TRADEOFFS BETWEEN IMPROVED PERFORMANCE AND INCREASED COST OF ADVANCED MATERIALS IN COMMERCIAL POWER PLANTS

M. S. Tillack and R. L. Miller
University of California San Diego
La Jolla, CA 92093-0417
(619) 534-7897

C. G. Bathke
Los Alamos National Laboratory
Los Alamos, NM 87545
(505) 667-7214

L. A. El-Guebaly
University of Wisconsin - Madison
1500 Engineering Drive
Madison, WI 53706-1687
(608) 263-1623

and the ARIES Team

ABSTRACT

Advanced structural materials for fusion in-vessel components offer the promise of improved safety and environmental features as well as improved engineering performance, as characterized by high thermal conversion efficiency and high power density limits. However, the cost of advanced materials is expected to be much higher than that of more conventional steel-based alloys. Therefore, the economic advantage is limited. In this study, we compare a high-performance vanadium-based power plant and a lower-performance ferritic steel plant. Self-consistency is maintained through the use of the ARIES systems code. The tradeoffs include the effect of coolant outlet temperature on thermal conversion efficiency, power density limitations, component lifetime and availability. Ideally, comparisons should be made between fully-detailed design concepts. However, a rough systems-level analysis allows identification of the relative magnitude of the economic advantages expected from "high performance" materials.

I. INTRODUCTION

In-vessel components constitute a significant fraction of the total cost of a fusion power plant (~10%). The cost of fabricated steel structures is anticipated to be approximately one fourth that of vanadium structures or one fifth that of SiC structures (see Section III.B for more details on material costs). Power plants employing steel components operating at relatively lower temperature and thermal efficiency might, therefore, be economically competitive with power plants employing V or SiC structures operating at higher temperature and thermal efficiency. In this work, the trade-offs between ferritic steel and vanadium-based power plants are examined to help understand under which conditions advanced materials offer significant improvements to the cost of electricity.

Safety and environmental advantages of advanced materials were not factors in this assessment. Equal level of safety assurance ratings (LSA=2) were assumed for all concepts. Safety credits and other safety-related constraints which might affect the comparison were not treated explicitly. All of the designs considered herein can meet at least the minimum requirements for commercial fusion power plants, as established in the Starlite Study.[1]

The ARIES-II Li/V blanket design[2] is the basis for this comparison, and was modified to reduce the cost by limiting the use of vanadium to those regions where it is necessary[3]. For the reference vanadium case, an outlet temperature of 610°C and a thermal conversion efficiency of 46% were assumed. Higher efficiencies have been postulated using advanced Rankine[4] or even Brayton gas turbine cycles[5]. A value of 46% is defensible.

The ferritic steel (FS) plant designs were obtained using the same major device characteristics as the ARIES-II plant, except with steel used to replace all of the vanadium structure and shielding material. Various assumed thermal efficiencies between 25% and 50% were explored. A thermal efficiency of 35–40% might be obtained with an optimized helium-cooled system, whereas a lower efficiency of 30–35% corresponds more closely to a water cooled Li_2O/SS system.

Neutron and surface wall loading constraints are important factors, since cost optimization tends to push lower-efficiency designs to higher power density. A lower power density in steel designs is enforced by limiting the peak neutron wall loading to ≤ 4 MW/m^2 and the first-wall surface heat flux to ≤ 0.5 MW/m^2. These are aggressive goals for FS materials.

II. DESIGN BASIS

A. Main Design Features

These assessments were performed on a "systems level" using the ARIES System Code (ASC)[2]. To provide a common basis for comparison, the ARIES-II design concept was adopted (see Figure 1). ARIES-II is a second-stability tokamak with a radiative divertor and "close-in" cryostat (wrapping around the outboard TF coil legs).

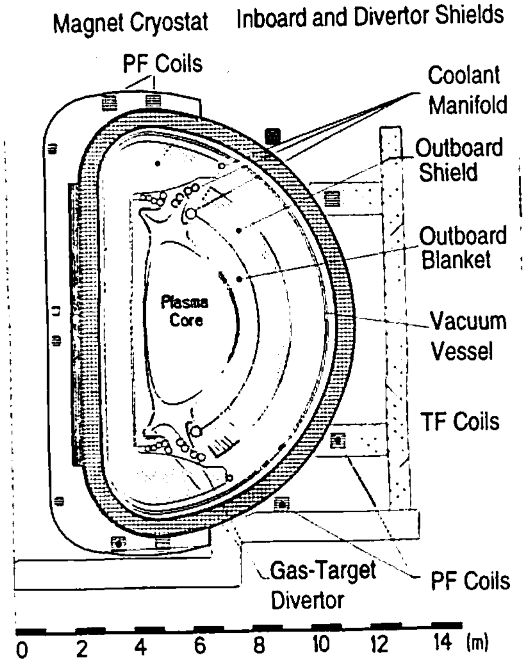

Figure 1. ARIES-II fusion power core elevation view

All design variants are required to provide a net electric output of 1000 MWe. The effect of **reduced efficiency** is to increase the size of both in-vessel and ancillary systems in order to produce the additional thermal power to reach 1000 MWe. Reduced **power density** mainly affects the size of the in-vessel components and coils. The system optimization also maintained a fixed aspect ratio A=4, plasma β=3.4% and peak allowable field at the TF coil ≤16 T.

Taking advantage of the low neutron flux in the shield, the original ARIES-II design was adjusted by replacing the 15% V structure in the outer layers of the shield by steel. By making this change, the cost of the vanadium in the shield (which represents a major cost item) has been reduced substantially as compared with earlier designs. The structures in the first wall, blanket and reflector are still made entirely of vanadium. The presence of steel in the shield is not expected to prevent the plant from meeting the Class C waste disposal or safety requirements.

To simulate a steel design in the ASC, the V structure simply was replaced with FS. The U.S. has not developed a serious power plant design using ferritic steel in many years (since STARFIRE[6]). Recent work in Europe[7,8] was consulted to determine the appropriate range of thermal conversion efficiencies to use. It is true that there will be many differences between the FS and V designs in terms of radial dimensions, energy multiplication, pumping power, power conversion system, LSA rating, etc., but these differences (which are both positive and negative effects) were not factored into this analysis.

B. Power Density and Fluence Limits

The lower power density of steel has been enforced by limiting the peak neutron wall loading to ≤4 MW/m^2. This limitation is design-dependent, and is based on engineering judgement. Perhaps more importantly, first-wall surface heat flux is constrained to ≤0.5 MW/m^2. Simple first-wall heat transfer calculations are sufficient to determine these limits.[9] Based on the ARIES-II reference design, peaking factors on the wall loading and surface heat flux of 1.75 and 1.2 were used, respectively. The surface heat flux peaking factor assumes peaking of only the bremstrahlung heat flux (edge plasma heat loads on the FW and divertor are still highly uncertain). For vanadium, engineering limits on power density are not reached in the reference design.

The end-of-life first-wall fluence used for the comparison is 15 MW-y/m^2 for both FS and V. This is based on a 200 dpa limit. These values are highly uncertain, given the absence of high-fluence data. In addition, they are likely to be dependent on the operating conditions, such as stress levels. At this time, there is insufficient data to defend different lifetimes for FS and V-alloy. Given a fixed fluence lifetime, the component operating life depends only on the wall loading and availability. Operating lifetime affects the replacement cost and also the availability (less frequent replacement lowers the annual replacement cost and increases the expected availability).

C. Thermal Efficiency

The gross thermal conversion efficiency used here is the ratio of the gross electric power divided by the total useful thermal power generated in the fusion power core. It does not include plant recirculating power factors. The key operating parameters which determine the maximum achievable gross efficiency are the maximum allowed material design temperatures and stresses. Lower efficiencies for FS result from both lower temperature limits and lower thermal stress factors.

For the coolant options under consideration, the V/Li self-cooled design utilizes an intermediate heat exchanger for the control of tritium leakage, and is coupled to a Rankine cycle power conversion system. Efficiencies as high as 49% have been predicted[4], but a more conservative value of 46% is adopted here assuming a lithium coolant outlet temperature of 610°C. For the helium-cooled option, a similar gross thermal efficiency can be reached with the Rankine cycle. Even though a secondary loop is not required, the maximum Rankine cycle efficiency is controlled by the thermodynamic properties of the steam side.

The helium-cooled design also has the option to use a Direct Cycle Gas Turbine (DCGT). With a recuperator effectiveness of 96%, a Brayton cycle operating at high helium pressure (>12 MPa) can reach a gross efficiency of 46%. This efficiency is again limited by the maximum allowable temperature of V-alloy.

For the FS designs, the thermal conversion efficiency was varied parametrically to determine the minimum goals for COE to be comparable with V systems. It is very important to consider the loss of useful thermal power in a FS divertor. The divertor power accounts for up to 25% of the heat removed from the power core, including neutron, thermal radiation, and transport power. High-heat-flux components using steel are likely to be constrained to operate with low coolant temperature, thus reducing the gross thermal efficiency of the plant substantially.

D. Availability and Component Lifetime

Operation at lower power density results in slower neutron damage accumulation, thus extending the operating life of components. Assuming the time to repair and replace components is not changed, this leads to higher availability. The cost of electricity (COE) is inversely proportional to the plant availability factor, which is expected to be dominated by the planned outages for regular in-vessel component replacement. Therefore, one expects a lower power density system to benefit with a higher COE.

A second, but more subtle effect on availability results from the fact that systems pushed to higher power density are likely to suffer from higher failure rates. This effect has been ignored in this analysis, as it is difficult at this time to quantify such an effect.

III. ECONOMIC REQUIREMENTS & ASSUMPTIONS

A. Economic Requirements

One of the most important requirements for a power plant is to be cost-competitive with alternative energy sources. In 1992 dollars, a goal of 65 mill/kWeh and requirement of 80 mill/kWeh has been established[1]. The projected COE includes a dominant contribution from the initial capital cost, levelized and annualized using standard financial assumptions[10], as well as contributions to the operation and maintenance (O&M) cost reflecting the scheduled changeout of first-wall and blanket components as fluence lifetimes are reached. Comparisons of life-cycle costs projected for various alternatives, together with environmental and safety characteristics, will continue to be a major determinant of the market penetration and commercial success of the fusion option.

B. Cost of Materials

This analysis is based on the unit cost of the V-alloy structure at $300/kg, ferritic steel structure (MHT-9) at $68/kg, and tenelon filler at $25/kg in constant 1992 dollars. The achievable cost of fabricated structures is still a subject of debate. The complexity of the structures, tolerances and inspection quality can have a large impact.

V-alloy is a relatively new advanced structural alloy. To date, there have not been major industrial applications to support its development. The three basic costing elements for a fusion structural material (production cost of different product forms, fabrication cost, and installation) are still to be developed for V-alloy. Therefore, there is no statistical information available to project a reliable unit cost. Only a rough estimate on the lower and upper bounds of the unit cost can be made.

Based on the application of advanced structural materials for fusion devices, the product form cost will amount to about 30% of the unit cost of the final component, including labor. Taking the 1995 cost of advanced Ni-based structural materials as a starting point, the product form cost is about $100/kg. If this is assumed to be the same for V-alloy, then the lower bound unit cost can be assumed to be about $300/kg.

A recently placed DIII-D contract for the V-4Cr-4Ti alloy material necessary for the upper divertor in the Radiative Divertor Program (RDP) shows a finished V-alloy component cost of about $600/kg. For a power plant, this unit cost is expected to be lower due to increased experience far into the future.

IV. RESULTS

The results reported here were obtained using the ASC.[2] Numerical fits to detailed equilibrium and stability calculations unique to each stability regime are used to provide normalized beta, β_N, scalings. These calculations optimize both β and the fraction of the plasma current sustained by the pressure-gradient-driven bootstrap effect, f_{BC}. Detailed equilibrium and ray-tracing calculations are used to determine the normalized current-drive efficiency for each stability regime. RF current drive is used for the designs described herein.

Central to the ASC is a zero-dimensional, steady-state plasma-power-balance model[11] that includes separate ion and electron energy balance; particle continuity; a specified impurity fraction; charge balance; and a β constraint. Constant-tension, D-shaped TF coils that provide sufficient room for horizontal maintenance of the blanket are used in all designs. For the designs herein, the superconductor is Nb_3Sn, and is limited to $B_{TF} \leq 16$ T.

The ASC costing algorithm allows for a detailed cost breakdown to four levels. The cost scalings used are consistent with U.S. fission nuclear-reactor experience[12]. Credits for appropriate Levels of Safety Assurance (LSA)[13] are included.

Table 1 lists the major device parameters adopted from ARIES-II. The COE for the modified V system (with steel used in the shield) is 3 mill/kWeh less than the previous reference case (with vanadium structure throughout).

TABLE 1
MODIFIED ARIES-II MAJOR PARAMETERS

Net Electric Power (MW)	1000
Useful Thermal Power (MW)	2570
Gross Thermal Efficiency	46%
R (m)	5.60
Peak/Average Wall Load (MW/m^2)	5.1/2.9
Peak/Average FW Heat Flux (MW/m^2)	0.37/0.31
On-axis Toroidal Field, B_T(T)	8.0
Field at TF Coil (T)	15.9
Fusion Power Density (MW/m^3)	4.8
FW/B/R Cost (M\$)	54
V.V. Cost (M\$)	51
Shield Cost (M\$)	256
Total Direct Capital Cost (M\$)	2048
FW/B/R Replacement Cost (mill/kWeh)	4.0
Net COE (mill/kWeh)	**71**

Tables 2 and 3 summarize the economic results for the FS cases. In the case with unconstrained wall loading, the COE is already competitive with the V plant at a very reasonable efficiency of 35%. However, in order to account for the lower conversion efficiency, the code has optimized by increasing the peak power density to over 5 MW/m^2 (and peak surface heating to nearly 0.5 MW/m^2).

The effect of imposing a wall-loading constraint on the FS designs is to increase the size by 25-30% and the COE by 6.2–7.7%, as shown in Table 3. Comparing all designs at a common LSA=2 rating, a wall-loading constrained steel design must attain a 39% thermal conversion efficiency to have a COE comparable to that for the modified V design, as shown in Figure 2.

TABLE 2
UNCONSTRAINED WALL LOADING COMPARISON

	η=0.25	0.30	0.35	0.40
R (m)	6.52	6.24	6.00	5.8
Peak Wall Load (MW/m^2)	7.7	6.9	6.2	5.7
Peak FW heat flux (MW/m^2)	0.57	0.50	0.46	0.42
On-axis toroidal field, B_T(T)	8.5	8.4	8.2	8.1
Field at TF coil, $B_{T,c}$ (T)	16.0	15.9	15.9	16.0
Fusion power density				
P_f/V_p (MW/m^3)	6.2	5.8	5.4	5.2
FW/B/R Cost (M\$)	26	24	22	21
Shield Cost (M\$)	261	242	226	214
V.V. Cost (M\$)	69	64	59	55
Direct Capital Cost (M\$)	2398	2206	2067	1975
Electricity Cost (mill/kWeh):				
FW/B/R Replacement Cost	3.78	3.0	2.5	2.1
Net COE (LSA=2)	**81**	**74**	**70**	**67**

TABLE 3
CONSTRAINED WALL LOADING COMPARISON

	η=0.25	0.30	0.35	0.40
R (m)	9.08	8.16	7.48	6.96
Peak Wall Load (MW/m^2)	4.0	4.0	4.0	4.0
Peak FW heat flux (MW/m^2)	0.29	0.30	0.30	0.30
On-axis toroidal field, B_T(T)	6.6	6.8	7.0	7.1
Field at TF coil, $B_{T,c}$ (T)	11.2	11.9	12.5	13.0
Fusion power density				
P_f/V_p (MW/m^3)	2.3	2.6	2.8	3.0
FW/B/R Cost (M\$)	43	37	32	28
Shield Cost (M\$)	443	377	326	289
V.V. Cost (M\$)	132	107	90	78
Direct Capital Cost (M\$)	2718	2431	2235	2098
Electricity Cost (mill/kWeh):				
FW/B/R Replacement Cost	2.9	2.4	2.1	1.9
Net COE (LSA=2)	**89**	**80**	**74**	**70**

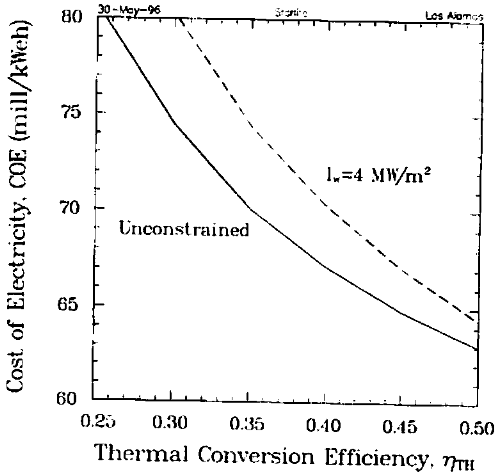

Figure 2. Effect of gross thermal efficiency on COE for a ferritic steel power plant.

The cases examined above have assumed a fixed plant factor (76%), which also implies a fixed availability. Clearly, the availability will depend on some of the parameters which were varied. Availability depends on planned outages, which are due in part to replacement of components at the end of their useful life, as well as unplanned (or "forced") outages. Forced outages are caused by unanticipated failures. Data on failure probabilities are not generally known for fusion components.

If we consider only scheduled outages due to in-vessel component replacement, then the availability will depend inversely on the power density:

$$A_{so} = \frac{1}{1 + t_r I_w / L}$$

where t_r is the time to replace, I_w is the peak wall loading, and L is the fluence lifetime. Higher power densities lead to shorter operating life and thus lower availability. Comparing the FS cases limited to 4 MW/m^2 peak wall loading with the reference case at 5.1 MW/m^2, and assuming in-vessel components can be replaced within 4 weeks, the 20% change in peak wall loading amounts to only a 0.5% change in availability, or less than 0.5 mill/kWeh.

From the tables above, differences in the blanket replacement cost account for an additional 2 mill/kWeh savings for the FS cases. The replacement cost is a significantly more important factor than the impact on availability.

V. DISCUSSION AND CONCLUSIONS

The full range of cases examined here have a net COE between 70–80 mill/kWeh. This is a significant, but not definitive difference. In the modified ARIES-II design, the fusion power core cost does not dominate the COE; therefore savings obtained by further minor adjustments are not expected to save more than a few mill/kWeh.

The lower efficiency of a ferritic steel plant results in a larger tokamak and larger plant equipment (at fixed net electric output). The reactor plant equipment for the wall load constrained, 35% efficiency steel plant is $356M more than the improved ARIES-II case (sum of direct and indirect costs). The first wall and blanket are actually cheaper for the steel case, but the remainder of the plant equipment is more expensive.

Comparing all designs at a common Level of Safety Assurance rating, LSA=2, a 34% gross thermal efficiency (ratio of gross electric to total thermal power) is required for the unconstrained wall-loading steel design to be comparable in cost to the improved V design. For a wall-loading constrained steel design, a 39% thermal efficiency is required to obtain a COE comparable to that for the improved V design. If the ferritic steel system is unable to meet the LSA=2 rating, the difference between the COE of the FS and V systems will become larger.

ACKNOWLEDGEMENTS

This work was supported by the US Department of Energy under contract DE-AC03-95ER-54299.

REFERENCES

1. L. M. Waganer, et al., "What Must Demo Do?," 16th IEEE Symposium on Fusion Engineering, Sept 30.-Oct. 5, 1995.
2. F. Najmabadi, R. W. Conn, and the ARIES Team, "The ARIES-II and ARIES-IV Second Stability Reactors," Fusion Tech. 21 (1992) 1721-1728.
3. L. A. El-Guebaly and C. G. Bathke, "Cost-Effective Shield Designs for Environmentally Attractive Fusion Power Plants," these proceedings.
4. M. Z. Hasan, et al., "Thermal Cycle Power Conversion for the ARIES-I Tokamak Reactor," IEEE 13th Symposium on Fusion Engineering, Knoxville TN, October 1989.
5. C.P.C. Wong, et al., "Evaluation of U.S. Demo-I Helium-cooled Blanket Options," IEEE 16th Symposium on Fusion Engineering, Champaign IL, Oct. 1995.
6. C. C. Baker, M. A. Abdou, et al., "STARFIRE - A Commercial Tokamak Fusion Power Plant Study," ANL/FPP-80-1, Sept. 1980.
7. M. Dalle Donne, L. Anzidei, H. Kwast, F. Moons and E. Proust, "Status of EC Solid Breeder-blanket Designs and R&D for DEMO Fusion Reactors," Fus. Eng. Des. 27 (1995) 319-336.
8. L. Giancarli, G. Benamati, S. Malang, A. Perujo, E. Proust and J. Reimann, "Overview of EU Activities on DEMO Liquid Metal Breeder Blankets," Fus. Eng. Des. 27 (1995) 337-352.
9. X. R. Wang, D. K. Sze, M. S. Tillack, and C. P. C. Wong, "Heat Flux Limits on the Plasma-Facing Components of a Commercial Fusion Power Plant," 16th Symposium on Fusion Engineering, Champaign IL, Oct. 1995.
10. R. L. Miller, "Fusion Power Plant Economics," these proceedings.
11. K. A. Werley, "Reversed Field Pinch Ignition Requirements," Nuclear Fusion 31 576 (1991).
12. J. G. Delene et al., "Nuclear Energy Cost Data Base," US DOE report DOE/NE-0095 (1988).
13. J. P. Holdren et al., "Report of the Senior Committee on Environmental, Safety, and Economic Prospects of Fusion Reactors," LLNL report UCRL-53766 (1989).