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HELIUM-COOLED, FLiBe-BREEDER, BERYLLIUM-MULTIPLIER BLANKET FOR MINIMARS

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ABSTRACT

We adapted the helium-cooled, FLiBe-breeder blanket to the commercial tandem-mirror fusion-reactor design, MINIMARS. Vanadium was used to achieve high performance from the high-energy-release neutron-capture reactions and from the high-temperature operation permitted by the refractory property of the material, which increases the conversion efficiency and decreases the helium-pumping power. Although this blanket had the highest performance among the MINIMARS blankets designs, measured by $M\eta_{th}$ (blanket energy multiplication times thermal conversion efficiency), it had a cost of electricity (COE) 18% higher than the University of Wisconsin (UW) blanket design (42.5 vs 35.9 mills/kW·h). This increased cost was due to using higher-cost blanket materials (beryllium and vanadium) and a thicker blanket, which resulted in higher-cost central-cell magnets and the need for more blanket materials. Apparently, the high efficiency does not substantially affect the COE. Therefore, in the future, we recommend lowering the helium temperature so that ferritic steel can be used. This will result in a lower-cost blanket, which may compensate for the lower performance resulting from lower efficiency.

INTRODUCTION

The helium-cooled, FLiBe-breeder blanket formed the basis for the Princeton reference design[1]—the first, large, multidisciplinary fusion-reactor design study. With this design, tritium breeding was submarginal, but adding beryllium corrects this problem. A large amount of beryllium in a zone of pebbles 0.5 m thick results in such a good breeder that this idea formed the basis for the fusion-breeder design described in Ref. 2. One fusion-breeder plant using this blanket design can produce 1 GW_e of electricity and enough fissile material (6 tonnes/y) to fuel fifteen 1-GW_e light-water reactors. The electric power-plant version of this fusion reactor was proposed to the Blanket Comparison and Selection Study (BCSS)[3] for evaluation on a common basis with other designs. The BCSS design is documented in a series of articles in Ref. 4. An adaptation of the BCSS blanket design for use in MINIMARS[5] is shown in Figs. 1 and 2.

Our goals for the MINIMARS design are (1) to achieve a low COE through high performance that results from high-temperature operation and from a large value of blanket energy multiplication and (2) to design passive afterheat-removal methods that use lower-cost non-nuclear grade material for the balance of plant. We use vanadium to achieve high performance through a high-energy release from neutron-capture reactions. Employing vanadium as a structural material also permits higher temperature operation, which both increases the conversion efficiency and decreases the helium-pumping power. For this Lawrence Livermore National Laboratory (LLNL) blanket, the product $M\eta_{th}$ (M is the energy released in the blanket per incident 14-MeV neutron divided by 14 MeV, and η_{th} is the thermal conversion efficiency) is 0.80 compared with 0.61 for the reference UW blanket design. Although the LLNL blanket had the highest performance measured by $M\eta_{th}$, it resulted in a COE 18% higher than the UW design (42.5 vs 35.9 mills/kW·h). This increased cost was the product of using higher-cost blanket materials (beryllium and vanadium) and of using a thicker blanket, which resulted in higher-cost central-cell magnets. O

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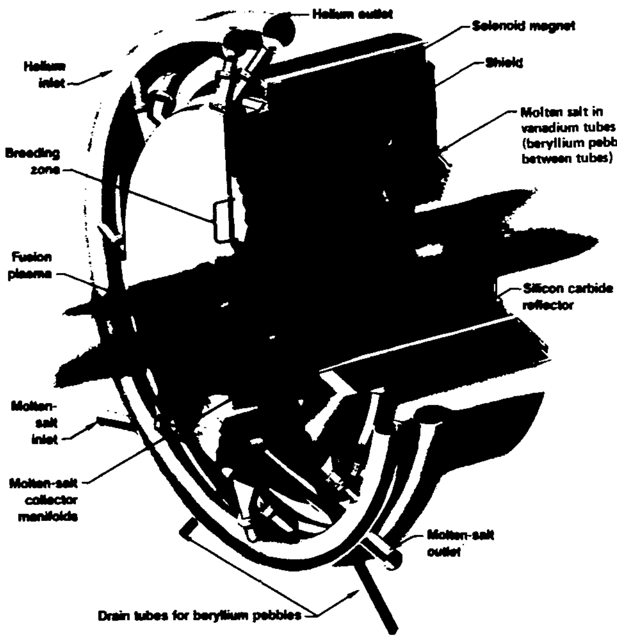

Fig. 1. One module of a helium-cooled molten-salt blanket. Helium under 8-MPa pressure flows from the inlet ring header to the apex of each pod, then radially outward through the blanket to the outlet ring header, and then to heat exchangers to generate electricity.

conclusion from the economic analysis (discussed in more detail later) is that the high performance allowed by the use of a thick beryllium zone and vanadium is not cost effective by a margin of 18% when electricity is the only product for sale.

The blanket parameters are summarized in Table 1. For this blanket, the design stress was initially taken to be 240 MPa for vanadium and later was reduced to 160 MPa. The costs were based on the higher stress. To accommodate this design change, the first wall is 0.75 cm thick rather than 0.5 cm, and the structure volume fraction is 6% rather than the assumed 5%. That is, if 1% of the volume is in the form of vanadium tubes, then 5% would give 160-MPa average stress (i.e., 80 atm = 8 MPa; 8 MPa/0.05 = 160 MPa). The amount of vanadium used should be increased by 20%; this should have a relatively small effect on the COE.

The volume fractions of the blanket are given in Table 2 for the higher stress. We assumed a unit cost of 250$/kg for vanadium, 440$/kg for beryllium, 37$/kg for FLiBe, and 78$/kg for SiC. Assuming that the first wall begins at 0.6-m radius, the volume and cost per meter of length for each material was: 0.49 m^3 and $0.85 million for vanadium, 1.45 m^3 and $1.17 million for beryllium, 0.31 m^3 and $0.022 million for FLiBe, 1.36 m^3 and $0.22 million for SiC. We have estimated the cost of beryllium to be 350$/kg, but we use the consensus value from the BCSS of 440$/kg.

NUCLEAR DESIGN AND ANALYSIS

The initial nuclear design and analysis of this blanket was done at LLNL while the final analysis[4] was done at UW using the ONEDANT[6] code with MATXS5[7] data. The Be thickness used (23 cm at full density) was taken to be a reasonable compromise between maximizing neutron multiplication and minimizing Be zone and overall blanket thicknesses, but no cost minimization was done specific to MINIMARS. The desired tritium breeding of 1.05 is obtained by varying the amount of natural FLiBe (2.5% in this case). The excess neutrons produced by Be (n, 2n)

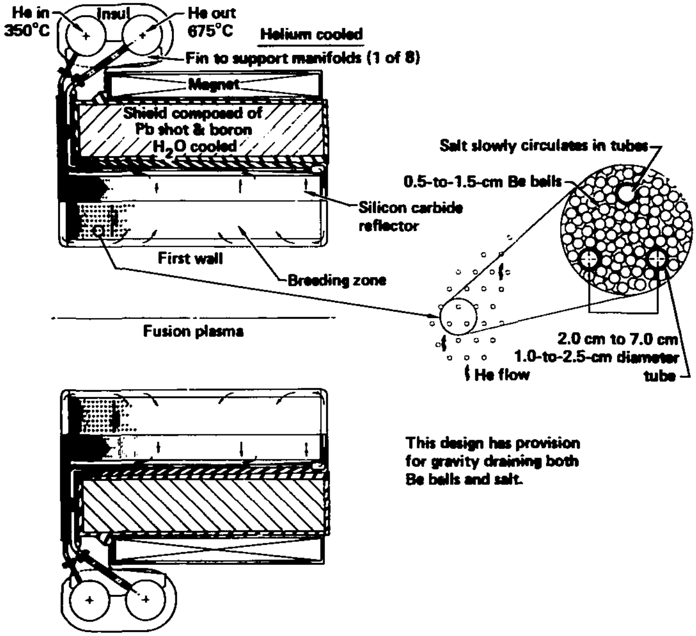

Fig. 2. Cross section along the axis of one segment of a helium-cooled molten-salt blanket, showing arrangement of helium flow and of beryllium spheres and tubing for the molten salts. Vanadium was chosen as the structural material for high temperature and for large neutron-capture energy release, but, for lower performance and lower cost, ferritic steel could be used.

reactions are captured in V to give this blanket its high M of 1.80.

ANALYSIS OF ECONOMIC PERFORMANCE

The COE was 42.5 mills/kW·h for the LLNL blanket, which was 18.4% more than the COE for the UW blanket. This increase is primarily due to two factors: the higher plant cost and the higher component replacement cost, both resulting from the use of large amounts of expensive beryllium and to a lesser degree expensive vanadium. For the LLNL plant, the direct capital cost is $997 million, $90 million or 9.8% more than the cost of the UW plant. The LLNL blanket, costing $133 million, is $112 million more than the UW blanket and accounts for most of the increased plant cost. Thus, the increased blanket cost accounted for half the increase in COE. The LLNL case has a scheduled component-replacement cost of $28.7 million/y, which is 97% more than for the UW case; a single, automated, hot repressing may be all that is needed to reuse the beryllium at a lower cost, and, therefore, reduce this component-replacement cost. A beryllium recycle cost of 200$/kg is used here; however, we have estimated that beryllium pebbles can be recycled for 75$/kg (see Ref. 2, p. 470). The blanket cost consists of ~52% for beryllium and ~38% for vanadium. If the amount or the cost of beryllium and vanadium were cut in half, the COE would drop by 10%.

Vanadium allows a helium-coolant temperature of 675°C. Apparently, this high efficiency does not substantially affect the COE. By lowering the helium temperature, ferritic steel can be used with a lower blanket cost, which may compensate for the lower performance resulting from lower efficiency. Furthermore, the beryllium zone thickness may be too large. Another way to reduce blanket cost is to increase the first-wall radius. There are fewer cubic meters by 20% of blanket-per-wall area at $r_{1st\ wall}$

= 1.2 m, when compared with 0.6 m. If we increase the fusion power and hence the total power, the blanket becomes proportionately less costly and, similarly, higher M blankets become relatively more economical.

In conclusion, we found that the high-temperature operation permitted by the use of vanadium and the high blanket-energy multiplication permitted by the use of a thick beryllium zone were not cost effective when compared with the UW blanket. We speculate that optimized designs using less or no vanadium and less beryllium with larger electric power output would produce a lower COE, but these design changes may not result in a COE that is lower than the COE for an optimized UW blanket.

Table 1. Blanket parameters.

$T_{He\ out}$ (°C)	675
$T_{He\ in}$ (°C)	350
$T_{Vanadium\ max}$ (°C)	725
$T_{Vanadium\ first\ wall}$ (°C)	<400
First-wall design stress	
0.5 cm thick (MPa)	240
0.75 cm thick (MPa)	160
Tritium barrier and corrosion inhibitor	
Tungsten barrier on i.d. of tubes (μm)	10
Tungsten barrier on steam-generator tubes (μm)	10
Aluminum on low-temperature section of tubes (mm)	1
First wall (structure and tubes)	Vanadium
Neutron multiplier	Be pebbles
Tritium breeder	FLiBe-in-tubes
Tritium breeding ratio	1.05
Coolant	Helium
M	1.8
η_{th}	0.447
$M\eta_{th}$	0.80
P_{fusion} (MW)	989
$P_{electric}$ (MW)	600
Γ (MW/m^2)	4.05
$L_{central\ cell}$ (m)	62.1
COE (mills/kW·h)	42.5

Table 2. Radial build for neutronics calculations.

Zone	Thickness (cm)	Material (vol fraction %)
First wall Manifold	15	V (6)
Inner blanket	50	V (5) FLiBe[a] 2.5 Be (98% dense) (47)
Outer blanket	20	V (5) SiC (80)
Manifold Back wall	15	V (15)

[a]FLiBe (47 mol% Li(nat)F + 53 mol% BeF_2).

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