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ABSTRACT

A self-consistent procedure has been established for economic design optimization of the lithium-lead (LiPb) blanket for the MARS tandem mirror reactor. The procedure is necessarily iterative and enables progress in blanket design to be assessed in terms of the minimization of an economic figure of merit F for the complete reactor system. Typical economic design questions regarding blanket and central cell parameters such as tritium breeding ratio, neutron energy multiplication factor, thermal cycle efficiency, blanket radial thickness, magnet radii, etc., can then be addressed in terms of their influence on overall system costs. This procedure is not necessarily specific to MARS and has general applicability to fusion reactor blanket design optimization. Application of the procedure resulted in a blanket with small (~ 38 cm) radial thickness, highly enriched (90%) lithium, adequate tritium breeding ratio (1.14) and a neutron energy multiplication and thermal efficiency approaching those for blankets of considerably larger radial dimensions.

INTRODUCTION

The Mirror Advanced Reactor Study(1) (MARS) is a major conceptual design study of a commercial tandem mirror fusion reactor. MARS has evolved from an original 3500 MW fusion power, 1700 MW electric device, to the current baseline (March 1983) of a 2574 MW, 1200 MW_e, device. This analysis will be for the original 1700 MW_e case although the principles are completely general. Thermal power production and tritium breeding in MARS take place in a cylindrical central cell region of 150 m length which is divided into 84 blanket modules. In addition to electric conversion of the blanket thermal power, a significant fraction (~ 26%) of the total electrical output of the reactor is provided by the plasma direct convertors located at each end of the device.

A cross-section through the MARS blanket and central cell is shown in Fig. 1. The blanket comprises the flowing liquid metal eutectic $Li_{17}Pb_{83}$, performing a dual breeder/coolant role, contained in HT-9 ferritic steel structure. A water-cooled reflector composed of Fe-1422 surrounds the blanket. The reflector is, in turn, surrounded by a separate water-cooled shield for protection of the central cell superconducting magnets. It should be noted here that the coolant water from the reflector contributes to the overall thermal cycle as subsidiary feed-water heating to the main LiPb stream. Depending on the blanket design parameters, a relatively large fraction of the total recoverable energy is deposited in the reflector, thus the overall energy multiplication is sensitive to the choice of reflector material and its radial thickness.

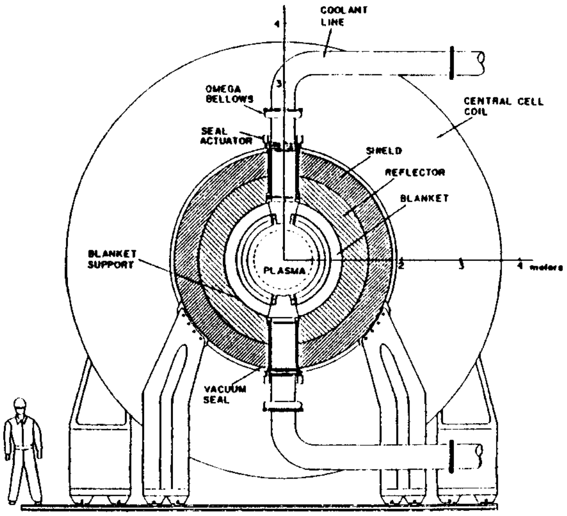

Fig. 1. Cross Section of the MARS Central Cell.

Under the original terms of reference of the MARS study, the blanket was required to be simple in concept, easy to fabricate and provide for convenient maintenance. However, given these initial constraints, the following important question was posed: "For a fixed fusion power and, therefore, for a fixed incident neutron power, how should the structural and neutronic design of the blanket proceed so that its economic performance can be optimized?" Clearly, examination of possible optimization procedures leads to associated performance questions such as: What tritium breeding ratio (T) should be required? What is the maximum neutron energy multiplication (M) attainable for this value of T? Should we design a thick blanket in order to maximize M or should we design a thin blanket in order to minimize blanket and superconducting magnet costs? Would a thin blanket with corresponding thick radiation shield be more economic than a thick blanket with corresponding thin radiation shield? Would a thinner blanket result in a larger energy deposition in the reflector/shield with associated economic penalty in the thermal cycle efficiency? What maximum fraction of the total neutron energy should be permitted to be deposited in the reflector and shield? Etc.

Ideally, the above design optimization questions would be answered by a formal reactor systems cost code. However, although such cost codes are in regular use for tokamak reactors,(2,3) at the outset of the MARS study there existed no convenient code for tandem mirror devices. Accordingly, a blanket design optimization procedure was established such that progress in the evolving engineering design of the MARS LiPb blanket could be assessed in terms of improving economic performance. As will be seen in the following sections this procedure is necessarily iterative and requires the minimization of an economic figure of merit F for the overall reactor system.

DESIGN OPTIMIZATION PROCEDURE

The following procedure was adopted for design optimization and coded accordingly:

1. Establish a self-consistent economic figure of merit F for blanket design optimization (see below).
2. Specify the desired tritium breeding ratio (T) for the blanket system.
3. Establish a blanket and reflector point design by specifying dimensions, volume fractions of the constituents (LiPb/HT-9 for the blanket and Fe-1422/H_2O for the reflector) and percentage enrichment of ^{6}Li in the LiPb.
4. Perform neutronic analyses on this point design to obtain the neutron energy multiplication M and fractional energy deposition in the reflector for the constant tritium breeding ratio T.
5. Determine gross thermal efficiency η and LiPb pumping power for the thermal hydraulic (energy conversion) system.
6. Determine neutron/gamma design constraints for the central cell superconducting magnets and required external radioactivity conditions at shutdown. Design blanket shield so that all conditions are satisfied. This requires an "inner-iteration" routine to minimize the sum of shield costs, magnet costs, cryoplant capital costs and cryoplant operating costs.
7. Given the outer radius of the shield from above and, therefore, the minimum inside radius of the central cell magnets, determine magnet winding pack dimensions and center to center spacing.
8. Cost all reactor items whose specifications depend on either the blanket multiplication M or thermal cycle efficiency η (i.e., blanket, reflector, shield, magnets, thermal hydraulic system, turbine plant and electric plant).
9. Compute the figure of merit parameter F (see below).
10. Iterate this procedure from step 3 and, by variation of the blanket/reflector point design, minimize the figure of merit parameter F.

THE ECONOMIC FIGURE OF MERIT PARAMETER

It is now necessary to select an appropriate economic figure of merit F for the blanket system such that minimization of F in the above iteration procedure leads to an optimized design. From a cursory view of this problem, it would appear expedient to minimize the capital cost of the central cell through design; i.e. a thin blanket implies a small inner bore for the central cell magnets and, therefore, low capital costs. However, it is not sufficient for the blanket optimization to just minimize central cell costs or, equivalently, just maximize central cell thermal parameters. Instead it must seek to maximize the overall economic performance of the reactor through blanket design. Further elucidation of these arguments requires the formulation of a detailed sensitivity study with explicit functional dependencies on M and the thermal cycle efficiency η and, as such, is beyond the scope of this paper. Accordingly, further details may be found in an associated publication[1] where the definitive figure of merit F employed for the MARS study is shown to be:

$$F = \frac{C_{CC}(M\eta) + C_{TH}(M\eta) + C_{TP}(M\eta) + C_{EP}(M\eta)}{P^e_{CC}(M\eta) + P^e_{DC} - P^e_P(M\eta) - P^e_R}$$

$$+ \frac{C_{MP} + C_{PM} + C_H + C_{DC} + C_B}{P^e_{CC}(M\eta) + P^e_{DC} - P^e_P(M\eta) - P^e_R}$$

where: C_{CC} = total central cell costs
C_{TH} = cost of thermal hydraulic system
C_{TP} = cost of turbine plant equipment
C_{EP} = cost of electrical plant equipment
C_{MP} = cost of miscellaneous plant equipment
C_{PM} = cost of plug magnets
C_{DC} = cost of direct convertors
C_B = cost of buildings and site facilities
P^e_{CC} = electric power from central cell
P^e_{DC} = electric power from direct convertors
P^e_P = electric power requirements of LiPb pumps
P^e_R = recirculating electrical power requirements for reactor less the LiPb pumping power
M = blanket multiplication factor
η = thermal cycle efficiency

F as defined here is thus the overall capital cost of the reactor normalized to the net electrical output. It is commonly expressed in units of $\$/kW_e$. It should be noted that, conventionally, the LiPb pump power P^e_p would be included in the overall recirculating power requirements of a reactor. It is separated in this analysis so that the net recirculating power requirements P^e_R can be expressed independently of $M\eta$.

Note the following interesting properties of F. The first four terms in the numerator (C_{CC}, C_{TH}, C_{TP} and C_{EP}) are dependent on the blanket and thermal cycle properties and therefore on the product of $M\eta$ as shown, while the last five terms (C_{MP}, C_{PM}, C_H, C_{DC} and C_B) are independent of the blanket properties. In the denominator, the first and third terms (P^e_{CC}, P^e_P) are blanket dependent (and, therefore, $M\eta$ dependent) while the second and fourth terms (P^e_{DC} and P^e_R) are blanket-independent. In addition, for a tandem mirror such as MARS, the electrical output from the direct convertor P^e_{DC} is comparable in magnitude to the sum of the recirculating power requirement P^e_R and the LiPb pumping power P^e_p. Depending on the particular design, these three terms can effectively cancel each other in the denominator.

The figure of merit can therefore be represented as

$$F \sim \frac{C(M\eta) + C'}{P^e_{CC}(M\eta)}$$

where C represents the cost of all blanket-dependent items, C' represents the cost of all non-blanket-dependent items and P^e_{CC} is the electric power from the central cell only. Notice now that there is a large term C' in the numerator which is independent of $M\eta$ and, therefore, of blanket properties, while the denominator is directly proportional to $M\eta$. The figure of merit parameter F is, therefore, quite sensitive to changes in the blanket properties $M\eta$ via the denominator P^e_{CC}, while it is not so sensitive to changes in the blanket-dependent costs C (which are dependent on $M\eta$) due to the influence of the large constant term C'.

APPLICATION OF THE FIGURE OF MERIT PARAMETER TO THE MARS BLANKET

A wide range of point blanket designs for MARS was investigated for the same fusion neutron power via the iterative procedure above. Each iteration incorporated the systematic adjustment of one of the four key design parameters: blanket radial thickness, LiPb/HT-9 volume fraction, ^{6}Li enrichment and reflector material. All neutronics/photonics calculations were performed with the 3-D Monte Carlo transport code MCNP with evaluated data from ENDF/B-V.(1) Blanket thermal cycle efficiencies η were evaluated for the same LiPb inlet and outlet temperatures, namely 350°C and 500°C, respectively.

Two major conclusions resulted from the optimization study. First, maximum values of the product of $M\eta$ and, therefore, maximum values of the central cell electric power P^e_{CC} are obtained for a blanket of large radial thickness containing natural isotopic enrichment of ^{6}Li in the LiPb coolant/breeder. By contrast, the cost of the blanket-dependent items is minimized for a blanket of small radial thickness containing highly enriched ^{6}Li. (Note that, due to high atomic fraction of Pb in the $Li_{17}Pb_{83}$ eutectic, the cost of LiPb containing highly enriched (90%) ^{6}Li is only ~ 11.6 $/kg compared with ~ 3.75 $/kg for LiPb containing natural (7.42%) isotopic composition of ^{6}Li.) However, the blanket of small radial thickness exhibits a lower value of the $M\eta$ product than the former design and, therefore, a lower value of P^e_{CC}. Blankets with thicknesses intermediate between these extremes and designed for the same tritium breeding ratio exhibit corresponding properties which interpolate approximately linearly with radial thickness. The optimum blanket is that which minimizes the figure of merit parameter F in terms of overall $/kW$_e$.

It is instructive here to examine some selected results from this study for two near-optimum central cell designs which differ primarily in the radial thickness of their blanket regions. For convenience of identification below, they will be designated the "thin" and "thick" blanket designs, respectively. Accordingly, Table 1 compares the principal design features for these two blankets in the MARS central cell including geometry, composition and neutronics properties. Note that in the case of the thin blanket, 28% of the total recoverable blanket energy appears as heat in the water-cooled reflector. Since this heat is employed only as feed-water heating to the main LiPb cycle, the thin blanket suffers an economic penalty in terms of overall thermal cycle efficiency.

Table 2 illustrates the cost for those items of the reactor system which are dependent on the blanket design and, therefore, on the parameters M and η. The basis for these costs is given in Ref. 1. These items include the central cell components (blanket, reflector, shield and magnets) together with the thermal hydraulic system (LiPb piping, pumps and double-wall heat exchangers), turbine plant equipment and electric plant equipment. Note that the total central cell costs are dominated by the magnet costs. It is evident that the difference in blanket-dependent costs for the thin blanket and thick blanket systems is mainly due to the difference in magnet costs. These magnet costs are strongly dependent on magnet bore radius and, therefore, on blanket radial thickness.

TABLE 1. Principal Design Features of the Thick and Thin LiPb Blankets

	Thin LiPb Blanket	Thick LiPb Blanket
Blanket radial thickness (m)	0.382	0.872
Reflector thickness (m)	0.43	0.28
Shield thickness (m)	0.41	0.44
Mean radius of magnet winding pack (m)	2.49	2.93
Neutron wall loading (MWm^{-2})	5	5
^{6}Li enrichment (%)	90	7.42
Fraction of energy in reflector (%)	27.6	13.4
Blanket multiplication M	1.390	1.374
Tritium breeding ratio T	1.135	1.078
Gross cycle efficiency η	0.40	0.42
$M\eta$	0.556	0.572
LiPb pumping power(MW_e)	54.7	63.6
Net cycle efficiency	0.386	0.400
Central cell thermal power (MW_t)	3892	3847
Central cell gross electrical power (MW_e)	1556	1603
Central cell net electrical power (MW_e)	1501	1539

TABLE 2

System Costs for Blanket-Dependent Items[a]

	Thin LiPb Blanket	Thick LiPb Blanket
Blanket cost (M$)	36.1	63.8
Reflector cost (M$)	53.4	46.8
Shield cost (M$)	31.0	40.8
Magnet cost (M$)	309	390.3
Total c. cell cost (M$)	429.5	541.7
Thermal hydraulic system (M$)	262.5	279.1
Turbine Plant (M$)	262.7	266.8
Electric Plant (M$)	158.1	161.2
Total blanket-dependent items (M$)	1113	1249

[a] Costed in 1982 current dollars

TABLE 3

System Costs for Non-Blanket-Dependent Items[a]

Miscellaneous plant equipment (M$)		150
Plug magnets (M$)		250
Direct convertor (M$)		142
Buildings and Site Facilities (M$)		300
Heating Systems (M$):		
ECRH	280.2	
Neutral beams	14.0	
ICRH	14.8	
Heating total		309
Total non-blanket-dependent items (M$)		1151

[a] Costed in 1982 current dollars.

TABLE 4

Summary of Economic Parameters and Figure of Merit

	Thin LiPb Blanket	Thick LiPb Blanket
Cost of blanket-dependent items C (M$)	1113	1249
Cost of non-blanket dependent items C' (M$)	1151	1151
Total system direct costs (M$)	2264	2400
Central cell electric power (MW_e)	1556	1603
Direct convertor electric power (MW_e)	545	545
Net recirculating power requirements (MW_e)	367	367
LiPb pumping power requirements (MW_e)	54.7	63.6
Total system net electric power (MW_e)	1679	1717
Figure of merit parameter F ($/$kW_e$)	1348 (1.0)	1398 (1.04)

Table 3 shows the cost breakdown for the non-blanket-dependent items of the reactor systems. Included here are the cost of all items which have no dependence (or very weak dependence) on the blanket parameters M and n. It should be noted that these figures represent initial estimates of direct capital costs and should not be taken as final definitive costs for the system. Indeed these figures apply to the point MARS reference design as of December 1982 and are subject to fluctuations as the plasma engineering design progresses. As will be seen below, the fact that these figures are subject to some uncertainty does not compromise the validity of the conclusions of the optimization procedure.

Table 4 summarizes the important economic factors for the thin and thick blankets including the blanket-dependent and non-blanket-dependent costs and the net electric power from the central cell and the overall system. Note that the electric power output from the direct convertors at the ends of the machine effectively supplies the electric power requirements for both the net recirculating power and the LiPb pumping power.

The figure of merit parameter F is shown in Table 4 for both the thin and thick blankets. It is evident that the thin blanket provides the most economic option, since its F parameter is ~ 4% smaller than that for the thick blanket. This is a small but significant difference.

It might be argued that any uncertainties in the costs C' of the non-blanket-dependent items from Table 3 would tend to mask the significance of a 4% difference in the F-parameters for the two blankets. That this is not so can be seen from Fig. 2. Here the relative parameter:

$$F_{\text{thick blanket}}/F_{\text{thin blanket}} - 1$$

is plotted as a function of the cost C' of the non-blanket-dependent items. Clearly while this parameter remains greater than zero, the thin blanket is economically preferable. The present design point of C' = 1151 M$ with a corresponding relative F-parameter ratio of ~4% is indicated. The essential feature of Fig. 2 is that the cost of the non-blanket-dependent items C' would have to increase from 1151 M$ to ~ 4875 M$ (i.e. a factor of 424%) for the optimization conclusion to be reversed and the thick blanket to prove the most economic option. Therefore, although absolute magnitude cost figures have an associated degree of uncertainty, the uncertainty in the ratio of the F-parameters is very insensitive to the uncertainty in C'.

CONCLUSIONS

A range of point LiPb blanket designs for the MARS tandem mirror reactor were investigated via the iterataive procedure above employing the

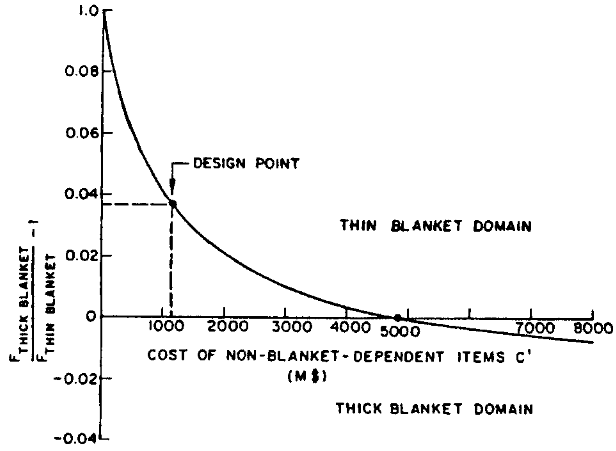

Fig. 2. Ratio of the F-parameters for the thick and thin blankets as a function of the cost of the non-blanket-dependent items.

economic figure of merit parameter F. Optimized performance in terms of minimization of F was obtained for the "thin" blanket parameterized in Tables 1, 2 and 4. This optimized design is achieved by utilizing a LiPb/HT-9 blanket region of small radial thickness containing highly enriched (90%) ^{6}Li, therefore enabling other central cell radial dimensions (reflector, shield, magnets, etc.) to also be kept small. Overall central cell costs are therefore minimized. This blanket is able to achieve a neutron energy multiplication factor M approaching that for blankets of considerably larger radial thickness while retaining an adequate tritium breeding ratio of ~ 1.14. With these features, this compact blanket design exhibited the lowest value for the figure of merit parameter F and, therefore, proved to be the most economic in terms of overall $/kW$_e$ for the reactor system.

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