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ELECTRICAL ENGINEERING PROBLEMS IN PULSED MAGNETICALLY CONFINED FUSION REACTORS

by

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ABSTRACT

Electrical engineering problems are considered for pulsed magnetically confined toroidal fusion reactors. These are based on the Theta-pinch, Reverse Field Pinch and Tokamak magnetic field configurations. The major problems are concerned with the magnetic field system (eddy current losses and transient forces), pulsed power supplies and associated aspects such as circulating power fraction and economic factors. All systems require the transfer of several 1,000 MJ at high efficiency and with peak power ratings probably more than 5 times the plant electrical output. A solution of this problem may require that the pulsed field energy (MJ) be no more than about 3 times the reactor nuclear power (MW) and transferred in a time > 1.0 s. This condition is most likely to be met in the Reverse Field Pinch and Tokamak systems, since the Theta-Pinch proposal is based on a transfer time of 30 ms. Of these two alternatives the Reversed Field Pinch using copper coils appears to be the least complex and cheapest system, because the Tokamak requires additionally a large high field superconducting field system and probably extra plasma heating.

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(1) INTRODUCTION

Magnetically confined toroidal fusion reactors have been proposed for pulsed operation based on Theta-Pinch(1), Reversed Field Pinch(2,3,4) and Tokamak(5) magnetic field configurations. These pulsed reactors differ from continuous or quasi-continuous reactors in that they do not require fuelling during the pulse or need a magnetic diverter. Some of the important electrical engineering design problems that are particularly relevant in pulsed reactors are considered for the above systems. These are mainly associated with the magnetic field system, pulsed power supplies and resulting problems concerned with circulating power and economic aspects. However, it is only possible to discuss these problems realistically if they are based on self-consistent reactor parameters (especially as regards dimensions and power supply ratings). The relevant parameters are therefore first summarised for the three systems.

A detailed system design study for a Theta-Pinch Reactor (TPR) has been made at Los Alamos as reported by Ribe et al(1) and will be used here as a basis for discussion. A detailed design study of the Reversed Field Pinch Reactor (RFPR) has not recently been carried out. Therefore, to enable a valid comparison of the RFPR to be made with the other systems, new RFPR parameters are proposed. These are based on assumptions similar to those made for the other two systems and other current reactor studies. The Tokamak alternative considered has dimensions close to those used by the Wisconsin University group in their study of a quasi-continuous Tokamak(6). Studies of a pulsed Tokamak reactor have also been made as reported by Fraas(5) and of Tokamak pulsed field systems by Knobloch et al(10).

(2) REACTOR PARAMETERS

2.1 Theta-Pinch Reactor (TPR)

The parameters of the reference theta-pinch reactor (referred to as RTPR) proposed by Ribe(1) are summarised in Table 1 for a blanket radial depth of 0.4 m. It will be seen below that the blanket depth is a very critical design parameter, so that parameters for a hypothetical blanket depth of 0.9 m are

SYSTEM	θ-PINCH (1350 MW_E)		REVERSED FIELD PINCH (600 MW_E)				TOKAMAK (1400 MW_E)			
ALTERNATIVE	0.4 m BLANKET	0.9 m BLANKET	COPPER WINDINGS (R)		SUPERCONDUCTING WINDINGS (S)		OPTIMISTIC PLASMA (O)		PESSIMISTIC PLASMA (P)	
Z-CIRCUIT φ_z			1.2 LI	2 LI	1.2 LI	2 LI	1.2 LI	2 LI	1.2 LI	2 LI
DIMENSIONS (m)										
Major Radius (R)	56	56	12	12	12	12	13	13	13	13
Plasma Radius (r_p)	0.11 (min)	0.11 (min)	2	2	2	2	5	5	5	5
Wall Radius (r_w)	0.5	0.5	3	3	3	3	5.5	5.5	5.5	5.5
Blanket Depth (Δr_b)	0.4	0.9	0.5	0.5	1.7	1.7	1.7	1.7	1.7	1.7
Coil Depth (Δr_c)	0.4	0.4	1.0	1.0	0.3	0.7	0.9 + 0.5	0.9 + 0.5	2.0 + 0.7	2.0 + 0.7
Coil Radii (r_c)	0.9/1.3	1.4/1.8	3.5/4.5	3.5/4.5	4.7/5.0	4.7/5.4	7.2/8.6	7.2/8.6	7.2/9.9	7.2/9.9
THERMONUCLEAR RATINGS (MW)										
Thermonuclear (P_{TH})	3300	3300	1775	1775	1775	1775	3540	3540	3540	3540
Mean Elec. (P_E)	1350	980	520	470	590	510	1270	1200	1180	980
Plasma Vol. (m^3)	220/14	280/14	950	950	950	950	6400	6400	6400	6400
Wall Area (m^2)	1110	1110	1420	1420	1420	1420	2830	2830	2830	2830
Wall Density	3.2	3.2	1.3	1.3	1.3	1.3	1.25	1.25	1.25	1.25
PLASMA PARAMETERS										
q							1.75	1.75	3.0	3.0
β_θ			0.4	0.4	0.4	0.4	1.07	1.07	0.5	0.5
β	1.0	1.0	0.4	0.4	0.4	0.4	0.052	0.052	0.008	0.008
T (keV)	20 (max)	20 (max)	20	20	20	20	11	11	11	11
n (cm^{-3})	2.5×10^{16}	2.5×10^{16}	0.7×10^{14}	0.7×10^{14}	0.7×10^{14}	0.7×10^{14}	0.8×10^{14}	0.8×10^{14}	0.8×10^{14}	0.8×10^{14}
B_θ (kG)	-	-	22.5	22.5	22.5	22.5	8.4	8.4	12.3	12.3
I_z/I_m (MA)	-	-	22.5/0	22.5/0	22.5/0	22.5/47	21/38.7	21/87	30.7/64.5	30.7/145
B_z (kG)	110	110	7.5	7.5	7.5	7.5	38	38	94	94
I_θ (MA)	3100	3100	45	45	45	45	247	247	610	610
ELECTRICAL PARAMETERS										
φ_z (Vs)			365	608	451	694	317	528	532	866
W_z (MJ)	-	-	5,800	9,600	71,150	10,600	4,700	7,800	11,400	19,000
W_m (MJ)	-	-	0 (Iron)	0 (Iron)	0 (Iron)	15,900	6,100	17,000	23,000	64,000
W_θ (MJ)	63,000	141,000	1,100	1,100	1,500	1,500	94,500	94,500	580,000	580,000
Total W_{BT} (MJ)	63,000	141,000	6,900	10,700	8,600	28,000	105,300	119,300	614,400	663,000
Core Area (m^2)	-	-	191	191	160	154	66	66	34	34

Table 1

General Parameters of Pulsed Reactor Systems also given to illustrate this aspect. The plasma dimensions are 56 m major radius and 0.5/0.11 m minor radius to give 3600 MW_{TH}. The proposed pulse length is about 100 ms and the cycle time about 10 s.

2.2 Reverse Field-Pinch Reactor (RFPR)

Previous system parameters published for a proposed RFPR were based on first wall loadings much higher than the 1 to 2 MW/m^2 now thought to be desirable. Modified parameters are therefore now proposed in Table 1, based on a wall loading of 1.3 MW/m^2 and a major radius of 12 m. These are similar to those recently proposed by the Wisconsin University group(6) in their studies of a quasi-continuous Tokamak reactor.

The plasma aspect ratio ($A = R/r_p$) is chosen as 6.0, so that with copper windings an iron cored transformer can be used to establish the plasma current (I_z). The choice of parameters was also aimed at achieving a convenient power unit size of 1775 MW_{TH} and 600 MW_E. However, no optimisation of performance has been carried out so that further detailed studies will be necessary to obtain optimum parameters.

Alternative sets of parameters are given in Table 1 to take account of the use of superconducting (S) and copper (R) windings with their differing blanket dimensions. It has already been pointed out that one of the major advantages of the RFPR is that since its field values are so low, the use of copper windings is possible(3). The blanket depth for these windings is arbitrarily chosen as 0.5 m for comparison with the RTPR. Variation of the I_z circuit volt-seconds (φ_z) between 1.2 L_zI_z and 2.0 L_zI_z where L_z is the plasma inductance, is also considered. These alternatives are designated:

Copper windings, Iron Core	1.2 L_zI_z	- RI(1.2)
Copper windings, Iron Core	2 L_zI_z	- RI(2)
Superconducting winding, Iron Core	1.2 L_zI_z	- SI(1.2)
Superconducting winding, Air Core	2 L_zI_z	- SA(2)

2.3 Tokamak Reactor

The dimensions chosen for the Tokamak Reactor are based on those proposed in the Wisconsin University study of a quasi-continuous reactor(6). Alternative plasma parameters referred to as optimistic (O) and pessimistic (P) are considered and also variation of the I_z circuit volt-seconds φ_z as discussed above for the RFPR. The optimistic parameters are similar to those normally used as a basis for present Tokamak reactor studies, whereas the pessimistic values are near those at present being achieved in Tokamak experiments. The large difference between these sets of parameters is a very significant factor in assessing the feasibility of Tokamak reactors(4).

The alternative sets of parameters are designated as follows:

Optimistic, 1.2 L_zI_z - O(1.2)
Optimistic, 2 L_zI_z - O(2)
Pessimistic, 1.2 L_zI_z - P(1.2)
Pessimistic, 2 L_zI_z - P(2)

(3) SYSTEM DESIGN ASPECTS

3.1 I_z Circuit (RFPR and Tokamak)

In the RFPR and Tokamak, supplying the pulsed energy to establish the I_z plasma current is one of the most formidable engineering problems to be overcome. This energy is dependent on the peak current I_z and φ_z the associated volt-seconds required in the transformer core. In present experiments φ_z is usually about 2 L_zI_z where L_z is the maximum plasma secondary inductance(4). However, it may be possible, in principle, to reduce this to say, 1.2 L_zI_z.

The energy (W_z) supplied to the plasma circuit is assumed to be:

$$W_z = 0.7\ (\varphi_z I_z) \qquad \ldots\ (1)$$

The factor 0.7 is chosen to give some margin above a value of 0.5 that would be applicable if the voltage $V_z = L\ {di_z}/{dt}$ with L a constant.

If the transformer magnetising inductance is L_m the magnetising current (I_m) and associated magnetic energy (W_m) are:

$$I_m = \varphi_z/L_m \qquad \ldots\ (2)$$

$$W_m = \frac{1}{2}\ \varphi_z^2/L_m \qquad \ldots\ (3)$$

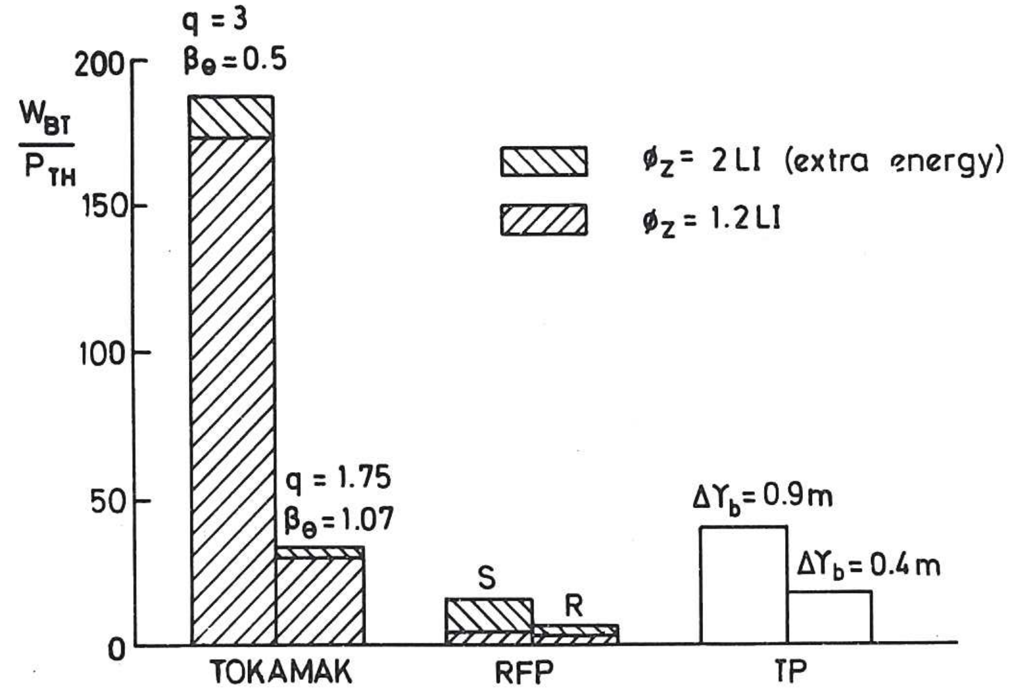
It will be seen from Table 1 that in three of the RFPR alternatives the dimensions, aspect ratio and φ_z are such that an iron core transformer can be used (with a flux swing equivalent to about ± 18 kG) making L_m very large and W_m almost zero. This makes a significant reduction in the total pulsed energy $(W_m + W_z)$ to about 40% of that with an air core. Since $W_m \propto \varphi_z^2$ it is very important, if not essential, that φ_z be minimised if an air core is used.

An important difference between RFPR and Tokamak is the low aspect ratio (A = 2.6) required in the latter case to achieve adequate plasma parameters. This is because β (the plasma/total magnetic pressure ratio) is proportional to $^1/_{A^2}$. This has a significant effect on the design of the I_z circuit transformer, because an air core is almost certain to be necessary with a low value of magnetising inductance L_m. This results in a considerable increase in pulsed magnetic energy in the I_z circuit, as can be seen from Table 1, and an impossibly high field of about 250 kG in the Air Core of the most pessimistic alternative. Further, it should be noted that the Tokamak will require more additional plasma heating, in addition to ohmic heating, than the RFPR and that this energy is not included above.

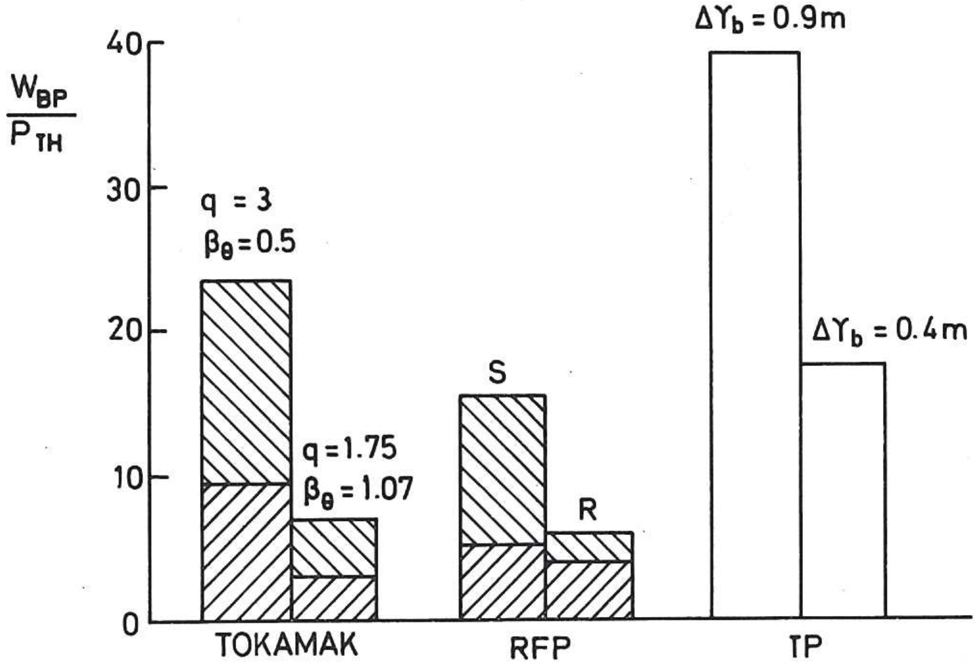
3.2 Magnetic Field Energy Ratios

The magnetic field energy W_θ is also given in Table 1 and hence the total magnetic energy W_{BT} can be obtained. The ratio W_{BT}/P_{TH} (where P_{TH} is the thermonuclear power) is given in Fig.1 for the three reactor systems and also the ratio W_{BP}/P_{TH} where W_{BP} is the pulsed magnetic energy. W_{BT}/P_{TH} is important as regards the overall cost of the reactor system, whereas W_{BP}/P_{TH} indicates how severe are the problems of the pulsed power supply (PPS). It will be seen from Fig.1 that assessment of Tokamak performance is very dependent on the plasma parameters assumed. The pulsed field energy ratios W_{BT}/P_{TH} for the RFPR with copper windings and the Tokamak with optimistic plasma parameters are only about 35% of that for the TPR. If these former systems can be set-up with $\varphi_z = 1.2\ L_z I_z$ their values of W_{BP}/P_{TH} will be only about 25% of that for the TPR.

Since W_{BP}/P_{TH} is very similar for the RFPR and the Tokamak systems, a very approximate cost comparison can be made by allowing for the additional cost of the B_z field in the Tokamak system.



(a) Total field energy ratio



(b) Pulsed field energy ratio

Fig.1 Magnetic Field Energy Ratios.

Such a comparison suggests that the total plant cost/kW_E of the optimistic and pessimistic Tokamak proposals would be about 1.4 times and 2.0 times the corresponding RFPR plant cost, respectively.

3.3 Direct Conversion of Plasma Energy (TPR)

In the RTPR studies by Ribe et al, direct conversion of plasma energy during the expansion phase of the operating cycle is said to be important as regards the overall energy balance and circulating power. The plasma pressure-volume diagram for this system is given in Fig.2 (taken from reference 1), which shows that 9.8 MJ/m of plasma energy (62% of α-particle energy) is recovered into the pulsed power supply (PPS) every pulse. This almost compensates for all the losses in the PPS (2% losses assumed) and field windings, and limits the circulating energy to 6 MJ/m.

A significant parameter in this analysis is the low blanket radial depth (Δr_b) of 0.4 m that is used, since this limits the energy transferred and therefore the losses in the PPS. For example, using the parameters in Table 1 for the hypothetical 0.9 m deep blanket, the circulating energy/pulse would be increased to about 16 MJ/m.

From an electrical engineering point of view, it is useful to consider an operating cycle based on the magnetic field as the working fluid, where ampere-turns i_θ and flux φ_θ are the relevant parameters. In this case the work done per cycle is $\oint(i_\theta \frac{d\varphi_\theta}{dt})dt = \int i_\theta \, d\varphi_\theta$. Such operating cycle diagrams for the two values of Δr_b are given in Fig.3 with the same symbols as in Fig.2. The useful work done is proportional to the area a b c d of the diagram and is the same for both values of Δr_b, whereas the magnetic energy supplied is the area under the diagram and increases appreciably with Δr_b. Since the system losses are proportional to the latter energy, Fig.2 emphasises how inefficient this system might be if the efficiency of the pulsed power supply was not high and the energy supplied was not kept to the minimum, by keeping Δr_b as low as possible.

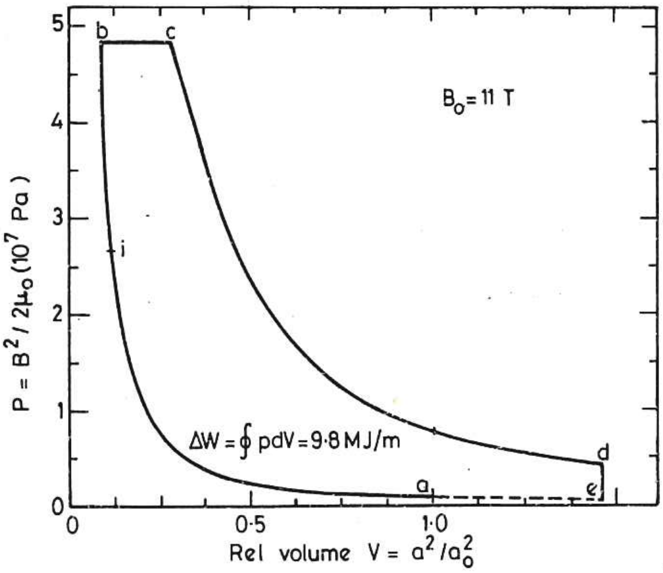


Fig.2 RTPR Plasma Pressure - Volume Diagram.

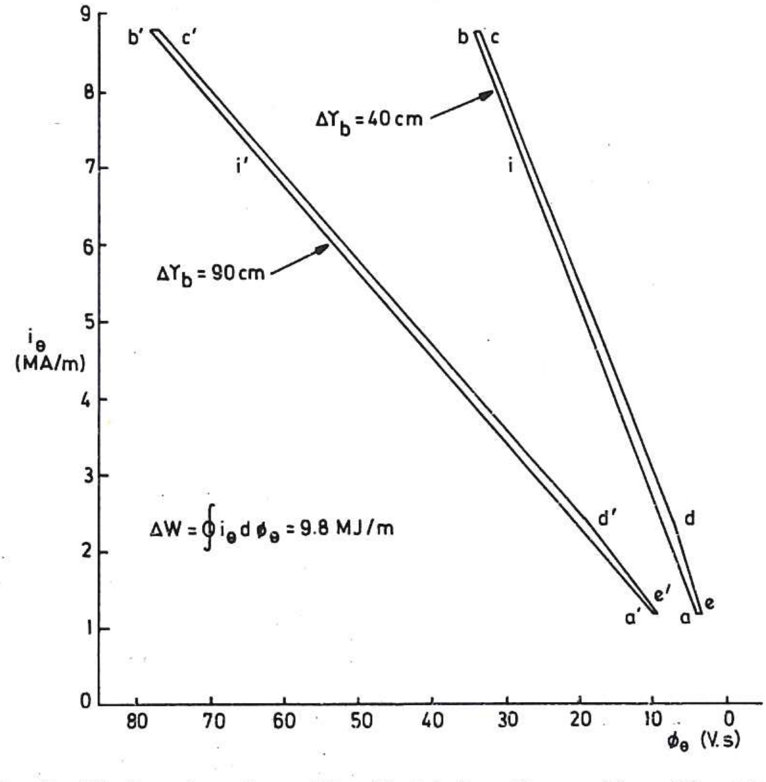


Fig.3 TP Reactor Magnetic Field Amp Turn - Flux Diagram.

3.4 Circulating Power Fraction (ε%)

The circulating power fraction (ε) equals the ratio of the circulating power P_c to the total electrical power generated P_{ET}. It is essential that ε be minimised, possibly to less than 30%, if an economic system is to be achieved. The losses associated with the large PPS makes ε one of the important limiting parameters in pulsed reactors.

Values of ε are plotted in Figs.4, 5 and 6 for the three reactor systems, as a function of the ratio of the losses W_{SL} in the PPS to the pulsed field energy transferred W_{BP}. In calculating P_c it is assumed that 58% of the plasma energy is lost/pulse and that auxiliary plant consumes 2% of P_{ET}.

Values of ε in Fig.4 for the TPR confirm the importance of the direct conversion of plasma energy. They also indicate how critical are the PPS losses W_{SL} and the blanket depth Δr_b. In the case of the RFPR and Tokamak, if the pulse time can be extended to about 100 s, ε is acceptably low (<20%) for all alternatives. However, if in these systems the pulse time is limited to only 10 s and $\varphi_z = 2 L_z I_z$, it may be difficult to achieve values of $\varepsilon < 30\%$, though it should be noted that neither of these systems has yet been optimised to minimise ε. Further investigations are therefore necessary to investigate how ε varies with other parameters, such as aspect ratio and relative dimensions of first wall, blanket and field coils.

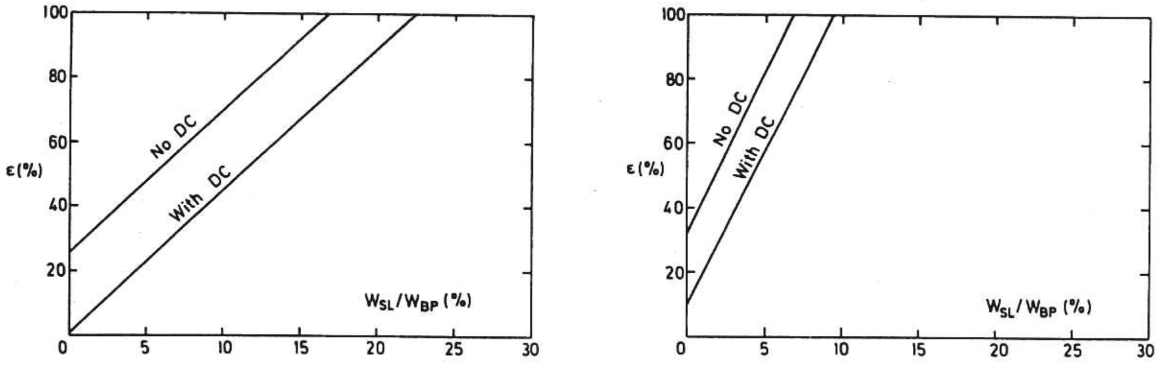
(4) PULSED POWER SUPPLIES (PPS)

4.1 PPS Ratings for RFPR and Tokamak

The peak rating P_S of the PPS if the current rise time is t_r is:-

$$P_S = 2 W_{BP}/t_r$$

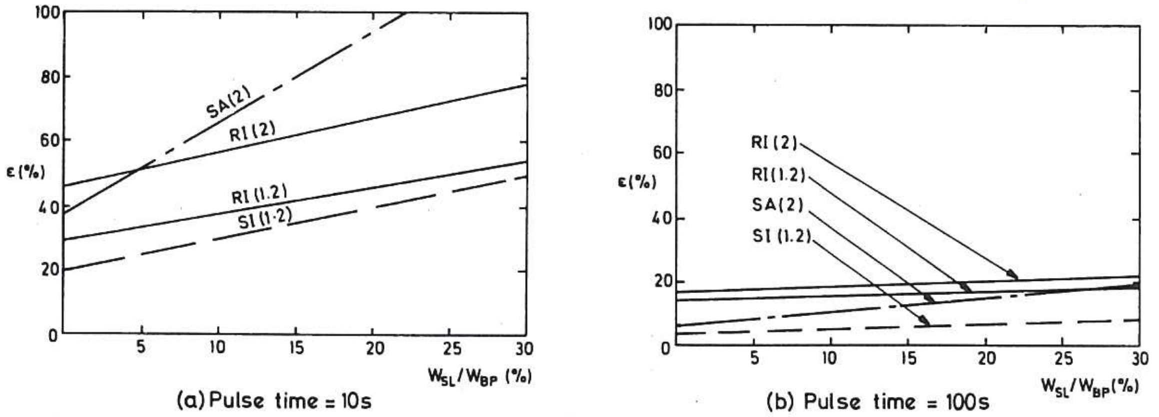
The ratio P_S/P_{EO}, where P_{EO} is the net plant electrical output, is plotted in Figs.7 and 8 for the RFPR and Tokamak, respectively, as a function of t_r. This ratio gives an indication of the relative size and cost of the PPS. The extremely high values of the ratio given in Figs.7 and 8 show how vital it is to minimise the pulsed field energy W_{BP} and maximise the current rise time t_r in pulsed reactors.



(a) Blanket depth (ΔY_b) = 0.4 m

(b) Blanket depth (ΔY_b) = 0.9m

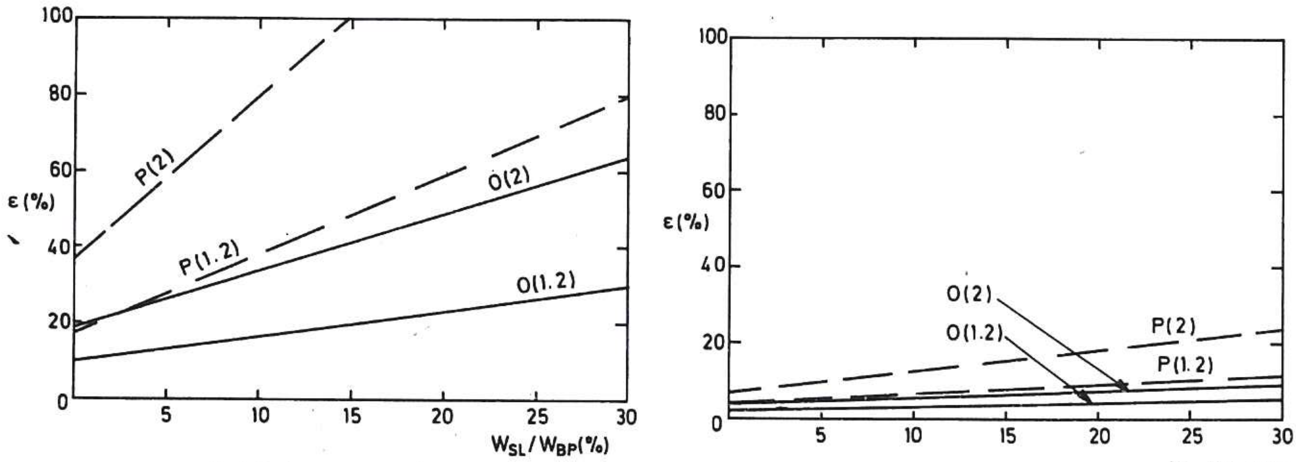
Fig.4 TP Reactor Circulating Power (ε).



(a) Pulse time = 10s

(b) Pulse time = 100s

Fig.5 RFP Reactor Circulating Power (ε).



(a) Pulse time = 10s

(b) Pulse time = 100s

Fig.6 TOKAMAK Reactor Circulating Power (ε).

The values of ε and P_S/P_{EO} that are dependent mainly on economic factors. Both parameters can be high if the total system cost (excluding PPS) and the relative PPS cost is low and vice versa. A general expression can be deduced relating these parameters, as follows:

If PPS cost $= C_{PS}\ P_S$

Basic cost $= C_B\ P_{ET}$
($C_{PS} = 0,\ \varepsilon = 0$)

Total plant cost $= C_P\ P_{EO}$

A specific cost ratio K_c, relating C_{PS} (PPS costs/peak kVA) and C_B (basic cost/kW_E) can be defined as:

$$K_c = C_{PS}/C_B$$

Then $$C_P = C_B\left(\frac{P_{ET}}{P_{EO}} + K_c\,\frac{P_S}{P_{EO}}\right)$$

and the total plant cost ratio C_P/C_B, relating the total plant cost/kW_E including the PPS cost and the effect of circulating power with the basic plant cost/kW_E, excluding the PPS cost and with no circulating power, is given by:

$$\frac{\text{Total cost}/kW_E}{\text{Basic cost}/kW_E\ \left(\begin{matrix}\text{ex PPS}\\ \varepsilon = 0\end{matrix}\right)} = \frac{C_P}{C_B} = \left(\frac{1}{1-\varepsilon} + K_c\,\frac{P_S}{P_{EO}}\right) \quad \ldots (4)$$

Equation (4) is plotted in Fig.9 for values of K_c from 0.5% to 10%. A possible power supply equipment cost could be about 10 UC/peak kVA, compared with a plant cost of perhaps 500 UC/kW_E giving a K_c value of 2%. With this value of K_c Table 2 gives PPS parameters P_S/P_{EO} and t_r for assumed values of C_P/C_B and ε for the RFPR and Tokamak, as deduced from Figs.7, 8 and 9. (1 UC ≈ \$1).

Table 2

PPS Parameters for RFPR and Tokamak
Assumed Parameters $C_P/C_B = 2$, $K_c = 2\%$, $\varepsilon = 30\%$.

Reactor Alternative	RFPR RI (1.2)	RFPR SA (2)	Tokamak O (1.2)	Tokamak P (2)
P_S/P_{EO}	30	30	30	30
P_S (GVA)	17	17	44	44
t_r (s)	0.8	3.6	0.5	3.7

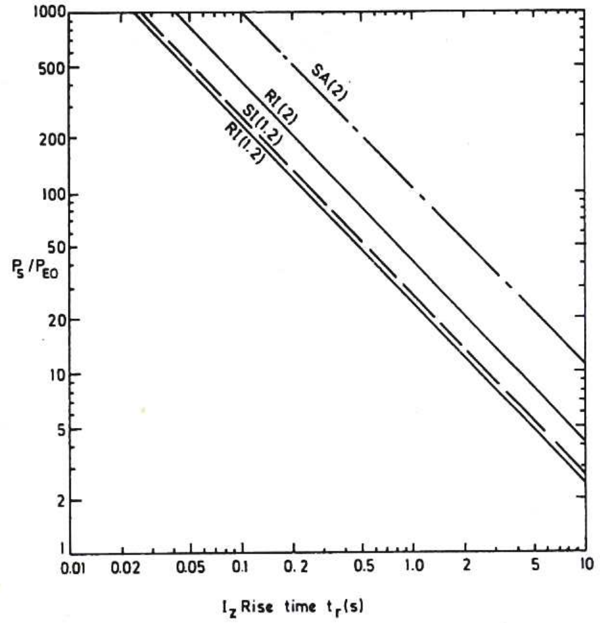


Fig.7 RFP Reactor - Pulsed Power Supply Peak Power Ratio (P_S/P_{EO}).

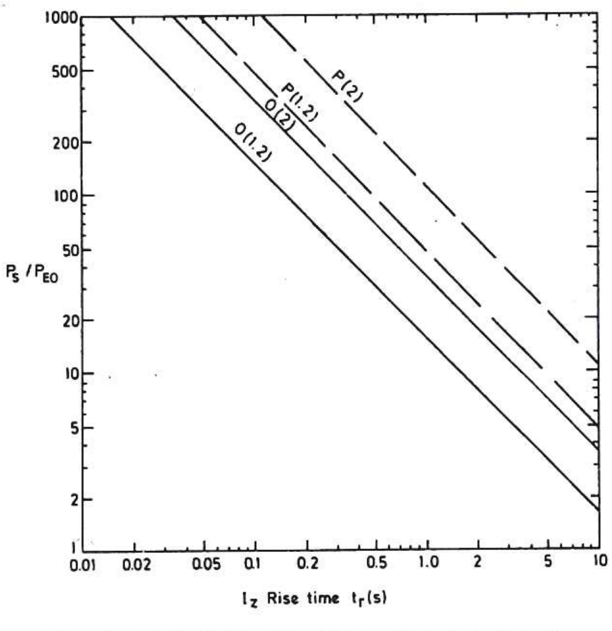


Fig.8 TOKAMAK Reactor - Pulsed Power Supply Peak Power Ratio (P_S/P_{EO}).

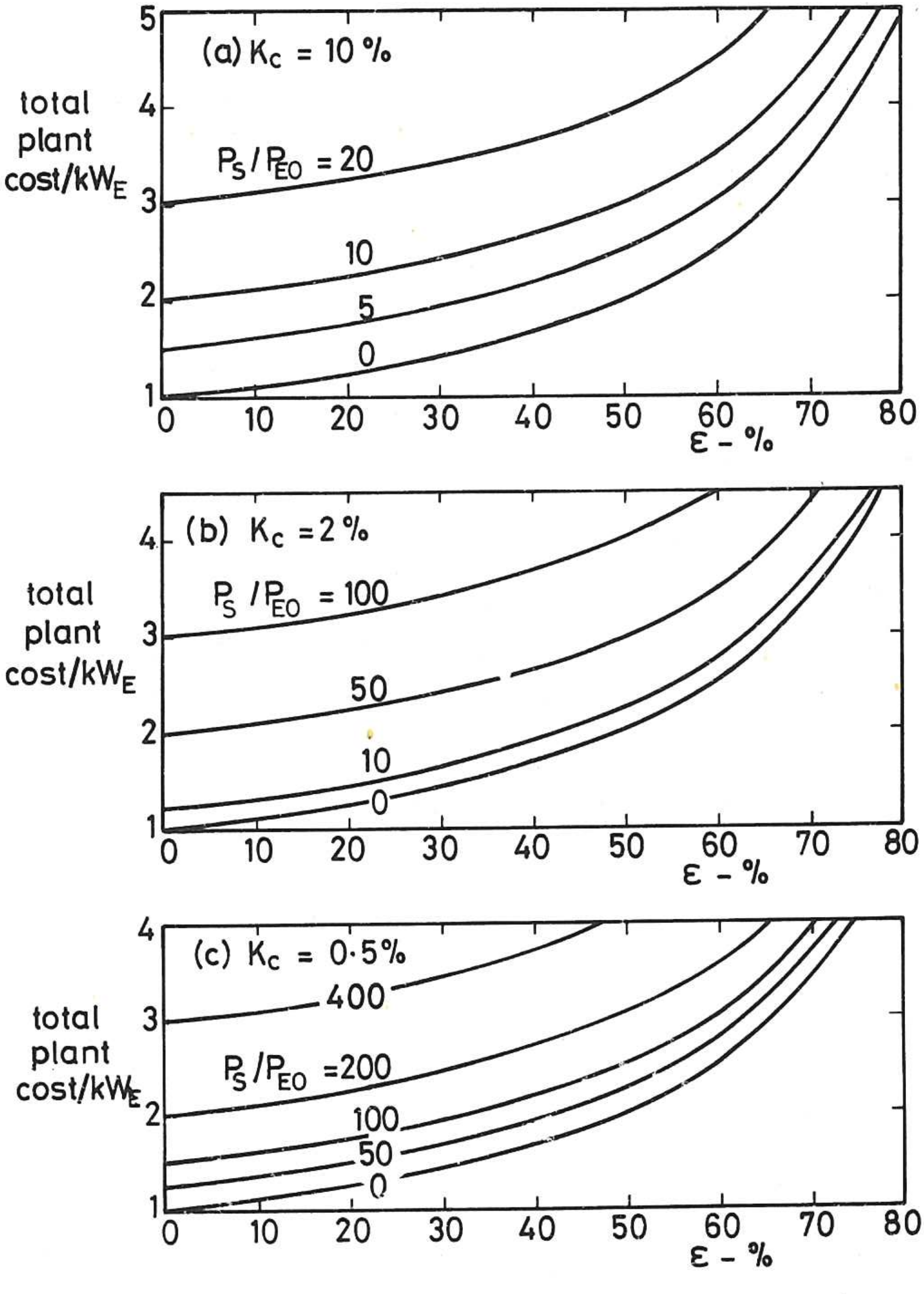


Fig.9 Pulsed Reactor Total Plant Cost (Relative units).

Though the values in Table 2 only represent one range of extremely approximate assumed parameters, they suggest that t_r can be as low as 1.0 s in RFPR and Tokamak systems, only if the optimistic alternatives in Table 1 can be justified. Even with these conditions, where W_{BP} is as low as 3 P_{TH}, the PPS cost would be half the total plant cost, and its peak rating ~ 20 to 40 GVA. The above PPS peak GVA ratings would result in mean energy transfers rates from the PPS of about 8 to 20 GW for plant outputs of only 0.5 to 1.5 GW. Further more detailed studies are obviously required to suggest solutions to such a formidable energy transfer problem.

Possible energy transfer schemes were identified in 1969(3) based on rotating machines, rotating inductive stores (see Section 4.2)(7) and inductive energy stores with rectifier/inverter transfer equipment(8) but little progress seems to have been made since in their evaluation. It is probable that future studies will suggest that rise times of several seconds are necessary to minimise the PPS ratings and total plant cost. In this case a pulse time of, say 50 to 100 s or more would be required, though this may in turn be limited by impurity problems and plasma burn-up. The 20% fractional burn-up time for the proposed RFPR and Tokamak in Table 1 is about 20 s.

4.2 Rotating Inductive Store for TPR

The RTPR proposal requires the transfer of 180 MJ/m or 63 GJ total in 30 ms equivalent to a mean energy transfer rate of 2.1 MMW. This is clearly beyond the capability of any conventional electrical equipment, so that a rotating superconducting inductive storage system, which does not require any circuit switching is being considered as a PPS for this duty(9). Since this energy transfer system was originally proposed by Smith et al(7) in 1967 for a 1.0 s rise time application, a design study of a 1 m diameter prototype has been completed at the Rutherford Laboratory (UK). However, apart from this there does not yet appear to be adequate information on which a judgement of the engineering feasibility of a large number of units operating with a transfer time of 30 ms can be based. An approximate assessment of economic factors can however be made.

The total magnetic energy stored at various times in the rotating store is about six times that transferred or 360 GJ total for the RTPR. Assuming a cost of 5000 UC/MJ stored the total cost for the PPS would be 1800 MUC. The basic plant cost excluding the PPS would be about 750 MUC based on 1500 MW_E and 500 UC/kW_E. Thus, these assumptions would result in a PPS cost about twice the basic plant cost or about 70% of the total plant cost. It is, of course, very difficult to predict the store cost accurately, because it is very dependent on future superconducting costs. On the other hand, compared with the cost/ton of proposed superconducting generators, the above figure of 5000 UC/MJ seems too low by a large margin.

It will be seen from Fig.4 that the percentage loss W_{SL}/W_{BP} in the PPS is a critical factor as regards energy balance, a value of 3% being said to be necessary in the RTPR design study. This means that the losses in the rotating store would need to be as low as 0.5% of the total stored energy. This may be difficult to achieve with magnetic fields changes of perhaps 50 kG occurring in 30 ms.

Thus, the main engineering problems of the proposed rotating store are associated with technical feasibility, cost and losses. However, at the very high PPS ratings required for the RTPR it is difficult to propose a better solution.

4.3 Shock Heating Systems for TPR

The shock heating and compression coil arrangement shown schematically in Fig.10a has been proposed for the RTPR. The equivalent circuit of these two coil systems is shown in Fig.10b. The shock heating coil proposed is an end-fed fractional turn design fed from capacitor banks. The blanket is divided radially into 100 sections to limit the volts between the sections and the eddy current losses in the blanket.

The engineering problems of such a system include the following:

(a) Circuit coupling between the shock heating and compression coil/blanket system.

(b) Low inductance switching and connections in shock heating system.

(c) Cost and reliability of the shock heating capacitor banks.

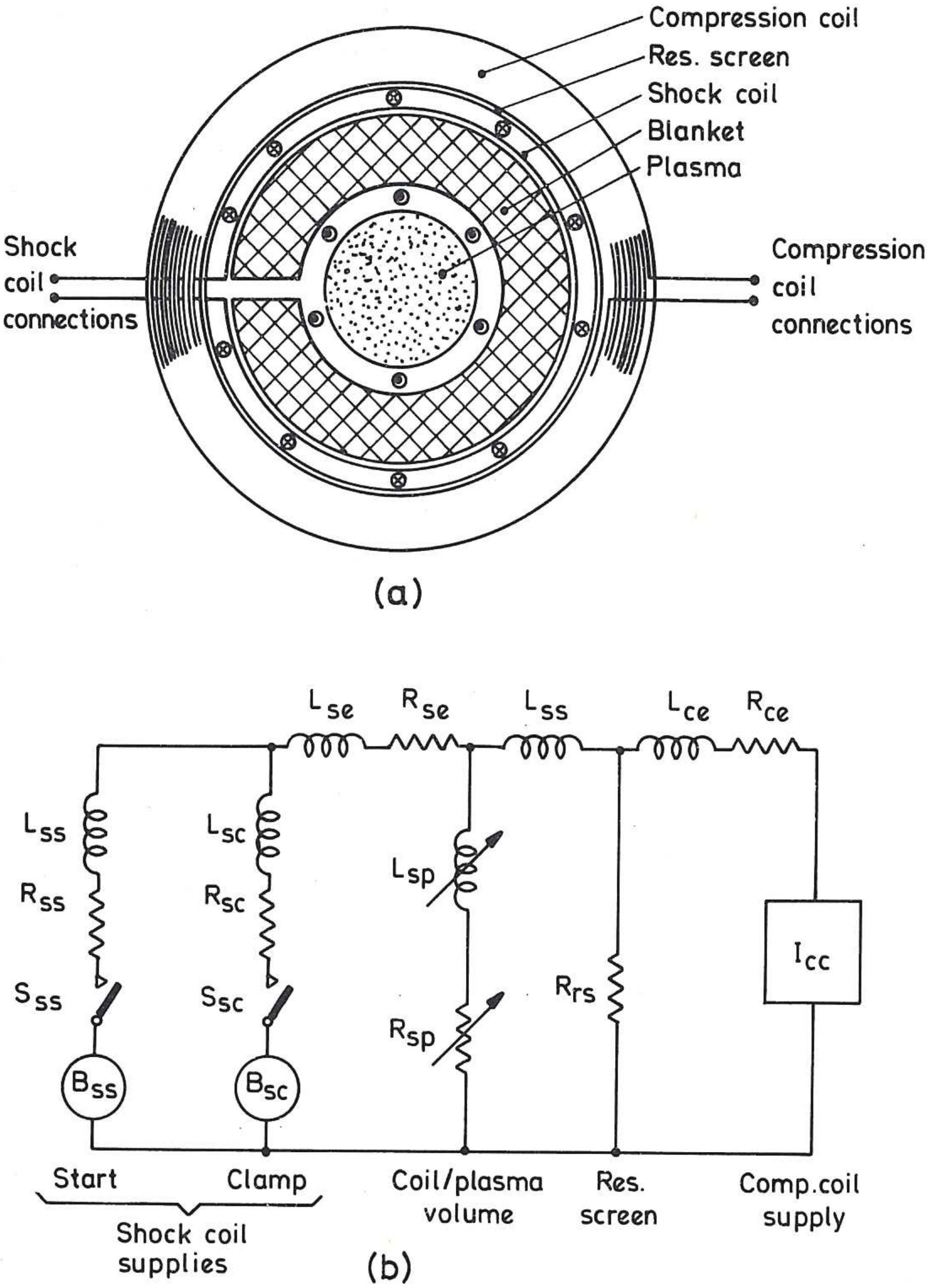


Fig.10 TP Reactor - Magnetic Field System and Equivalent Circuit.

Regarding the circuit coupling problem, since the voltage/turn of the shock heating coils is ~ 650 kV, it will be necessary to prevent any significant flux change inside the multi-turn compression coil, otherwise very high voltages would be induced in it. A possible solution to this problem would be to place a resistive screen R_{rs} inside the compression coil with an adequate distance, say about 10 cm, between it and the shock heating coil. However, it does not appear to be possible to choose suitable inductive (L_{SS}) and resistive (R_{rs}) parameters in Fig.10b to simultaneously limit the induced voltage in the compression coil and the ohmic losses induced in the screen (R_{rs}) during the compression phase. It may also be necessary to isolate the shock heating banks from the compression coil system during the compression phase, which could prove difficult to achieve on such a fast time scale if arcing switches are used.

To achieve the required rise time t_{SH} of ~ 1.0 μs the bank inductance would need to be equivalent to about 0.4 μH/m/turn. This would mean an actual inductance of ~ 4 nH/m for a 60 kV bank and 0.1 turn shock heating coil, or perhaps about 2.0 nH/m each in the bank connections and start bank capacitor/switching units and about 0.2 nH/m in the clamp (or crowbar) circuit. It would appear to be difficult to accommodate such low inductance connections in a 1 m wide module of the reactor and achieve a uniform current flow into the end-fed shock heating coil. The capacitor/switching inductance requirements could, in principle, be met with 20 units/m in the start bank and 200 units/m in the clamp (or crowbar) bank, or 7,000 and 70,000 units, respectively, for the complete TPR. However, switches with the required reliability (possibly < 1 failure in 100 million pulses) and low erosion rates are not thought to be available at present, and may be extremely difficult to develop in the future.

The cost of low inductance capacitor banks with rise times of ~ 1 μs and a life of several million pulses, is expected to be more than 0.8 MUC/MJ. Thus, for the RTPR the 900 MJ banks would cost ~ 700 MUC or ~ 500 UC/kW_E of plant output. This might be of the same order as a possible basic plant cost (see Section 4.2), so that although the energy stored in the shock heating banks is relatively low, their cost is a very important economic factor.

(5) EDDY CURRENT LOSSES

5.1 Eddy Current Losses in Blanket Regions

To reduce the eddy current losses in the blankets of pulsed reactors, it is necessary to minimise the minimum width of electrically conducting regions in the direction of current flow (see Fig.11). It follows that there must also be no closed conducting loops round the minor or major circumference or they must be of very high resistance.

It can be shown(11) that for an exponentially rising external magnetic field (time constant τ_r) the eddy current ratio W_E/W_{BO} of the eddy current losses W_E to the pulsed magnetic energy W_{BO} finally stored inside the conducting region is given by:

$$\frac{W_E}{W_{BO}} = \frac{\tau_b}{\tau_b + \tau_r} \qquad \ldots (5)$$

$$\text{where } \tau_b = \left(\frac{\mu_o}{\rho}\right)\left(\frac{A_f}{S_f}\,\delta_i\right) \qquad \ldots (6)$$

τ_b is the time constant of field diffusion into the region and is dependent on resistivity ρ, ratio of flux area A_f to its perimeter S_f and δ_i an effective current skin depth. The same result will be obtained for a trapezoidal waveform if the rise time $t_r = 2\,\tau_r$.

The eddy current ratio W_E/W_{BO} given by equation (5) is plotted in Fig.11. Assuming that W_E is the same during the rise time and decay time of the field, the total loss ratio is $2W_E/W_{BO}$ This can be deduced as a function of ℓ_θ or ℓ_z from equations (5) and (6) as shown in Fig.12, for a resistivity ρ_b of $35.10^{-8}\,\Omega$m, a value which approximates to that of blanket materials eg Lithium.

It may be desirable to keep $2\,W_E/W_{BP}$ down to about 0.25% as proposed in the RTPR study. If W_{BO} the magnetic energy finally stored in the conducting blanket regions is ~ 25% of W_{BP} then $2\,W_E/W_{BO}$ would be ~ 1.0%. For the RTPR this would require ℓ_θ to be about 1 cm for t_r = 30 ms and for the RFPR ℓ_z would be about 10 cm for t_r = 1.0 s. This value of ℓ_θ is much lower than proposed for the RTPR, though this may be due to the approximate blanket data used here. If circular blanket modules are used their diameter should be limited to these same values.

For a field rise time constant $\tau_r \ll \tau_b$ the eddy current losses W_E equals the magnetic energy W_{BO} giving a loss ratio W_E/W_{BO} = 1. (Refer equation 5). This is the case for the shock heating field of the TPR.

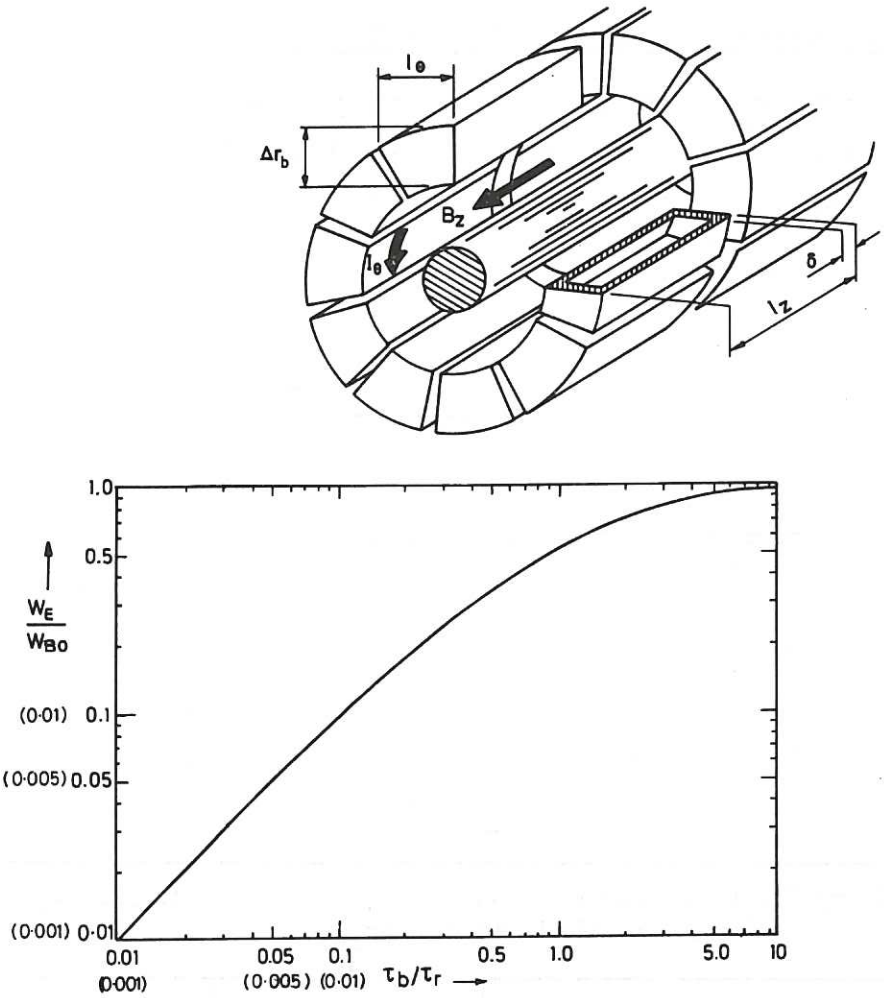


Fig. 11 Pulsed Reactor Blanket Arrangement and Eddy Current Losses Ratio.

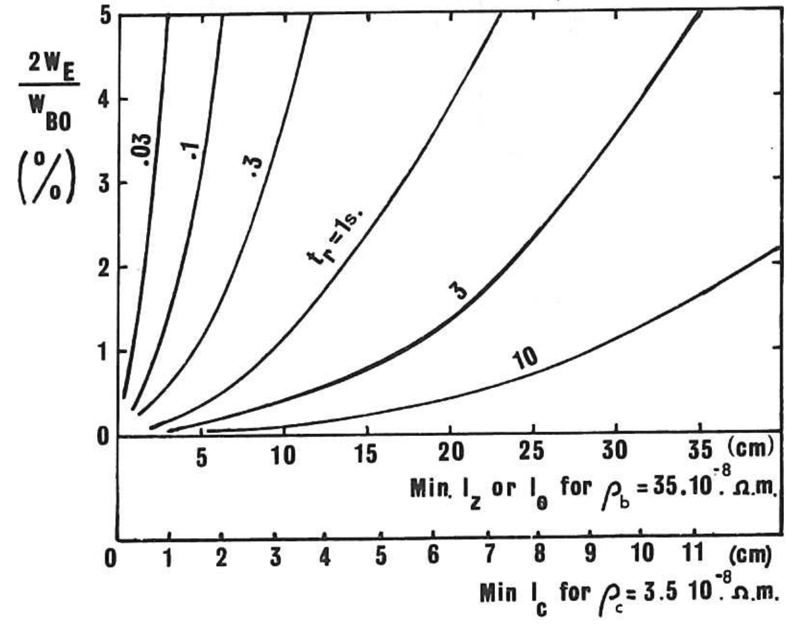


Fig. 12 Total Eddy Current Loss Ratio ($2W_E/W_{BO}$) [t_r = Current rise and decay time].

5.2 Eddy Current Losses in Field Coils

The eddy current losses in the pulsed field coils may be deduced in a similar manner to that described above in Section 5.1 using Fig.12 with ρ_C the conductor resistivity $\sim 3{\cdot}5 \,.\, 10^{-8}\,\Omega\mathrm{m}$. The ratio 2 W_{EC}/W_{RC} of the total eddy current losses (field rise and decay) in a coil to its normal ohmic losses has been shown to be given by$^{(11)}$:-

$$\frac{2\,W_{EC}}{W_{RC}} = \frac{1}{16\,t_r\,t_p}\left(\frac{\mu_o}{\rho}\,\ell_c\,\Delta r_c\right)^2 \qquad \ldots(7)$$

$$= \frac{100}{t_r\,t_p}(\ell_c\,\Delta r_c)^2 \text{ approx. for } \rho_c = 3{\cdot}5 \,.\, 10^{-8}\,\Omega\mathrm{m}$$

and t_p = pulse length.

The conductor thickness ℓ_c required to maintain the loss ratio 2 W_{EC}/W_{RC} at 3% or 30% deduced from equation (7) is given in Table 3 for various typical parameters.

Table 3

Eddy Current Limits on Conductor Thickness ℓ_c (Coil radial depth Δr_c = 1.0 m)					
t_r/t_p	(s)	0.030/0.1		1.0/10.0	
2 W_{EC}/W_{RC}	(%)	3	30	3	30
ℓ_c (cm)	(Max)	0.2	0.7	17.0	54
No. of Conductors	(Min)	500	140	6	2

(6) MAGNETIC FORCES

6.1 Forces on Field Coils

The mechanical stresses on field coils and their support structure are very approximately proportional to the magnetic pressure p_m. The magnetic pressure p_{mc} at the coil radius due to the internal effective magnetic field B_e is given for the three reactor systems in Table 4. The magnetic pressure P_{mA} in the air cores is also given in Table 4. It will be noted that p_{mc} for the TPR and Tokamak is about 50 times, and 7 to 40 times that for the RFPR, respectively. This is to be expected since $p_m \propto \frac{(nT)}{\beta}$ and the RFPR has the advantage of both a relatively low (nT) and a high β, whereas the TPR has a high (nT) and the Tokamak a low β.

Table 4

Effective Magnetic Pressure p_{mc} on Field Coils

System	TPR	RFPR		TOKAMAK	
		(R)	(S)	(O)	(P)
B_e (kG)	110	15	12	39	94
p_{mc} (MN/m²)	48	0.9	0.6	6	35
Relative p_{mc}	53	1.0	0.63	6.7	39
B_A Air Core (kG)	-	-	45	>60	>200
p_{mA} Air Core (MN/m²)	-	-	8	14	158

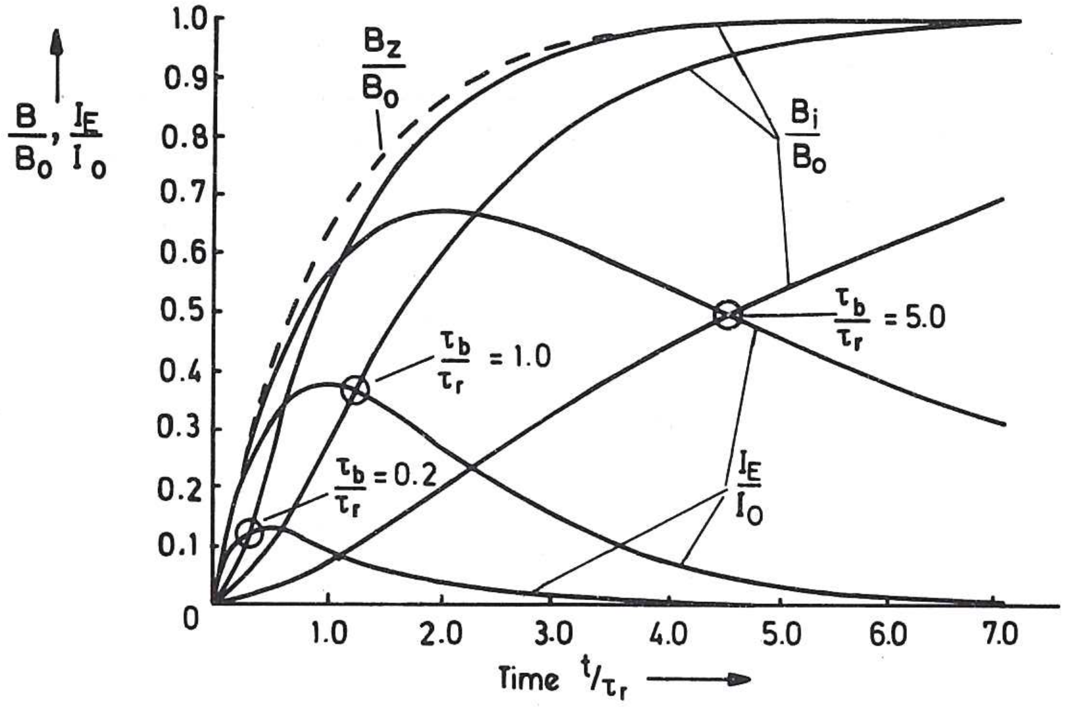
Such a low coil pressure, combined with the use of copper windings, represents a very significant advantage for the RFPR from the point of view of both simplicity and cost. The highest magnetic pressure p_{mA} occurs in the air core of the Tokamak (at >200 kG) being >20 times that in the RFPR air core.

6.2 Transient Forces on Blanket Structures

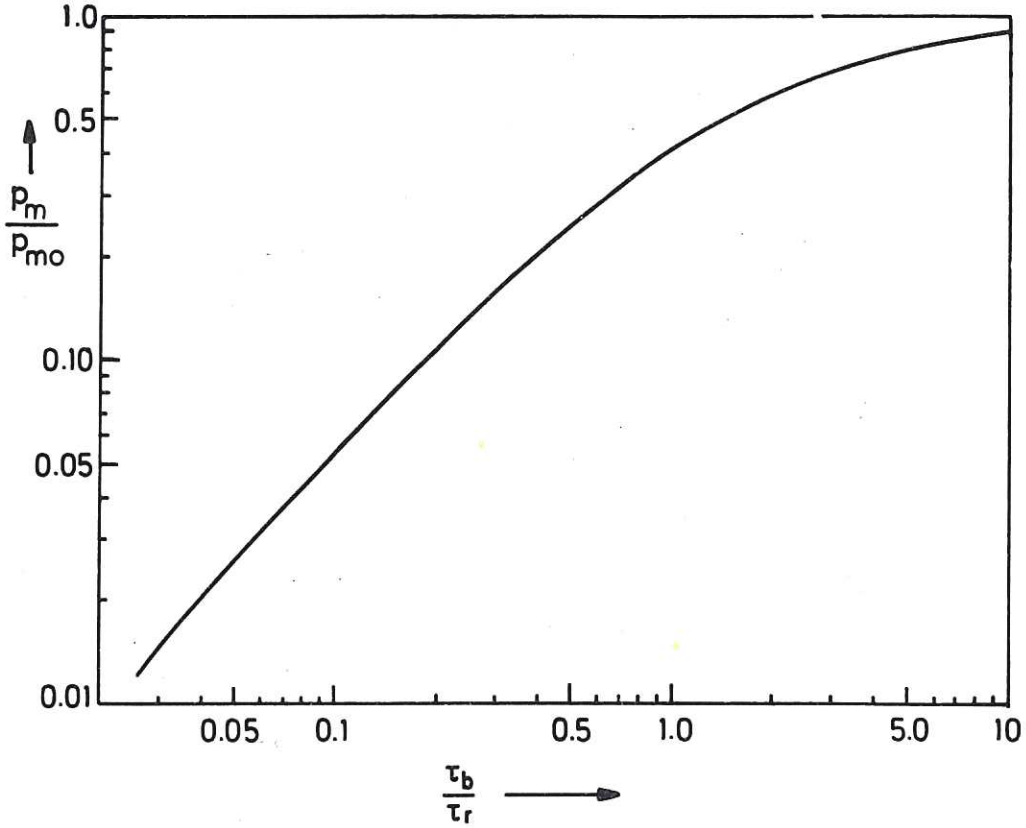
During the diffusion of magnetic field into the blanket region there will be a net inward magnetic pressure p_m on the outer regions of the blanket. In a homogeneously conducting region p_m is not likely to be high, but opposite a region of poor conductivity the forces on the outer wall may be significant.

This problem has been analysed(11) for fields rising exponentially with a time constant τ_r to a peak value B_o, using the thin-wall approximation for magnetic field diffusion. The resulting internal field waveforms B_i/B_o, are given in Fig.13 for various values of τ_b/τ_r, where τ_b is the blanket region time constant. B_i is deduced from the induced eddy currents ratio I_E/I_O where I_o is B_o/μ_o per metre length. The net peak magnetic pressure ratio $p_m/p_{mo} = (B_z^2 - B_i^2)/B_o^2$ is plotted in Fig.13 as a function of τ_b/τ_r, though the values of τ_b/τ_r used in Fig.13 (to illustrate the problem) are much higher than can be tolerated in most practical cases ($\tau_b/\tau_r < 0.002$).

Table 5 shows values of p_m, deflection $\Delta\ell_\theta$ and mechanical stress f_m in a flat blanket wall for the hypothetical case of an



(a) Magnetic field and current density time histories



(b) Peak magnetic pressure ratio (p_m / p_{mo})

Fig.13 Field Penetration and Resulting Magnetic Pressure in Pulsed Reactor Blankets.

Table 5

Blanket wall Transient Force Parameters
Peak magnetic pressure p_m, stress f_m, deflection $\Delta\ell_\theta$
(Unsupported length Δr_{bu} = 0.1 m)

$2W_E/W_{BO}$ (%) τ_b/τ_r	0.5 0.0025		5 0.025	
System	TPR	RFPR	TPR	RFPR
t_r (s)	0.030	1.0	0.030	1.0
τ_b (ms)	0.038	1.25	0.38	12.5
ℓ_θ or θ_z (m)	0.015	0.14	0.05	0.28
B_o (kG)	110	15	110	15
p_{mo} (MN/m^2)	48	0.9	48	0.9
p_m/p_{mo} (%)	1.25	1.25	12.5	12.5
p_m (MN/m^2)	0.6	0.011	6.0	0.11
f_m (δ = 1 mm) (MN/m^2)	3,000	55	30,000	550
$\Delta\ell_\theta$ (δ = 1 mm) (mm)	10	0.17	100	1.7
f_m (δ = 4 mm) (MN/m^2)	190	3.5	1,900	35
$\Delta\ell_\theta$ (δ = 4 mm) (mm)	0.16	0.002	1.6	0.02

unsupported length Δr_{bu} of 0.1 m for typical parameters. With an eddy current loss ratio of 0.5% the maximum value of p_m of about 0.6 MN/m^2 (for B_o = 110 kG, t_r = 30 ms in TPR) is relatively low if the blanket design has to take account of a possible static internal blanket pressure of some 4.0 to 6.0 MN/m^2 (12), though at lower internal pressures the effect of the magnetic forces could be significant. However, if a higher eddy current loss ratio of 5% is acceptable the p_m value of 6.0 MN/m^2 could not be tolerated. At B_o = 15 kG and t_r = 1.0 (RFPR) p_{mo} can be almost be neglected.

To withstand the high static internal pressure, blanket modules of circular cross-section are favoured because of their intrinsically stiff self-supporting geometry. However, the additional transient magnetic stress is expected to necessitate some reduction in the static stress and consequently the blanket internal pressure(13). In the hypothetical case of an unsupported 0.1 m length in a flat 1 mm blanket wall, Table 5 shows that the mechanical stress would be excessive at 110 kG (TPR) under all conditions and also with a 4 mm wall at 5% eddy loss ratio and 0.030 s rise time. At the lower field of 15 kG (RFPR) the stresses are probably acceptable except for a 1 mm wall and 5% eddy loss ratio.

(7) CONCLUSIONS

Electrical engineering problems in the pulsed magnetically confined reactors considered can be summarised as follows:-

General

(a) All three systems require the transfer of several 1,000 MJ of energy into and out of the reactor field system every pulse, at high efficiency and peak power ratings, probably more than 5 times the plant output. There does not yet appear to be a sufficiently efficient, reliable and cheap method of achieving this energy transfer. Further studies of these problems are urgently required as the credibility of pulsed reactors depends on their solution.

(b) To enable an adequate solution of the pulsed power supply problem to be realised, it is desirable that the pulsed field energy be reduced to not more than about 3 times the reactor nuclear power P_{TH} in MW and be transferred in more than 1.0 s.

Theta-Pinch Reactors (TPR)

(c) The TPR poses the most severe energy transfer problems of any system, since about 63 GJ and 1 GJ have to be transferred in 30 ms and 1.0 μs, respectively. Though the proposed superconducting rotating store and capacitor banks are 'in principle' solutions, there appears as yet to be little evidence that they are sufficiently efficient, reliable or cheap.

(d) The low circulating power required in the TPR is critically dependent on a small blanket depth, direct conversion of α-particle energy back into the rotating store and an efficiency of ~ 98% in the latter.

(e) The short pulse time of the TPR means that a high plasma density is required, giving rise to high static and transient magnetic forces on field coils and blanket modules though the use of copper coils is a significant advantage.

Reverse Field Pinch Reactor (RFPR)

(f) The RFPR has much the lowest ratio (n/β) of plasma density (n) to plasma/field pressure ratio (β) and hence a very low magnetic field, decreasing away from the plasma. Thus, its total magnetic energy and forces will be low, which combined with the use of copper field coils should result in possibly the least complex and cheapest pulsed reactor system.

(g) Since the RFPR aspect ratio is not a limiting factor, it can be chosen to be sufficiently large (combined with the small blanket depth needed with copper field coils) for an iron core transformer to be used in most circumstances. This significantly reduces the pulsed field energy required and represents a major advantage compared with the Tokamak system.

(h) The value of the transformer core flux φ_z required in the RFPR to induce the plasma current is a critical factor regarding the pulsed power supply rating, plant cost and the circulating power fraction at short pulse times (say 10 s). The reduction of φ_z to about 120% of the plasma inductive flux may be necessary.

Tokamak Pulsed Reactors

(i) The engineering problems in the pulsed Tokamak reactor are difficult to assess realistically because the assumed plasma parameters can modify the magnetic energy requirements by a factor of about 5. With optimistic plasma parameters it may be comparable with the RFPR. Using pessimistic plasma parameters, the required DC superconducting field system storing some 600 GJ at a mean field of about 100 kG would make the Tokamak considerably more complex and expensive than the RFPR (perhaps more than twice the plant cost/kW_E).

(j) The need for a small aspect ratio and large minor radius superconducting coils (due to large blanket depth) makes an air core transformer necessary with relatively high pulsed energy requirements. The limitations on the core flux φ_z discussed in (h) above for the RFPR is, therefore, equally important for the Tokamak reactor. The latter may also require additional plasma heating above that given by ohmic heating.

(8) ACKNOWLEDGEMENTS

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