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FACTORS AFFECTING THE MINIMUM CAPITAL COST OF A TOKAMAK REACTOR

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ABSTRACT The Mk IIA Culham conceptual tokamak reactor design is a 2500 MWe steady-state reactor developed on the basis of a cost optimisation. A revised 1200 MWe conceptual design, the Mk IIB, used a lower wall loading and lower thermodynamic efficiency. A detailed costing of the Mk IIB design, however, showed it to have an unacceptably high capital cost. Since this high cost is a common characteristic of many fusion reactor designs, the cost optimisation of the Mk II design has been reconsidered.

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1. REACTOR DESCRIPTION

The Culham MkII conceptual tokamak reactor design was first published in 1976 [1]. It incorporated several features currently being discussed in relation to future large tokamak experiments, such as an elliptically shaped plasma minor cross-section and an iron transformer with saturated centre core to minimise the plasma aspect ratio, and therefore has a superficial similarily to the JET experiment.

A revised design was published in 1977 [2] with more conservative parameters and the addition of a single-null poloidal divertor, and these two designs are now designated Mk IIA and IIB. Both assume quasi-steady operation with refuelling and a means of exhausting reaction products, although these features were not considered in detail. Other features which were implied but not specified in detail included the means of initiating the plasma current and heating the plasma to ignition and means for controlling the plasma temperature and hence the reactor power output. Some of these aspects were discussed in a more recent study [3] of a pulsed tokamak reactor, the Mk IIC. The initial assumptions on which these designs were based and the resulting parameters are shown in tables I and II.

1.1 Tokamak Reactor Mk IIA

The parameters of the Mk IIA reactor were deliberately chosen to obtain a low capital cost. Thus a high output power was assumed and a higher wall loading than was used in similar designs at that time. The maximum values allowed for plasma parameters such as the plasma pressure ratio β and safety factor q or for engineering parameters such as the maximum level of toroidal magnetic field B_m, although optimistic, were not too unrealistic.

TABLE I

Mk II reactors, initial assumptions

	IIA	IIB	IIC
Net power output, MWe	2500	1200	600
Poloidal beta - K_β	1.0	1.0	1.0
- E_β	0.5	0.5	0.66
Safety factor $(q_0)^\beta$	1.0	1.0	1.0
Plasma ellipticity	1.75	1.75	1.68
Burn time/off time	∞	20	1.93
Max. toroidal mag. field, T	$\leqslant 8.0$	$\leqslant 8.0$	~8
Max. core magnetic field, T	$\leqslant 6.0$	$\leqslant 6.0$	~8
Blanket & shield thickness, m	1.5	1.5	2.1
Thermal efficiency, %	45	40	40
Recirculating power, %	5	8	19
Max. neutron dose, x 10^{25} /m^2	100	20	40

TABLE II

Mk II reactors, parameters

	IIA	IIB	IIC
Net power output, MWe	2500	1200	600
Gross thermal power, MW	5830	3240	1825
Major radius, m	7.4	6.7	7.8
Minor radius, m	2.1	1.9	2.0
Aspect ratio	3.5	3.5	3.9
Plasma current, MA	11.7	10.2	11.0
Toroidal beta(β_t), %	9.3	9.2	7.7
Tor. mag. field (on axis), T	4.0	4.0	3.9
Peak core magnetic field	4.2	5.6	7.8
Wall power loading, MW/m^2	6.7	4.5	2.1
Unit cost (£/kWe in 1976)	156	254	510

The blanket of the Mk IIA reactor is constructed in a cellular form with liquid lithium breeder and helium cooling. The choice of structural material was not discussed in detail, but it was assumed that operation would be possible at a sufficiently high temperature to give 45% efficiency for the conversion of heat to electricity.Because of the high wall loading it was accepted that the first wall structure would suffer extensive radiation damage and therefore have to be replaced during the life of the reactor. Thus the Mk II designs have incorporated the means of maintaining and repairing the internal reactor structure by remotely operated machines, and the development of these maintenance concepts has been a predominant feature of the Culham reactor studies.

1.2 Tokamak Reactor Mk IIB

The Mk IIB reactor represents a development of the IIA design to include a poloidal divertor and further detail in the construction and maintenance of the blanket and shield. The engineering assumptions on which the design was based were more conservative with reductions in the net power output, wall loading, and thermal efficiency, and an increase in the recirculating power for auxiliary equipment.

To obtain a more realistic structure in the 1.5m space allowed for the blanket and shield the breeding blanket consisted of an inner zone of lithium-lead and an outer zone of lithium orthosilicate enclosed in an inconel cell. The inner section of shield was mounted within the blanket cell to maximise the energy recovery, both being cooled by helium supplied through a co-axial duct.

1.3 Tokamak Reactor Mk IIC

The Mk IIC design was developed specifically to allow a comparison of the tokamak reactor with a Reversed Field Pinch reactor. In both cases pulsed operation was assumed without refuelling during the burn. Because of its pulsed operation the wall loading was again reduced. The net power output was also reduced to 600 MWe, with the result that the physical size of the reactor was similar to that of the Mk IIA and IIB designs.

Further consideration was given in the Mk IIC study to the requirements for initiating and heating the plasma and to the poloidal magnetic field system required to maintain and control the plasma. Twenty primary coils and fourteen vertical field coils were required to give the necessary magnetic field distribution. Filamentary niobium-titanium conductors were assumed for the poloidal field windings, whereas niobium-tin strip was proposed for the toroidal field windings. For the pulsed reactor an air cored transformer appears preferable.

2. COST STUDY

The parameters of the designs described above were all determined by a cost optimisation procedure using a computer program TCOST [4] developed at Culham. The program includes the equations linking the physical and technical parameters of the reactor, and calculates a cost based on the physical size or power rating of each component in a possible design. The program then adjusts parameters within given limits to find either the minimum total capital cost of a reactor or the minimum unit cost at a given power output. The quoted cost refers to the reactor and its building and does not include conventional generating plant.

The cost data used as input to the program were generated from published costs of fission reactors or engineering structures of a similar size and complexity. The input and output data has also been checked against information given in earlier published reactor designs and against data used in the optimisation of the JET experiment[5]. The main components of the cost input are given in table III.

TABLE III

Input cost data, at 1976 values

Superconductor	7.5×10^{-2}	£/kA.m.T
Magnet stabilizer (copper)	5.6×10^{4}	£/m^3
Magnet manufacture	2.8×10^{4}	£/m^3
Magnet structure (steel)	5.0×10^{3}	£/m^{2}T^2
Cryogenic insulation	2.0×10^{3}	£/m^2
Refrigeration	1.1×10^{2}	£/MW
Blanket	1.7×10^{4}	£/m^2
Shield	5.5×10^{4}	£/m^2
Primary circuit	9.0×10^{3}	£/MW
Reactor auxiliaries	6.5×10^{3}	£/MW
Iron transformer core	1.1×10^{4}	£/m^3
Poloidal power supply	2.0×10^{4}	£/MJ
Plasma heating	3.5×10^{5}	£/MW
Reactor building	4.5×10^{2}	£/m^3

The physical relationships and cost data incorporated in the program were updated several times until 1978, but costs have been kept at 1976 values to facilitate comparisons between new designs and the original Mk IIA costing. A limitation of the input data, inherent in any program of this type, is that it cannot take account of the influence of minor changes in designs or materials. Whilst adjustments have been made for major changes, for example the change from niobium-titanium to niobium-tin superconductor, it has not been possible to reflect changes in the structural design except through gross changes in size or weight.

The capital costs of the three reactor designs calculated with the program TCOST are shown in table II. It is clear that as the physical and engineering assumptions have become more conservative the unit cost has increased. An independent, and more accurate, costing of the Mk IIB design [6] has indicated that the later costs are unacceptably high, and that every effort must be made to reduce the costs if a tokamak reactor is to be competitive compared to alternative power sources. For this reason the influence on the capital cost of several of the initial assumptions and limitations has been investigated.

TABLE IV

Initial Parameters for Study,
Optimum Parameters and Sensitivities

	IP	OP	S
Net power output, MWe	1200		-0.44
Poloidal beta - K_β	1.0		-0.31
Safety factor (q_o)	1.0		0.66
Burn time/off time	20		-0.02
Max. toroidal mag. field, T	≤15	9.5	0
Max. core magnetic field, T	≤15	15.0	-0.02
Blanket & shield thickness, m	1.5		0.56
Thermal efficiency, %	40		-0.57
Recirculating power, %	8		0.05
Wall power loading, MW/m^2	≤20	6.1	0
Major radius		6.0	
Minor radius		1.6	
Unit cost (£/kWe in 1976)		194	

As a starting point most of the assumptions corresponding to the Mk IIB design have been used. However, in order to leave as many free parameters as possible the maximum toroidal magnetic field, the maximum magnetic field in the core and the maximum wall loading have been increased. Assumptions and optimum parameters for the standard case are shown in table IV.

2.1 Plasma Beta and Safety Factor

The poloidal plasma pressure ratio βp was assumed to be related to plasma aspect ratio R/a through the constants K_β and E_β so that $\beta_p = K_\beta (R/a)^{E_\beta}$. In the standard design the values of K_β and E_β were taken to be 1.0 and 0.5 which is currently thought to be a reasonable assumption, but the effect on unit capital costs of values of K_β up to 2.0 are shown in fig. 1 for three sizes of reactor. Clearly values below unity lead to high costs, but the reductions in unit cost for values much above unity are not great. The effects of some more restricted engineering parameters are indicated.

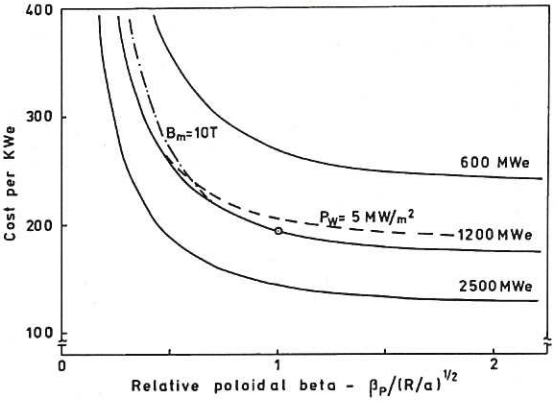

Fig 1. Effect of poloidal beta on cost.

The safety factor q_o on the plasma axis was assumed to be unity in the standard design. For values in the range 1 to 2 the unit costs are roughly proportional to the safety factor, as seen in fig 2, emphasizing the importance of reaching in practice the theoretical limit. The effect of ellipticity in the plasma minor cross-section has not been studied, since the theoretical model in the program linking the current in the poloidal field windings with the plasma shape was not considered sufficiently accurate to give reliable results.

2.2 Fixed Engineering Parameters

The effect of changing the reactor power output is shown in fig. 3. In the central range of sizes the variation is close to the 2/3 power law common in engineering, and it is only at sizes below 600 MWe that the unit cost rises more rapidly. Thus, whilst there is an advantage in constructing larger units, the cost of fusion reactors will not change strongly in relation to other power sources if comparisons are made between systems of the same size. The question of the optimum wall loading is considered later, but it should be noted from fig. 3 that if the wall loading is limited the advantage of large systems is reduced.

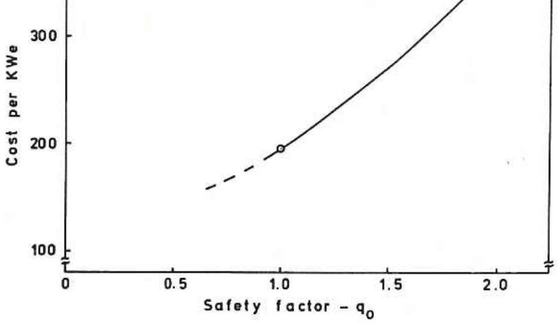

Fig 2. Effect of safety factor on cost.

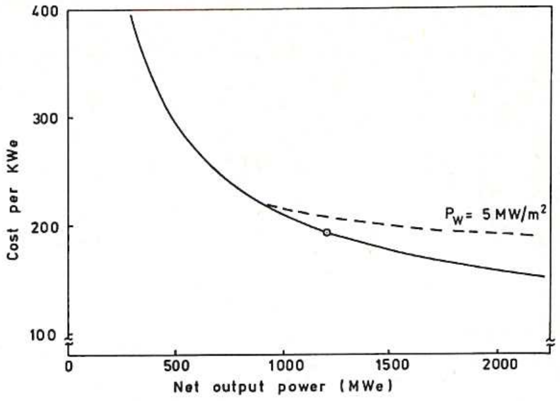

Fig 3. Effect of power output on cost.

It is well known that the space required for the blanket and shield on the inboard side is an important parameter in determining the cost of a reactor. In the standard design it was fixed at 1.5 m, and the effect of changes in the range 1.0 to 2.5 m is shown in fig 4. Increasing the inboard space to 2.0 m increases the unit cost by 20%. The corresponding space on the outboard side is 4.0 m to allow full access for maintenance and repair of the reactor, and here a 0.5 m increase only raises the cost by 2%.

The efficiency of conversion of heat to electricity is also important in determining the unit cost. Fig 5 shows the effect of changes in efficiency on the over-simple assumption that the higher temperature operation required for higher efficiency does not imply higher material prices. A more detailed investigation of this relationship would be valuable, but is beyond the scope of this study.

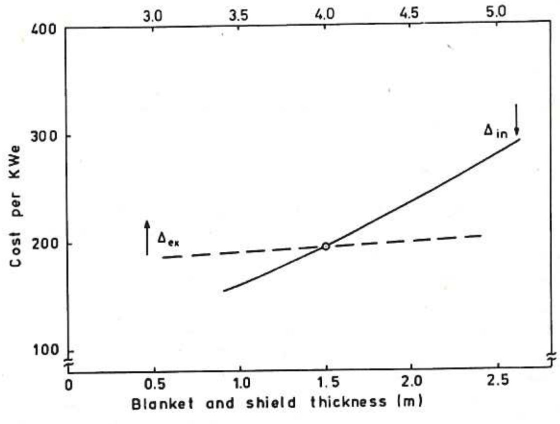

Fig 4. Effect of blanket and shield thickness on cost.

2.3 Wall Loading Limit

In this study the limit on the wall power loading (defined as the total power deposited on, or passing through, the wall) was set at the unrealistically high value

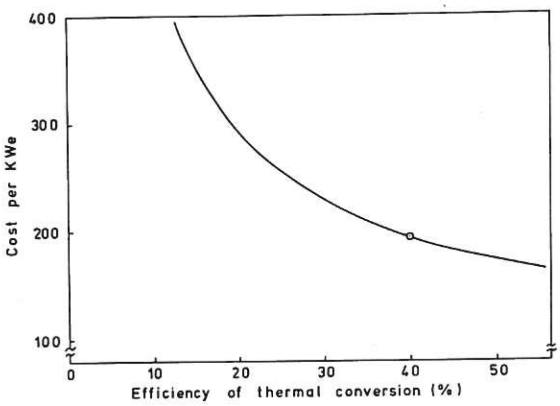

Fig 5. Effect of efficiency of thermal conversion on cost.

of 20 MW/m^2. In most cases, however, as seen in fig 6, minimum costs were obtained with lower levels of wall loading, and only for reactors of output power exceeding 1000 MW$_e$ does the optimum level exceed a value of 5 MW/m^2 which has been considered practical in several reactor designs. As already noted, the cost advantage of large reactors is closely associated with the possibility of operating with high wall loadings, and with wall loadings below about 3 MW/m^2 the advantage of reactors with power outputs above 600 MWe almost disappears.

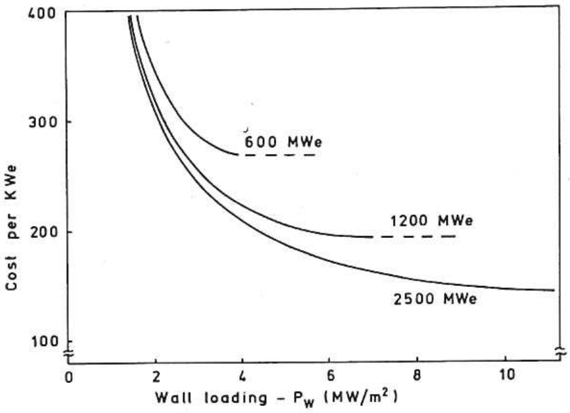

Fig 6. Effect of wall loading on cost.

Since one of the least certain factors in the physics assumptions is the value of poloidal beta, it is of interest to investigate how the optimum wall loading changes with beta. The variation of the optimum wall loading is shown in fig. 7, together with the optimum maximum toroidal magnetic field. The optimum wall loading increases with increasing beta, but saturates until the maximum magnetic field in the core reaches its limit and then increases again. Decreasing the limiting value of the maximum core magnetic field increases the optimum wall loading, whereas at lower values of beta reducing the maximum toroidal magnetic field decreases the optimum wall loading. It is concluded that improvements in the achievable value of beta, which are desirable to reduce capital costs, also require an increase in the wall loading. However, as seen from fig. 1, the effect on the cost of limiting the wall loading at higher values of beta is not strong, which shows that the optimum is rather broad.

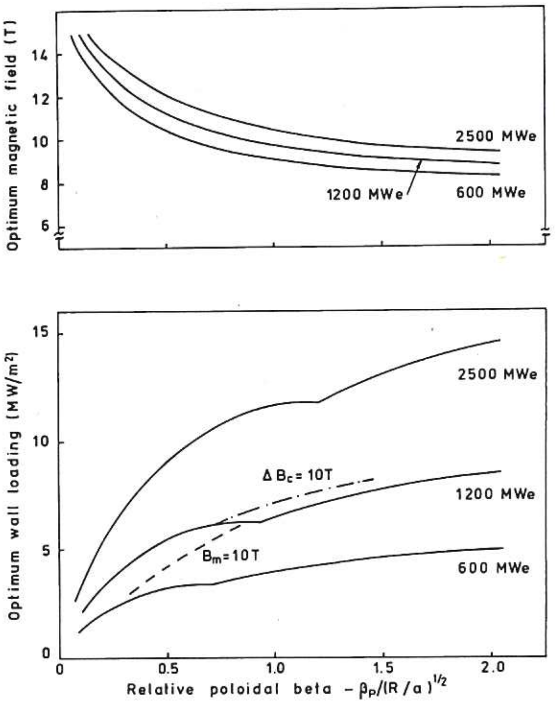

Fig 7. Optimum wall loading and toroidal magnetic field.

2.4 Magnetic Field Limits

In the present study the upper limits for the maximum toroidal magnetic field (i.e. the magnetic field at the inboard surface of the toroidal field coil) and the maximum core magnetic field were set at the high value of 15 T. In all cases of interest the minimum costs are obtained with values of the maximum toroidal magnetic field below 15 T, as seen in fig 8. The cost penalty of using lower levels of maximum core magnetic field is quite small , as seen in fig 9, unless values below about 5 T are specified.

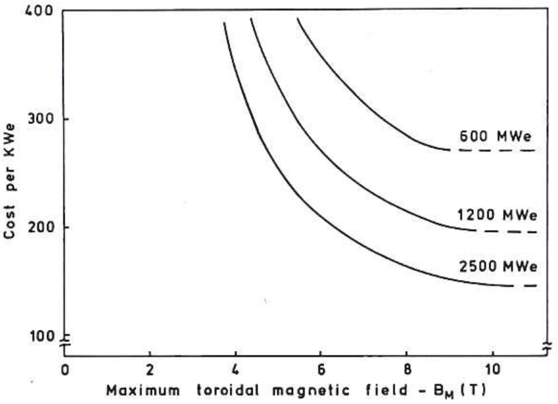

Fig 8. Effect of maximum toroidal magnetic field on cost.

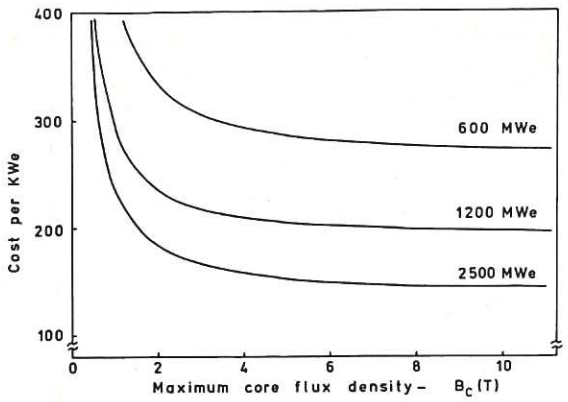

Fig 9. Effect of maximum core flux density on cost.

The optimum value of maximum toroidal magnetic field is around 10 T, and does not depend strongly on the reactor size. It is also seen from fig. 7 that it does not depend strongly on the poloidal beta assumed. Thus under the conditions assumed in this study a value in the range 8 to 10 T gives costs close to the minimum, and either niobium-titanium or niobium-tin superconductor could be used, depending on the margin of safety and reliability required.

2.5 Sensitivities

To judge the relative importance of the variables considered in the previous sections, the sensitivity of the cost to changes in each variable are shown in table IV. The sensitivity, S, is the slope of the curve of unit cost, C, as a function of a variable V, i.e. $S = (V/C)\ (dC/dV)$. In some cases the sensitivity is zero, because the optimum value of the variable is less than the higher limit used for the standard design. The highest values of the sensitivity are obtained for the plasma safety factor q_o and the blanket and shield thickness, but as indicated before the chosen values for these parameters are already optimistic. Nevertheless, means of controlling the plasma pressure profile to reduce the safety factor throughout the plasma might be effective in minimising costs, and a redistribution of the breeding blanket with a low level of tritium breeding in a thin blanket on the inboard side of the reactor and a high level over the larger outboard area could also be effective.

3. CONCLUSIONS

The effects of several changes in design parameters on the unit cost of a tokamak reactor have been studied. No single change leads to a substantial cost reduction, and the parameters which most strongly influence the cost such as the plasma safety factor q_o or the blanket and shield thickness have already been set at levels which are unlikely to be significantly improved. Thus reducing tokamak reactor costs must depend on improving all physics and engineering parameters or finding cheaper means of achieving the same parameters.

The optimum level of wall loading increases with the power output of the reactor and the value of poloidal beta obtainable. Reductions in unit costs can be achieved if these three parameters can all be increased, but neither increases in beta or power output are effective if the wall loading is limited to values below the optimum. For values of poloidal beta greater than the square-root of the aspect ratio and values of output power above 1200 MWe the optimum wall loading exceeds values used in many tokamak reactor designs, and thus the limitation on wall loading emerges as a major factor in raising the unit costs.

The optimum level of the maximum toroidal magnetic field is in the range 8 to 10 T for a range of other variables, and the sensitivity to the chosen value of maximum core magnetic field is low so that most reactor designs are already close to optimum in these respects. For this reason, and because the optimum wall loading is roughly proportional to the power output, the physical sizes of most optimised designs are similar. Thus the maintenance concepts developed with the Mk II design will remain valid for a range of optimum designs.

The analysis undertaken here is intended to illustrate the relative importance of various parameters in determining the capital cost of a tokamak reactor, and to indicate the ways in which this cost might be reduced. The study is far from complete and does not include several effects such as changes in ellipticity of the plasma cross-section, alternative structural materials or operating temperatures or the implications of different divertor systems, and much remains to be done in reducing the cost of fusion reactors to an economically attractive level.

4. REFERENCES

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