactor Apollo," these proceedings.

[3] R. D. O'Dell et al., "User's Manual for ONEDANT: A Code Package for One-Dimensional, Diffusion-Accelerated, Neutral Particle Transport," LA-9184-M, Los Alamos National Laboratory (Feb. 1982).

[4] J. G. Delene et al., "Generomak, Fusion Physics, Engineering and Costing Model," Oak Ridge National Lab. Report-ORNL/TM-10728, June 1988.

[5] G. A. Emmert et al., "Physics Issues for the Apollo Advanced Fuel Tokamak," these proceedings.

[6] L. Bromberg et al., "High Field Magnet Designs for the ARIES-I Reactor," these proceedings.