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R.B. Campbell, L.J. Perkins, D.T. Blackfield

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PHYSICS-MAGNETICS TRADE STUDIES FOR TANDEM MIRROR REACTORS*#

R. B. CAMPBELL (TRW)/L. J. PERKINS
Lawrence Livermore National Lab
P.O. Box 5511, L-644, Livermore, CA 94550
(415) 423-0707/(415) 423-6012

D. T. BLACKFIELD, Fusion Engineering Design Center/TRW
Oak Ridge National Lab, P.O. Box Y, Oak Ridge, TN 37830
(615) 576-5519

ABSTRACT

We describe and present results obtained from the optimization package of the Tandem Mirror Reactor Systems Code. We have found it to be very useful in searching through multi-dimensional parameter space, and have applied it here to study the effect of choke coil field strength and net electric power on cost of electricity (COE) and mass utilization factor (MUF) for MINIMARS type reactors. We have found that a broad optimum occurs at B_{choke} = 26 T for both COE and MUF. The COE economy of scale approaches saturation at quite low powers, around 600 MW(e). The saturation is mainly due to longer construction times for large plants, and the associated time related costs. The MUF economy of scale does not saturate, at least for powers up to 2400 MW(e).

I. INTRODUCTION

In this paper, we discuss and present results from a systems code intended to model tandem mirror reactors, with emphasis on the physics trade studies we have performed.

The code we have developed, called the Tandem Mirror Reactor Systems Code (TMRSC), can model tandem mirrors using both quadrupole[1] (MARS) and octopole[2] (MINIMARS) end plugs. Reference 2 discusses the advantages of the octopole. The TMRSC has two major packages. The design package (TMRSC-D), which is intended to be used to perform detailed costing, subsystem sizing and definition, checks on geometric constraints, and extensive plasma equilibrium and stability calculations, is the largest of the packages, and requires the most computer time. The present version of the design module can only treat quadrupole end cells. An upgrade to include octopole end plugs, is planned in the near future. For the details of the TMRSC-D, we refer the interested reader to the paper by R. L. Reid, et al.[3] in these proceedings. The optimization package, TMRSC-O, which will be described below, is used to do extensive scans of multi-dimensional parameter space in search of operating parameters which improve selected figures-of-merit. These parameters then can form a framework for the detailed calculations in the TMRSC-D.

The TMRSC-O is quite versatile, in that it can model reactors plugged by both quadrupole and octupole end plugs, and it can survey large regions of parameter space in a fraction of the time it would take to complete one design point with the TMRSC-D. We also can optimize a figure-of-merit, chosen by the user from several available, with respect to magnetic and geometric characteristics of the configuration. We gain this ability at the sacrifice of detail in defining the design point. For example, instead of solving the full set of equations which describe plasma equilibrium and stability within the code, we use a parametrization of the required beta value in the octupole "mantle"[2] for given beta values in the central cell and plug. Also, instead of solving sets of equations for the axial magnetic field profile given a set of coil locations, the optimization code uses a set of simplified scaling laws which calculate coil locations based on the preservation of mirror ratios in the vacuum field. A final simplification is that no detailed costing and sizing is performed for a given machine configuration. Instead, cost and size scaling laws are used which have been developed from point designs and well-established parametric dependencies (e.g., cost of magnets scales with magnetic energy, balance of plant costs scale as thermal power raised to a power close to one, etc.).

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An important point is that the normalizations of the costing algorithms also have incorporated in them some of the MINIMARS[2] cost and sizing objectives. Because of this, the results presented in this paper should be taken in the following light. First, the trends can be used with some confidence in picking an optimum design point because the same set of costing assumptions is used in each case. However, the absolute cost figures should be viewed as goals to be achieved, since they are based on the assumption that a certain degree of improvement can be made to the MARS design methodology. An example which is particularly important to cost is the ability to make cheaper, lighter magnets in both the central cell and plugs than in MARS. With the introduction of the octupole end plug and more efficient "sheet" coils in the central cell, these goals are being demonstrated in the ongoing MINIMARS study.[2]

II. PACKAGE DESCRIPTION

The module TMRSC-0 solves a general constrained optimization problem by simultaneously varying 26 plasma physics and engineering variables. There can be upper and lower bounds placed on all of these variables, chosen by the user. There are modules in the code which evaluate the physics equations, engineering power balance, direct converter performance, optimization constraints, and figures-of-merit.

There are 14 basic plasma physics variables, and they are always constrained to satisfy a set of radially averaged plasma particle and energy balance equations, originally contained in the TMRBAR code.[4] The most important variables from a systems standpoint are the central cell length, L_{cc}, central cell plasma radius, r_c, central cell vacuum magnetic field, B_{vac}, and choke coil vacuum field, B_{choke}. These can impact the cost and weight of the reactor portion of the power plant. Because part of the field produced by the choke coil is due to a normal conducting insert (from 2 to 12 T for 18 T on the superconductor), one needs to compare the benefits of lowering the end plug heating powers (high field) with the additional power required to drive the coil. This will produce a cost optimum when B_{choke} is varied.

There are also several other constraints which can be applied as the user desires. The code is general enough that only small coding changes are necessary to add other constraints, as the need arises. The two most important ones are the ability to fix the output power, either fusion power or net electric power, and the ability to fix the neutron wall loading.

III. SCALING LAWS AND FIGURES-OF-MERIT

Scaling laws in the TMRSC-0 package replace the involved costing, sizing, plasma equilibrium and stability calculations that the TMRSC-D design package includes. We shall first discuss the scaling laws (sizing, power) related to the physics and magnetics, and then proceed to the scaling laws related to cost and component weight. From these laws we then derive the figures-of-merit in a straightforward manner.

The major physics scaling law, in addition to the 14 physics balance equations, is that related to the maximum central cell beta value, β_c, attainable for given beta values in the end plug axisymmetric region, β_b, and in the good curvature octopole mantle region, β_m. This takes the place of the MHD equilibrium and stability codes used in the design module. The formula was derived[5] by parametrizing results of similar codes intended for use with octopole end plugs. Considerable improvement in machine performance could be realized if the central cell was stable on its own, perhaps by the presence of nearby conducting walls. In this event the dependence of β_m on β_c would be removed. This would allow the microwave powers required to produce the hot plasma in the mantle to drop thereby decreasing the recirculating power fraction. For the results in this study, we have kept the volume averaged central cell beta value fixed at 0.6.

Because we do not have a magnet design submodule in TMRSC-0, we use scaling laws to predict the end cell volumes (both core and mantle) when the central cell volume changes. Changes in the end cell volumes will impact supplementary heating power and magnet size which will then impact the cost and weight of these components. The most fundamental law is the conservation of magnetic flux ($\phi \propto B\, r^2$) from one axial point to another. For a larger central cell flux the radius of the coil, r_{in} must increase in order to fit the field lines defining the larger radius plasma through the plug coils, as well as provide proper magnet shielding. In order not to decrease the mirror ratio in the plug, which for several physics reasons should not be changed, the coils must be spread apart. This makes the plug length, L_b, scale with r_{in}. The length of the octopole coil, L_o, will then scale with L_b. For the mantle length, we scale it to be proportional to L_b, with the constant of proportionality related to the axial extent of the plug plasma pressure. The radial location of the mantle scales as the flux-mapped radius at the midplane of the plug. We obtained our scaling from an octopole magnet set intended for the Fusion Power Demonstration (FPD) machine which we generated rigorously.

From the results of the next section, the costs are dominated by the balance-of-plant costs (heat exchanger, steam cycle, piping, turbine and generator) which scale as $P_{th}^{0.8}$, where P_{th} is the total thermal power extracted from the machine. The cost and mass of the central cell and end cell magnets are both scaled from the magnetic energy contained within the enclosed volume. The blanket and shield costs for the central cell scale with the central cell length and wall loading. The same form for the scaling applies for mass, but it is multiplied by the blanket cross-sectional area. The cost and mass of shielding for the end cell coils is scaled from the surface area of the volume enclosed by the magnets.

The cost and mass of the choke coil are products of several factors, each factor is associated with different parts of the coil. The law is based on the experience gained from the MARS[1] study. There is a factor associated with the normal conducting (nc) insert magnet, which takes different forms depending on whether the field that the insert produces is greater than or less than 8 T. For $B_{nc} < 8$ T, it is a weakly increasing function, and for $B_{nc} \geq 8$ T, it becomes a fairly strong quadratic function. This two-part scaling was chosen to account for the fact that for fields lower than 8 T, cooling is not a particular problem, but as B_{nc} rises, heat removal becomes more of an issue, and the radial build of the outer superconducting coil must increase to accommodate the additional cooling lines to the n/c coil. The scaling factor due to the superconducting magnet is a quadratic function of only the field produced by the superconductor. Finally, the size of the choke coil will also be affected by the size of the plasma threading through its bore. This is taken into account through another factor which is quadratic in the inner bore of the choke coil. An important element in determining the recirculating power is that power required to run the normal conducting magnet. This power is scaled with the square of the normal conducting field and the choke coil radius.

The cost of the supplementary heating systems is assumed proportional to the wall plug power required to run these systems. We are currently taking \$1.5/watt of wall plug power as the proportionality constant.

We also include direct costs of building and land, scaled with the central cell length, miscellaneous reactor plant equipment, (tritium systems, maintenance equipment, instrumentation and control, spares, etc.) scaled with the 0.8 power of the fusion power, and cost of the direct converter, scaled with the 0.8 power of the total power which is handled by it (both heat and electrical power). The total direct capital cost is the sum of all the costs, corrected for contingency, which we take to be 15%.

To compute the MUF, we simply sum the masses described above and divide them into the net electric power generated in order to get the power generated per tonne of reactor weight. This may serve as a useful yardstick for comparing different fusion concepts. We shall explore this in the next section.

To compute the COE, we need to know several factors not yet discussed in addition to direct capital cost. Indirect capital costs are taken to be fractions of the direct cost, but the fractions depend on how large the fusion power is. This is done to model the fact that for smaller unit sizes, constructed on the same plant site, there can be shared construction and engineering costs. The cost includes construction facilities, engineering and construction management, and a combination of the owner's cost and other miscellaneous costs.

The total capital investment, which includes total capital cost plus costs related to borrowing the money, are sensitive to the construction time. We have used a construction time curve generated from the MARS design point, along with a polynomial scaling derived from fission industry experience. The latter is thought to be good up to plants of approximately 6000 MW_{th} output. The time related costs are then computed, knowing construction time. We have taken the interest during construction to be 10%, and have the option to work with a constant dollar, or include an escalation rate of 5%.

To get COE numbers, we need an availability. We include downtime due to scheduled and unscheduled maintenance. In lieu of a complete maintainability study, we take these times to scale as the 1/4 power of the fusion power, and plug injected power, respectively, with the MARS design point and fission reactor experience used to compute the scaling constants. For downtime from scheduled maintenance (turbines/generators, etc.), we normalize to 4.3 weeks at $P_{fus} = 1200$ MW. For unscheduled maintenance, we allow for a nominal 5 week time, with the time increasing to almost 9 weeks when the supplementary heating power reaches 30 MW. We purposely omit any scaling of availability with wall loading, because the operation of blanket replacement can be accomplished in parallel with scheduled maintenance of the balance-of-plant, or unscheduled maintenance of the heating systems. The blanket life due to high wall loading would have to be considerably less than 1 year to make availability wall load dependent. We do, however, include a wall loading scaling in the component replacement costs, because more spare modules will be needed at higher wall load.

The last element of the cost of electricity calculation is the operations cost. The operations and maintenance cost is taken to be 1% of the total capital cost, the fuel costs are taken to scale with the product of fusion power and availability, and the scheduled component replacement costs are scaled with the fusion power, normal conducting field and the first wall loading. The scaling law models the fact that more spares must be bought and replacements made more often when the wall loading and fusion power rise, and we account for the fact that the normal conducting insert must be replaced more often at higher wall load. The cost of electricity is computed in the standard way, with a fixed charge rate on capital investment set to 15% when the escalation rate is 5%, or 10% when there is no escalation. The results presented in the next section assume 5% escalation

IV. SAMPLE RESULTS

When the optimization package is used, it must be started off at a plausible physics operating point, from which the code searches in parameter space to optimize a chosen FOM. Table 1 shows the degree to which the code can search from a starting point, well off optimum, when requested to optimize COE.

Table 1. The TMRSC-0 has the ability to find optima far away from the starting point. P_{net} = 600 mW(e), optimizing for minimum COE.

Parameter	Starting	Optimum
P_{fus} (MW)	1367	1206
L_{cc} (m)	51	95
$B_{vac,c}$ (T)	3.5	3.
r_c (m)	0.6	0.42
B_{choke} (T)	32	26
P_{ecrh} (MW)	41	15.1
COE (mills/kW-hr)	72.	56.

We would like to examine: (1) COE and MUF as functions of B_{choke}, and (2) the economy of scale these reactors possess. The B_{choke} parametric is important, since there is substantial difference in technical feasibility between 18 T and 32 T magnets. We take the field produced by the superconductor to be 18 T for all of these cases.

Fig. 1 shows the COE as a function of choke coil magnetic fields for a machine at 600 MW(e). At each point, the other optimization variables are varied to give the best case at each field. There is a shallow optimum at 26 T, with a value of 56 mills/kW-hr. Note that the variation of the COE over this large range is only 5%. This variation is of the

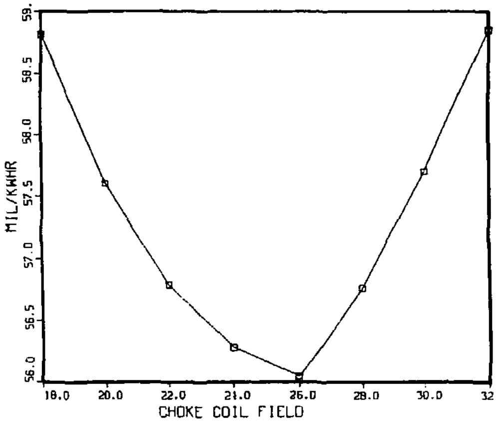

Fig. 1. COE versus choke coil field (T).

same order as the BOP costs, which scale as the total thermal power. At low choke coil field, supplementary heating powers are high but normal insert coil power is small; at high field the reverse is true. To maintain the same net electric power, the fusion power must vary to make up for the changing recirculating power fraction. If BOP were totally dominating the costs, then the optimum choke coil field would be at 20 T, because that is where P_{fus} minimizes. When the costs are tallied for the optimized case, however, costs of the heating systems and cost of end cell magnets (including choke coil) also contribute. Table 2 shows the breakdown in costs for the two limits in B_{choke}, and the optimum value. As can be seen, the largest swings in *absolute* numbers occur in the choke coil cost, the heating system cost, and the blanket and shield cost, reflecting the tradeoff when choke coil field is varied. The BOP, by far the largest single contributor, varies only a few percent.

Table 2. Direct costs breakdown for B_{choke} = 18, 26 and 32 T. P_{net} = 600 MW(e). COE minimized.

Item	Cost ($M) 18 T	26 T	32 T
C.C. magnets	28.6	28.3	30.4
C.C. blanket/shield	87.3	81.3	84
Buildings/land	57.8	47.4	46.
BOP	316	317	325
Choke coil	61	62.5	96
Heating systems	83	70.	62
End cell shield	89	77.7	71
Misc. reactor systems	54	54.9	56
Direct converter	10.7	10.8	11

Fig. 2 presents the maximization of MUF also as a function of B_{choke}. The optimum field is again at 26 T, with an optimum value of 81 kW(e)/tonne of reactor core. The central cell blanket and shield are the largest contributors to mass, with end cell magnets, central cell magnets, and choke coil being the next most massive, in that order.

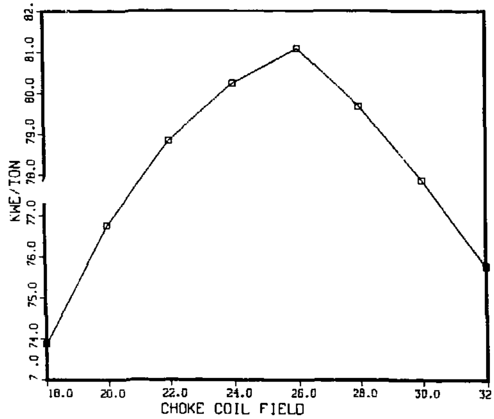

Fig. 2. MUF (kW(e)/tonne) versus choke coil field (T).

Even though the two cases optimize at the same choke coil field, the resulting machines have quite different characteristics. Table 3 shows some selected parameters for both optimized machines. The most striking differences, other than the values of the figures-of-merit themselves, lie in the length of the machines, their wall loadings, and the amount of electron cyclotron resonance heating (ECRH) required in the plug. The MUF is not sensitive to supplementary heating systems unless tney weigh a significant amount. MUF depends on heating powers, indirectly through recirculating power. The power required in the MUF case probably cannot be delivered in a MINIMARS size plug. The reactor in the MUF case has a shorter central cell because that is the way to minimize the weight of the central cell blanket and shield, the most massive component. On the other hand, the COE optimized case wants to minimize the end cell volume. It achieves this by making the central cell radius small (but not too small that alpha particle loss or thermal conduction is excessive) and the central cell long. The cost is not affected significantly by a long L_{cc}, because central cell magnets and blanket are relatively inexpensive. The total end cell costs are significant and larger choke coil and heating powers make P_{fus} larger for the same P_{net}, increasing BOP costs. These factors drive the central cell radius, which

Table 3. Comparison of reactor cores optimizing COE and MUF. P_{net} = 600 MW(e).

Parameter	COE	MUF
L_{cc} (m)	95	55.
r_c (m)	0.42	0.6
$B_{c,vac}$ (T)	2.95	3.07
Γ (MW/m^2)	2.7	3.93
P_{fus} (MW)	1206	1322
P_{ecrh} (MW)	15.1	48.
Direct capital cost ($B)	0.863	0.985
Mass of blanket and Shield (10^3 tonnes)	5.0	3.25
COE (mills/kW-hr)	56	67.5
MUF (kW(e)/tonne)	65.4	81.1

maps to an end cell volume (roughly like r_c^3), to smaller values.

We have also examined the scaling of COE and MUF as functions of net electric power, the so-called "economy-of-scale." Fig. 3 shows the COE as a function of net electric power. Note that the benefit of larger unit size saturates very rapidly, the cost only decreasing slightly as P_{net} rises from 600 to 1200 MW. The real improvements appear for $P_{net} \leq 600$ MW(e). The saturation occurs because of three effects. First, the availability is lower in the larger machines, going from 77% at 600 MW to 71% at 2400 MW. Second, the cost of central cell blanket, shield and magnets dominate the non-BOP costs at high powers. Third, the premature saturation occurs because of the time related part of capital investment. Time related costs amount to 19% of the capital investment at 600 MW but rise to 40% at 2400 MW. This is related to longer construction time.

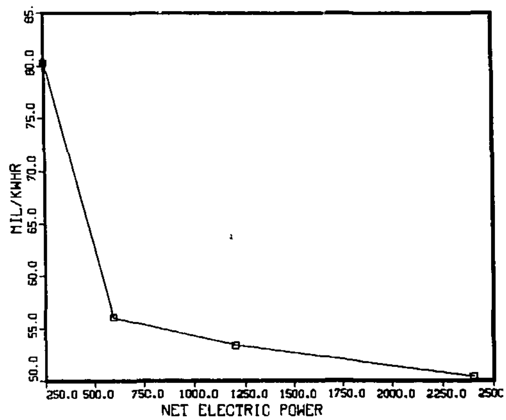

Fig. 3. Economy of scale for COE.

The MUF economy of scale is not affected by these considerations and shows no saturation, as shown in Fig. 4. Improvement in mass utilization is seen all the way up to 2400 MW(e). In this sweep, the central cell length only goes up by a factor of 1.6 when the electric power increases by a factor of 10. (The extra fusion power is generated by a larger radius plasma and higher central cell field). If the mass of the central cell blanket and shield scales only with the central cell length, we should see a factor of 6 increase in the MUF. Because the mass scaling law also depends on wall load and weakly on radius, the mass increases a factor of 1.9. The resulting factor of 10/1.9 = 5.3 is almost exactly the increase in MUF seen on Fig. 4.

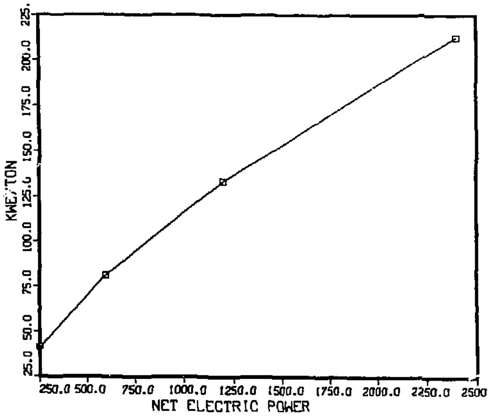

Fig. 4. Economy of scale for MUF.

V. CONCLUSIONS

We have developed the optimization package of the TMRSC, which has proved to be a useful tool in rapidly searching multi-dimensional parameter space to optimize the plasma engineering parameters of tandem mirror reactors. We have shown two examples of how the code can be used; a search for the optimum choke coil field, and the generation of the economy of scale curve. The figures-of-merit we have used are the cost of electricity (COE) and the mass utilization factor (MUF).

Although the optimum choke coil field at 600 MW turned out to be 26 T regardless of the FOM we used, the characteristics of the two optimum machines are quite different (Table 3). The machine optimum with respect to MUF favored a short central cell length and large end cell volumes. This resulted in high wall loading but very high supplementary heating powers. The COE-optimum machine tried to minimize end cell volume, and hence recirculating power. It did this by picking long, thin central cells.

The slope of the COE economy of scale curve (Fig. 3) is very steep for P_{net} < 600 MW(e) but saturates rapidly above this value. Reasons for this are discussed in Section IV. The MUF scale curve shows no saturation, in fact improves dramatically for larger unit sizes. This is because the ten-fold increase in net electric output is accompanied by only a factor of 2 increase in the most massive components.

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