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A B S T R A C T

The Reversed Field Pinch is an axisymmetric toroidal magnetic system in which the stable confinement of high β plasma has already been demonstrated experimentally. This study has reviewed the plasma physics relevant to a reactor based on the Reversed Field Pinch, defined a possible set of reactor parameters and undertaken a preliminary consideration of the mechanical and electrical engineering problems of this system. The design assumes pulsed operation without refuelling during the burn, ignition by ohmic heating alone, and the use of normal (i.e. not superconducting) magnetic field windings. For the chosen net output of 600 MW(e) and mean neutron wall loading of 1.5 MW/m^2 the plasma minor and major radii are 1.75 m and 16 m respectively. The energy multiplication factor Q of the system is 5.9.

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1. INTRODUCTION

The Reversed Field Pinch is an axisymmetric toroidal magnetic system in which the stable confinement of plasma at high values of the plasma pressure ratio β has already been demonstrated experimentally. The first exploratory studies for a reactor based on the Reversed Field Pinch(1,2) were reported in 1969, and the main potential advantages and problems with this approach were identified at that time. The objectives of this present study are to undertake a conceptual reactor design which will exploit most profitably the characteristics of the Reversed Field Pinch configuration, to develop this design to a level comparable with the more commonly studied Tokamak, and to comment on the implications of reactor considerations for the present plasma physics programme. This paper is an intermediate report on the study at the stage where the plasma physics relevant to a reactor has been reviewed, a possible set of parameters for a reactor has been defined, and preliminary consideration has been given to the mechanical and electrical engineering design of the system. It is already clear, however, that there are major uncertainties in the plasma physics which must be elucidated in future experiments and that much more thought must be given to the concept before it can be judged as the basis of a practical fusion reactor.

The Reversed Field Pinch confines plasma by a combination of toroidal and poloidal magnetic fields and, in contrast to the Tokamak, operates with a toroidal plasma current above the Kruskal-Shafranov limit (i.e. $q < 1$). MHD stability is maintained by ensuring that there is no minimum in the radial variation of magnetic pitch ($P = rB_\phi/B_\theta$) inside the plasma, which requires a reversed toroidal magnetic field in the outer regions of the configuration. The special features of the Reversed Field Pinch which are important in the present study are:-

i) The high value of β, resulting in lower levels of magnetic field being required than in present Tokamak reactor designs.

ii) The need for an electrically conducting shell close to the plasma to maintain plasma stability. If this shell is flux-conserving it also allows the magnetic field profiles to be established by the process of self-reversal.

iii) The possibility of ignition by ohmic heating alone, arising from the high current density in the plasma and the helical current configuration.

iv) The transient nature of the required plasma and magnetic field profiles, which are assumed to decay at a rate consistent with classical plasma resistivity.

v) No upper limit on the choice of toroidal aspect ratio is imposed by plasma physics considerations.

An early decision in the study was to consider a pulsed unrefuelled reactor, because of uncertainties in the means of refuelling the plasma and exhausting reaction products. The exhaust problem is particularly serious in the Reversed Field Pinch since the precise magnetic field profiles required and the presence of the conducting shell appear to preclude the use of a divertor. A second decision was to use normal (i.e. not superconducting) magnetic field windings. Whereas in a Tokamak it only appears economic to operate with a superconducting toroidal field winding, the high value of β in the Reversed Field Pinch allows the possibility of normal windings. The pulsed nature of the device increases the difficulty of using superconducting windings. A third decision was to rely on ohmic heating alone to achieve ignition of the fuel, both because this possibility is one of the advantages of the Reversed Field Pinch and because the cost of auxiliary heating at a power level exceeding the ohmic power will be very high.

A final decision was to fix the net power output of the reactor at 600 MW(e). The majority of Tokamak reactor designs have a net output in the range 1000 to 2500 MW(e), due to the requirements for a large minor radius for adequate plasma confinement at practical levels of magnetic field and an economic wall power loading. Whilst such sizes may be a reasonable extrapolation of current trends in power station construction, it is open to question whether such trends will continue in the future and whether fusion stations of this size are desirable. It will certainly be advisable to construct much smaller units when fusion reactors are first introduced and before their reliability and acceptability has been demonstrated.

2. PHYSICAL PRINCIPLES

One cycle of pulsed operation includes the following phases:-

i) Setting-up, which involves the establishment of the required magnetic field profiles on a time-scale determined by the plasma current rise-time.

ii) Heating, during which the plasma temperature is increased to the ignition point and then to its operating level.

iii) The burn, during which the nuclear reactions occur.

iv) Run-down, which terminates the burn and allows the current to be reduced to zero.

v) An off-time, during which fuel and reaction products are evacuated from the reactor and new fuel supplied.

The relevant physical processes occurring during the first four of these phases will be reviewed, and have been discussed in greater detail by Lawson.[3]

2.1 Setting-up phase The required magnetic field profiles are assumed to be obtained by self-reversal of an initial toroidal magnetic field inside a flux-conserving conducting shell when the toroidal plasma current is induced. Plasma turbulence during this phase results in high energy losses to the reactor wall and a flux swing in the transformer core in excess of the flux required to support the current change. The current rise-time must be a compromise between a fast rise which will minimise these losses and a slow rise which will ease the energy transfer problems. Uncertainties in the scaling laws for the losses allow only a range of possibilities to be considered, but a rise-time of 0.5 seconds was taken as being both physically realistic and practically possible.

2.2 Plasma heating The plasma is heated by ohmic dissipation and α-particles from nuclear reactions, and cooled by radiation and conduction losses. A simple power balance neglecting the conduction losses, gives a criterion for ignition of the form:

$$a^3 < f(T_b, \beta_\theta)/P_n$$

where a is the reactor minor radius, and P_n the neutron power loading of the reactor wall. Thus ignition by ohmic heating alone requires a small minor radius, which for wall loadings of 2 MW/m^2 and the assumed reactor operating conditions ($T_b \sim 10$ keV, $\beta_\theta \sim 0.35$) cannot exceed 3 m. More extensive computer calculations show that radii of about 2 m, corresponding to heating times of the order 5 seconds, are required for the optimum reactor.

2.3 Burn phase The main requirement during the burn phase is that sufficient energy should be released in nuclear reactions. This may be evaluated in terms of an energy multiplication factor Q, defined as the useful thermal energy released in the reactor divided by the net electrical energy required to establish and maintain the plasma, and depends on the variation of plasma parameters during the burn. Assuming that plasma stability requires the plasma boundary to remain close to the conducting shell, useful values of Q are only obtained if the plasma temperature is controlled at a low value (10-25 keV) by means of enhanced energy loss from the plasma. The mechanism for this control process is at present unknown, although there is speculation that it could be provided naturally through the limitation on β. The assumption concerning the plasma boundary and its consequences are the major differences between this reactor design and the Reversed Field Pinch reactor proposed by Los Alamos.[4]

Gross stability of the plasma is maintained in present experiments by the presence of a conducting shell, whose time-constant is much greater than the plasma confinement time. In a reactor the shell will have a short time-constant (see Section 5), and must be supplemented by active feed-back coils behind the blanket, programming of the toroidal magnetic field outside the shell and a vertical magnetic field. The shell itself will be constructed in segments, but a minimum length of about four times the reactor minor radius is judged necessary. This requirement implies a large toroidal aspect ratio.

The duration of the burn phase will be in the range 20 to 60 seconds. It is assumed that the fuel particle confinement time is long compared with the burn time, and values of the product $n\tau_p$ of 10^{22} $m^{-3}s$ are required.

2.4 Run-down phase It is envisaged that the plasma current will be reduced to zero in a time comparable with the current rise-time, i.e. 0.5 seconds. Two main requirements are that any energy stored in the plasma which is deposited on the reactor wall must be fairly uniformly distributed to prevent the formation of hot-spots and structural damage, and that as high a proportion as possible of the magnetic energy should be directly recovered by the storage system so that it is available for the next cycle. In the absence of any model of the physical processes during the run-down phase it is assumed that 40% of the energy inside the conducting shell can be directly recovered.

3. REACTOR PARAMETERS

The ultimate aim of any reactor design study will be to obtain the lowest possible electricity generating costs consistent with operational and safety requirements. A design criterion which has been used in many fusion reactor studies, however, is the optimization of the energy multiplication factor Q of the system. A minimum acceptable level of Q is in the range 10 to 20, corresponding to a fractional recirculating power of 25 to 12.5% with an efficiency of conversion of thermal to electrical power of 40%. In this study both the energy multiplication factor and the total power station capital cost have been considered, but where they lead to differing conclusions the cost has generally been taken as the better indication. The capital costs have been estimated on the basis of costs derived in the Culham Mk I Tokamak reactor study,(5) and are quoted in £/kW(e) at 1976 values. Further details of the arguments behind the choice of parameters are given by Hancox and Spears.(6)

3.1 Assumptions and constraints For the purposes of this study plasma pressure and magnetic field profiles derived by Robinson(7) were used, with the position of the conducting shell adjusted to give a pinch parameter θ of 2 and a reversal parameter F of -0.75. The limiting plasma pressure ratio β_θ (= 4×10^7 NkT/I^2) for which this profile is assumed to be stable is 0.35. To calculate the burn-up of fuel the plasma temperature was assumed to be constant across the profile and the density to fall to zero at the wall.

Of the engineering constraints assumed, the most important is the maximum allowable reactor wall power loading. Tokamak reactor studies show that high wall loadings lead to the most economic designs, with the limit set by radiation damage and the frequency with which the wall must be replaced. Most Tokamak studies, however, assume a divertor to reduce the direct interaction of the plasma with the wall. In the present Reversed Field Pinch reactor no such divertor is included, and consequently plasma temperature stabilization requires that the reaction energy imparted to the α-particles (3.5 MeV/reaction) must be deposited directly on the wall. Thus lower wall loadings must be used, and in this study a mean neutron wall loading of 1.5 MW/m^2 (based on 14.1 MeV/reaction) averaged over the whole cycle is assumed, corresponding to a mean total wall loading of 2.2 MW/m^2.

Other constraints and assumptions are shown in Table 1.

3.2 Parameter survey Within the specified constraints all the free parameters have been varied to obtain an optimised system. A choice also exists between iron cored and air cored reactors and the survey has been carried through for both of these options. In the air cored reactor the ratio of the current in the poloidal field winding during the burn to the plasma current is an additional free parameter, but was taken to be unity at this stage subject to the more detailed considerations of the electromagnetic system discussed in Section 4.

An example of a single parameter variation is given in Figure 1, which shows the effect of changing the current density in the magnetic field windings. In this case optimum Q and lowest capital cost are not obtained by the same choice of current density, since substantial increases in Q can be obtained by the use of massive windings operating at a low current density but at an increased cost. The current densities in the poloidal and toroidal field windings were also varied separately, but the choice of a common value of 2.5 MA/m^2 is close to the optimum cost. With this current density the ohmic dissipation in the magnetic field windings accounts for more than half of the net recirculating power in the reactor.

As a result of the survey it was possible to define parameters for alternative iron and air cored reactors with minor radii of 1.70 m and 2.15 m and aspect ratios of 9.0 and 5.7 respectively.

3.3 Sensitivity to assumptions The effect upon the energy multiplication factor Q and station capital cost C of small variations of any parameter, P, have been calculated. The cost sensitivities defined as (dC/dP).(P/C), are shown in Table 1. Of the plasma parameters, the most important is β_θ: a reduction in the assumed value from 0.35 to 0.25 increases the station capital costs by 30%. It is therefore important in future experiments to establish the practically achievable level of β_θ with plasma profiles which are usable under reactor conditions.

The wall power loading and net power output are the most important engineering parameters affecting the capital cost. If technically possible, higher loadings would have given lower costs although in a 600 MW(e) reactor only small gains can be achieved before reaching a limit imposed by the maximum allowable magnetic flux density in the core. In reactors of higher net output power, the possible economic advantage of higher wall loadings is greater.

The variation of capital cost with net reactor power output is shown in Figure 2. At low powers the limitation of magnetic flux density in the core gives a steep dependence, but the cost becomes almost independent of size for large units. This is due to the strong dependence of plasma heating time on plasma radius, which forces the optimisation to large aspect ratios and roughly constant minor radius. Thus the requirement to ignite the reactor by ohmic heating alone removes the economic advantage of large reactors, and is consistent with the initial choice of small unit size for this study.

3.4 Choice of parameters In making the final choice of parameters it was necessary to take into account the result of preliminary engineering studies. In particular, the minor radius is influenced by the difficulty of maintenance in a reactor which includes a conducting shell close to the first wall. In order to be effective this shell should have a length at least four times its radius, and this length determines the minimum length of a reactor segment which could be removed for servicing. A low aspect ratio reactor could only be divided into a few segments of large weight. For this reason the reactor parameters were adjusted to a common first wall radius of 1.75 m, which corresponds to a segment weight of 350 tonnes.

The choice between iron cored and air cored reactors depends on a more detailed analysis of the electromagnetic system. This is discussed in the next section and leads to the choice of an air cored reactor, both because it eliminates the expensive iron core and because there is a greater flexibility in the optimisation which allows a further reduction of capital cost. The final parameters are shown in Table 2, and a simplified view of the reactor in Figure 3. The energy multiplication factor Q of 5.9 is low and is a major factor leading to the high cost of 980 £/kW(e). This cost is nearly a factor 3 greater than an equivalent fission reactor station costed on the same basis.

4. ELECTROMAGNETIC SYSTEM

Early studies of Reversed Field Pinch reactors identified the electromagnetic energy storage and transfer system as an important part of the complete reactor system. In particular, the electromagnetic system links the pulsed reactor with the electricity distribution network which requires a steady power input so that its design must fulfil external constraints as well as internal requirements. Two alternatives are considered, in which the toroidal plasma current is induced by either an air cored or iron cored transformer. The ability of these alternatives to fulfil the required duties at lowest overall capital cost have been compared. Further details of the analysis have been given by Bobbio et al.[8]

4.1 Air cored transformer Establishment of the required magnetic field profiles in the plasma requires three sets of external windings. The toroidal field winding provides the initial toroidal magnetic field and maintains the reversed toroidal field during the burn. The poloidal field winding induces the toroidal plasma current and through the self-reversal of the toroidal magnetic field provides the majority of the magnetic energy in the reactor. A vertical magnetic field is also required to maintain gross plasma equilibrium in the toroidal geometry, and must be proportional to the plasma current.

The division of current between the poloidal field and vertical field windings is arbitrary. An idealised case is a poloidal field winding which is smoothly distributed around the minor circumference of the reactor in such a way as to produce no vertical field in the plasma, and a separate vertical field winding which has zero mutual inductance to the poloidal field winding. Two disadvantages are apparent with this approach. Firstly, the windings must in practice be distributed in such a way that gaps are available for access to the reactor, which results in a non-uniform current distribution in the windings. Secondly, some adjacent parts of the two windings carry currents in the opposite directions, so that the ohmic dissipation is higher than is necessary.

The preferred solution is to use a vertical field winding in which all currents flow in the same direction as in the poloidal field winding and to arrange that the current changes in both windings are driven by the same applied voltage. Thus the two windings together form the primary winding of the transformer, which requires that the turns ratio between the two windings is suitably chosen. The poloidal field winding may be biased before start-up, since it produces no vertical field, but the vertical field winding must carry zero current until the plasma current is induced. A computed distribution of the winding thicknesses with such an arrangement and the operating cycle described in Section 4.3 is shown in Figure 4.

In addition to the windings described above it may be desirable with the air cored transformer, to use an active winding at some distance from the reactor to compensate stray magnetic fields.

4.2 Iron cored transformer A reactor with an iron core differs in two main respects from the air cored case considered above. Firstly, due to the iron, the vertical field configuration cannot be described by a simple analytic expression and the required winding distribution must be computed. A lower field is required because of the stabilizing effect of the iron core. Secondly, the magnetizing current is small, so the primary current must be approximately equal to the induced plasma current and the poloidal field and vertical field windings can be combined to act together as the primary winding of the transformer. The magnetic field in the iron core may be biased before start-up to double the allowable flux swing.

The required distribution of currents for the reactor with an iron cored transformer is also shown in Figure 4. Compared with the air cored reactor the windings are more concentrated in the outer regions. One effect of this distribution is that the cross-sectional area of the iron required in the central core of the transformer is about 20% less than in the outer limbs. Even so, the radius of the core required is 9.8 m which is more than 60% of the reactor major radius and makes the transformer the most expensive component of the reactor.

4.3 Energy storage and transfer The most convenient and economic form of energy storage for use with a pulsed Reversed Field Pinch reactor appears to be homopolar generators, which with constant excitation flux have the circuit characteristics of a capacitor. Electrical and mechanical power losses in these generators have been assessed, and are included in the circulating energy analysis.

Simplified energy transfer circuits, for both air and iron cored reactors have been analysed and the energy storage required and the total system capital cost assessed. The reactor with an air cored transformer is preferred because it is substantially cheaper. The air cored system also has greater flexibility, allowing the level of stored energy to be minimised. In general an asymmetric current swing may be obtained by the use of two energy stores, but the optimum case is found to be a symmetric current swing with equal currents in the primary winding during the burn and off-times, for which a single store is sufficient. Since the homopolar generators are discharged during the burn and off-times in this particular case, it is actually the primary winding inductance which acts as the store whilst the homopolar generators act as a transfer element. The generators act mainly to store excess energy during the setting-up and run-down phases, so that both the power generated by the turbo-alternators and the power supplied by the power station are constant. The operating procedure during the setting-up phase, based on the simplified circuit shown in Figure 5, is then:-

i) Initially all the poloidal field energy is stored in the poloidal field winding inductance L_m, with switches S_p and S_v open and S_m closed.

ii) The plasma, represented by L_p and S_p, is ionized and the vertical field winding is connected in parallel with the poloidal field winding i.e. S_p and S_v are closed.

iii) Energy is transferred to the plasma by opening S_m. The voltage across the homopolar generator rises to a maximum and falls again as the plasma current rises. At peak plasma current S_m is closed.

iv) During the steady burn, ohmic losses in the windings are supplied by a steady power input from the feed points A,B.

During the run-down phase the reverse procedure is followed, with ohmic losses again being supplied during the off-time from the feed points A,B. The overall efficiency could be increased by reducing the current in the poloidal field winding to zero after de-ionization of the plasma, but the cost of the additional store required outweighs the savings.

5. ENGINEERING CONCEPTS

The mechanical arrangement of the components of the reactor first wall, blanket and shield is determined by the need for access for maintenance and repair operations. It is anticipated that some components will need to be replaced every five years due to the effects of radiation damage in the structural materials. The maintenance concepts proposed are similar to those adopted in the Culham Mk II Tokamak reactor,[9] and involve the division of the blanket into segments which may be removed horizontally from a permanent shield and vacuum vessel. Removal operations must be simple to achieve a high reactor availability, and conceived with the knowledge that remotely controlled machines will have to be used. A possible structural arrangement for the first wall and blanket is illustrated in Figure 6. Further details of the reactor layout have been given by Hollis and Mitchell.[10]

5.1 Reactor wall The inner wall of the nuclear blanket faces the plasma and receives as a surface power loading both the nuclear energy released to the α-particles during the burn and the plasma energy lost during the setting-up and run-down phases. These amount to 20% of the total energy released, so that efficient cooling must be provided. The first wall structure must be as thin as possible, however, since excessive structural material reduces the tritium breeding ratio and increases the energy deposition due to neutron and γ-ray absorption in the bulk of the material.

The wall is modelled on the membrane wall tube assembly used in fossil fuelled station boilers, but constructed from niobium for strength and good thermal characteristics. The tubes are welded together by electron beam welding, and are aligned in the toroidal direction to minimise temperature gradients in the structure round the minor circumference. Helium coolant is distributed to the tubes through manifolds at each end of the segment. The estimated film and bulk temperature drops are 130°C and 30°C, and gas outlet temperatures up to 550°C should be practical. It is expected that it will be necessary to weld sections of the wall together, thus forming a continuous liner, to eliminate arcing between sections. This would be achieved by means of a welding machine inserted into the reactor through vacuum pumping ports.

5.2 Conducting shell The conducting shell immediately behind the first wall of the reactor to provide plasma stabilization is a feature of the Reversed Field Pinch which has no parallel in Tokamak reactors. The aluminium or copper conductor adversely affects the tritium breeding ratio and absorbs energy from the neutrons to such an extent that only 2 to 5 cm of shell is tolerable. The effective time-constant of the shell is therefore limited to 0.5 seconds, which is comparable with the current rise-time. As with the reactor wall efficient cooling must be provided and a tubular construction is proposed, but to obtain high electrical conductivity in both directions rectangular tubes are used which are electron beam welded over their entire thickness.

An additional problem with the conducting shell is that it must be kept at a relatively low temperature to maintain good electrical conductivity and structural strength. Even with aluminium or copper alloys a maximum allowable shell temperature will be 400°C, corresponding to a coolant temperature of 300°C. Thus the shell must operate at a temperature at least 200°C below that of the physically adjacent first wall and blanket, and thermal insulation must be included on both sides of the shell, which is an additional constructional complication. Although operation of the shell at much lower temperatures would give a longer effective time-constant, not only would the thermal insulation problem be more severe but the useful heat lost from the reactor output would further reduce the energy multiplication factor Q and increase the station cost by up to 25%.

The possibility of cutting and welding the conducting shell in situ as part of a routine maintenance operation, with the objective of reducing the size of the blanket segment which must be removed in one piece, is considered remote. The shell is far less accessible than the first wall, with the result that the operation would be time-consuming and adversely affect reactor availability. The need to remove complete segments of the shell leads to the upper limit on the minor radius adopted in Section 3.4 and a corresponding lower limit on the toroidal aspect ratio.

5.3 Breeding blanket and shield Behind the reactor first wall and conducting shell lie the breeding blanket, inner shield, active stabilizing coils and coolant ducting, fixed outer shield and magnet windings. To reduce the circulating magnetic energy the total distance from the conducting shell to the main windings must be kept to a minimum and for this reason a thin blanket based on a General Atomic design[11] has been adopted, containing lithium-lead, lithium oxide, graphite and an inner shield within an inconel structure. The thickness of the different regions are shown in Table 3, together with the proportion of energy deposited in each and the total breeding ratios when used in conjunction with copper or aluminium shells.

Within each segment the blanket is constructed from individual cells, the maximum dimensions of which are determined by the requirement to minimise eddy current losses in the pulsed magnetic field. The losses depend on the effective electrical resistivity of the blanket and if this is taken to be resistivity of its major constituent, which is graphite, a 2% loss per cycle with a 0.5 second current rise-time limits the maximum cell size to 0.7 m.

Behind the blanket are situated the active stabilizing coils constructed from mineral insulated copper conductors, with 16 coils in each segment. In the same region ducts distribute the helium coolant to the individual blanket cells.

The shield is in two separate layers, the inner shield being thick enough to limit the radiation damage in the outer shield which forms a part of the permanent reactor structure. The outer shield also acts as a pressure boundary between the internal vacuum region and the controlled atmosphere of the reactor building, both as part of the primary vacuum envelope and as a second stage of tritium containment. It has vacuum tight doors through which the blanket segments are removed for maintenance.

A single 0.8 m diameter vacuum port is provided through the blanket and shield for each segment. The free volume to be pumped is 80 m^3 per segment, and a 50 m^3/s pump will allow the gas to be pumped down to the operating pressure in 5 seconds.

5.4 Reactor maintenance When necessary, segments of the reactor first wall and blanket can be removed for repair in local workshops, and new segments substituted to maintain reactor availability. The possibility of moving the toroidal field windings together with the complete reactor segment during a maintenance operation has been rejected because the total weight involved exceeds 1000 tonnes. The alternative is to move the windings side-ways to provide clearance for the removal of a segment. This is possible if two toroidal field windings are used for each segment, symmetrically placed to give equal spacing around the reactor. The windings associated with the segment to be removed can then be parked in positions at the ends of the adjacent segments. To allow free movement some additional space is required between the outer shield and the windings, and the two axes are slightly off-set; the ripple in the toroidal magnetic field at the plasma surface with this arrangement is ± 2%. Any other structure between the coils must be removed, ducts and services to the segment disconnected, and the vacuum door removed, before the blanket segments can be withdrawn.

6. CONCLUSIONS

The study has been limited to consideration of a pulsed, unrefuelled, Reversed Field Pinch reactor with normal (i.e. not superconducting) magnetic field windings. Ignition was assumed to be possible with ohmic heating alone. The unit size was fixed at 600 MW(e) net output. Alternative parameters were assessed in terms of their effects on the energy multiplication of the system Q and the station capital cost, and a preliminary concept of the reactor and energy transfer system has been developed. The main conclusions drawn at this stage of the study are:-

i) The reactor minor radius is limited by the requirement for ignition by ohmic heating and by the need to reduce the weight of segments removed for maintenance. A radius of 1.75 m was chosen.

ii) The control of plasma temperature at a low level is essential for achieving a net energy gain. A value of 10 keV was chosen as being close to the optimum. No suitable control mechanism is known.

iii) Plasma temperature control and the absence of a divertor imply that 20% of the energy released is deposited directly on the first wall. This, together with the cyclic nature of the reactor, severely limits the allowable wall neutron loading. A mean neutron wall loading of 1.5 MW/m^2 was assumed.

iv) The thickness of the conducting shell required for plasma stabilization is limited by its effect on tritium breeding and energy deposition in the blanket. Its time constant is limited to 0.5 seconds. The shell must therefore be supplemented by active stabilizing windings behind the blanket.

v) With the requirement that power must be supplied continuously to the electricity distribution network, a reactor with an air cored transformer and a symmetric primary current swing gives the lowest station capital cost. If the current density in the windings is chosen to give minimum capital cost, the ohmic dissipation in the windings accounts for more than half the circulating power.

vi) Within the assumptions adopted in this study the optimum reactor has an estimated station capital cost of 980 £/kW(e) and an energy multiplication factor Q of 5.9. A higher value of Q can be obtained at a higher cost.

During the study it has become clear that there are considerable uncertainties in the physical basis of the Reversed Field Pinch reactor. Important topics on which further information is required include: the magnitude and scaling of the energy losses during the setting-up phase, the conditions under which ignition by ohmic heating alone is feasible, the level of β_θ which can be maintained, whether a mechanism exists for plasma temperature control, the effectiveness of a thin conducting shell and active stabilizing coils, the minium length of shell required, and the conditions under which controlled run-down of the plasma can be obtained after the burn.

Extensive studies are also required on several engineering aspects, including the limitations on the first wall loading, the feasibility of welding the wall in situ, the structural implications of the conducting shell, the space requirements of the coolant ducting system, the provision of electrically insulating gaps in the reactor and the efficient control and transfer of energy in the electromagnetic system.

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Authors' note:- Since this is an intermediate report on the study, there may be minor inconsistencies in some quoted numbers and some changes may be necessary as the study is continued.

TABLE 1: Assumptions and constraints in the parameter survey, and the sensitivity of the station capital cost to the values assumed.

	Value	Sensitivity Air Core	Sensitivity Iron Core
Net power output	600 MW	- 0.18	- 0.22
Energy released per reaction	20 MeV	- 0.84	- 0.79
Plasma pressure ratio β_θ	0.35	- 0.66	- 0.67
Mean neutron wall loading	1.5 MW/m^2	- 0.30	- 0.24
Resistivity of windings	2.25×10^{-8} Ωm	0.27	0.26
Thickness of blanket and shield	1.6 m	0.26	0.26
Gross thermal efficiency	40%		
Neutron dose before maintenance	4×10^{26} m^{-2}	- 0.11	- 0.11
Switching losses	5%	0.09	0.04
Efficiency of energy recovery	40%	- 0.03	- 0.03
Max core flux density - air/iron	4.0/1.4 T	0.01	- 0.12
Current rise time	0.5 s	0.05	0.06
Off time	7 s	0.01	0.02

TABLE 2: Parameters for the air cored reactor

Net output power	600 MW(e)
Gross thermal power	2500 MW(th)
First wall radius	1.75 m
Major radius	16 m
Toroidal plasma current	19 MA
Plasma temperature during burn	10 keV
Fractional burn-up of fuel	0.3
Duration of heating phase	4.5 s
Duration of burn phase	27.5 s
Duration of full cycle	40 s
Energy multiplication factor, Q	5.9
Recirculating power fraction	42%
Estimated station capital cost	980 £/kW(e)

TABLE 3: Blanket and shield composition, energy deposition and tritium breeding ratios.

Zone	Thickness (cm)	Composition	Energy deposition (MeV/reaction) 2.5cm Cu	Energy deposition (MeV/reaction) 5.0cm Al
First wall	2.5	Niobium	4.2	4.2
Shell	2.5/5.0	Copper/Aluminium	3.8	3.0
Front Blanket	13.5	Lithium-lead graphite, inconel	4.1	4.0
Rear Blanket	18.0	Lithium-oxide graphite, inconel	3.5	3.2
Shield	20.0	Water, St.steel	0.6	0.6
Coils and duct	21.0	Copper, St.steel	0.1	0.1
			16.3	15.1
	Tritium breeding ratio		1.18	1.09

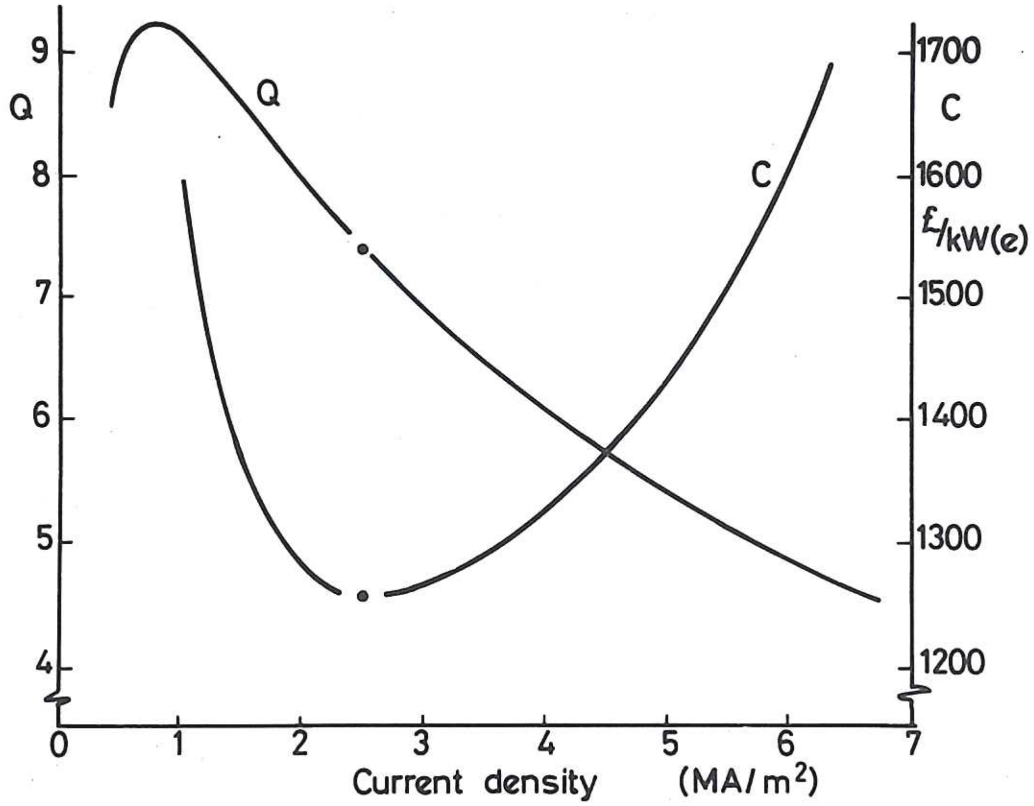

Fig.1 Variation of Q and station capital cost C as functions of the winding current density, for an iron cored reactor.

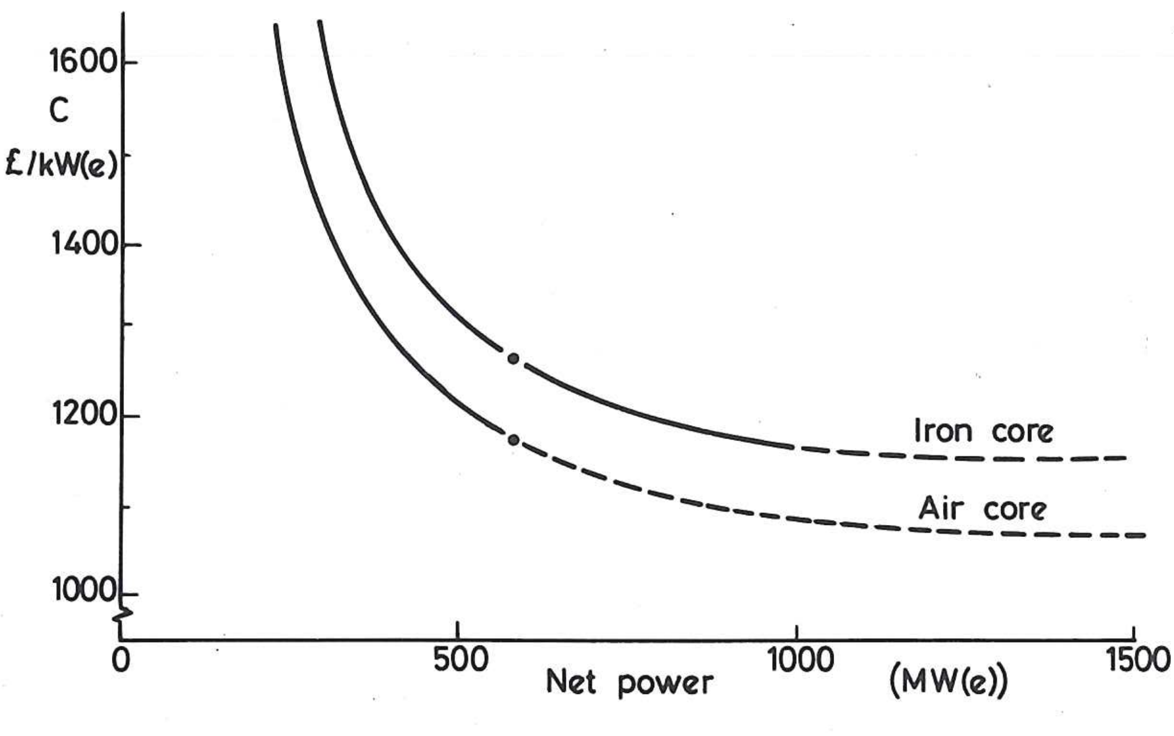

Fig.2 Variation of station capital cost with net power output. Dashed curve indicates that core flux density is below limiting value.

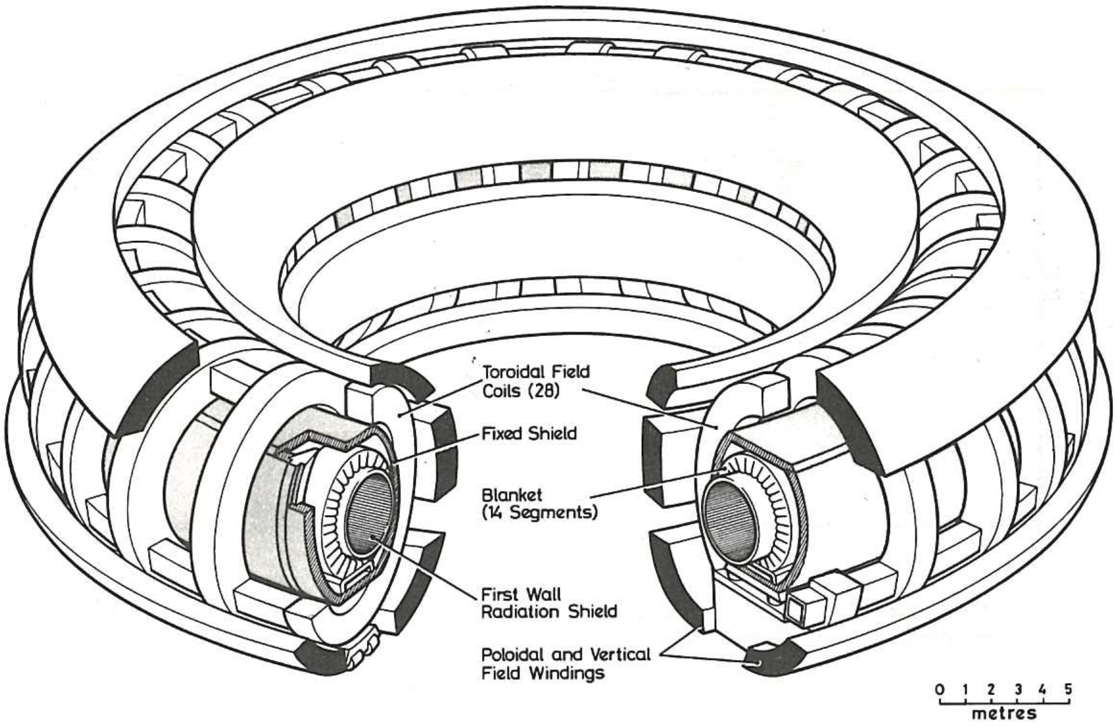

Fig.3 Artist's impression of the 600 MW(e) Reversed Field Pinch reactor.

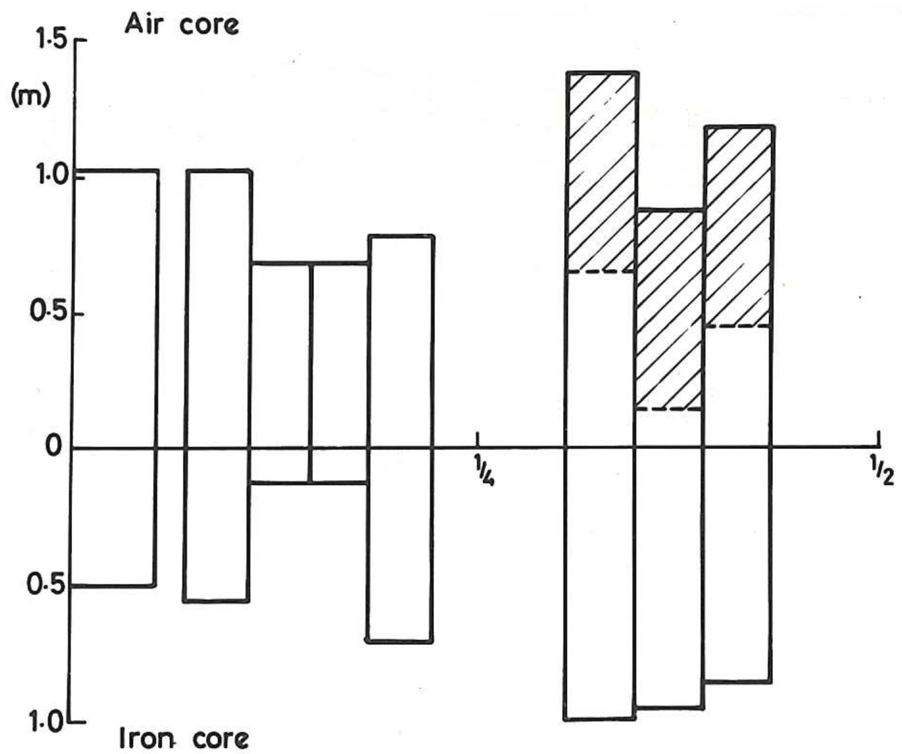

Fig.4 Distribution of primary winding thickness around the minor circumference of air cored and iron cored reactors. Space occupied by separate vertical field windings is shaded.

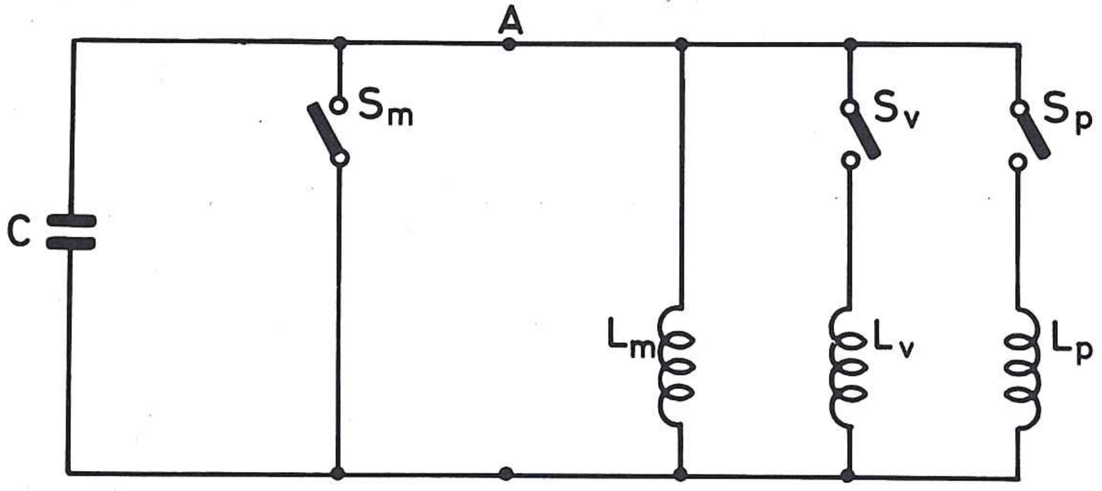

Fig.5 Simplified circuit diagram for energy transfer for the poloidal and vertical field windings of an air cored reactor.

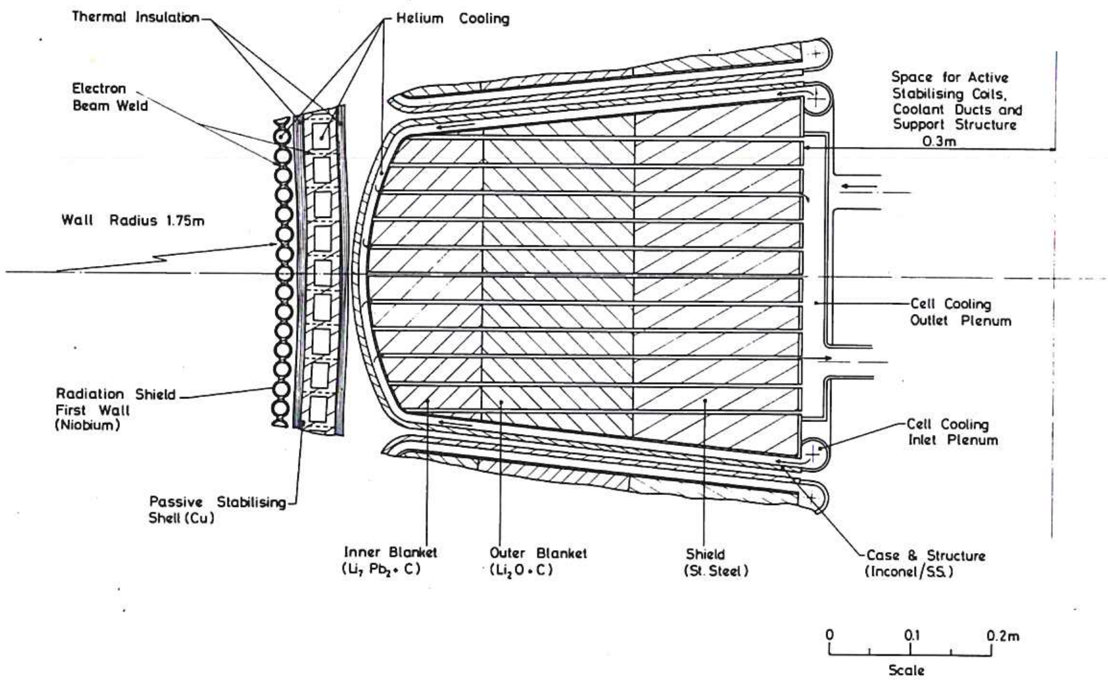

Fig.6 Schematic arrangement of principal components of the blanket.